Stellar Systems at Low Radio Frequencies

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100 — New Discoveries

100.01 — Review of TESS's First Year Survey and Future Plans

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Successfully launched in April 2018, NASA's Transiting Exoplanet Survey Satellite (TESS) is well on its way to discovering thousands of exoplanets in orbit around the brightest stars in the sky. During its initial two-year survey mission, TESS will monitor more than 200,000 bright stars in the solar neighborhood at a two minute cadence for drops in brightness caused by planetary transits. This first-ever spaceborne all-sky transit survey is identifying planets ranging in size from Earth-sized to gas giants, orbiting a wide variety of host stars, from cool M dwarfs to hot O/B giants.

TESS stars are typically 30–100 times brighter than those surveyed by the Kepler satellite; thus, TESS planets are proving far easier to characterize with follow-up observations than those from prior missions. Such TESS followup observations are enabling measurements of the masses, sizes, densities, orbits, and atmospheres of a large cohort of small planets, including a sample of habitable zone rocky worlds.

An additional data product from the TESS mission is its full frame images (FFIs), which are collected at a cadence of 30 minutes. These FFIs provide precise photometric information for every object within the 2300 square degree instantaneous field of view of the TESS cameras. In total, nearly 100 million objects brighter than magnitude I = +16 will be precisely photometered during the two-year prime mission.

The initial TESS all-sky survey is well underway, covering 13 observation sectors in the Southern Ecliptic Hemisphere during Year 1, and 13 observation sectors in the Northern Ecliptic Hemisphere during Year 2. A concurrent, year-long deep survey by TESS of regions surrounding the North and South Ecliptic Poles will provide prime exoplanet targets for characterization with the James Webb Space Telescope (JWST), as well as other large ground-based and space-based telescopes coming online in the next two decades.

The status of the TESS mission as it completes its first year of survey operations in July 2019 will be reviewed. The opportunities enabled by TESS's unique lunar-resonant orbit for an extended mission lasting more than a decade will also be presented.

100.02 — The Gemini Planet Imager Exoplanet Survey: Giant Planet and Brown Dwarf Demographics from 10-100 AU

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The Gemini Planet Imager Exoplanet Survey (GPIES) has observed 521 young, nearby stars, making it one of the largest, deepest direct imaging surveys for giant planets ever conducted. With detections of six planets and four brown dwarfs, including the new discoveries of 51 Eridani b and HR 2562 B, GPIES also has a significantly higher planet detection rate than any published imaging survey. Our analysis

of the uniform sample of the first 300 stars reveals new properties of giant planets (>2 MJup) from 3-100 AU. We find at >3 σ confidence that these planets are more common around high-mass stars (> 1.5 solar masses) than lower-mass stars. We also present evidence that giant planets and brown dwarfs obey different mass functions and semi-major axis distributions. Our direct imaging data imply that the giant planet occurrence rate declines with semi-major axis beyond 10 AU, a trend opposite to that found by radial velocity surveys inside of 10 AU; taken together, the giant planet occurrence rate appears to peak at 3-10 AU. All of these trends point to wide-separation giant planets forming by core/pebble accretion, and brown dwarfs forming by gravitational instability. If our power-law model that fits giant planets around high-mass stars is also applicable to solar-type stars, and these power-laws remain valid down to the mass of Jupiter and inward to 5 AU, then the occurrence rate for giant planets more massive than Jupiter within 100 AU could be less than 40%. Looking beyond these results, we present our early analysis of the full GPIES sample, whether these trends persist over all 521 observed stars, and implications for future observations from Gemini-North with an upgraded GPI.

100.03 — Three Red Suns in the Sky of the Nearest Exoplanet Transiting an M Dwarf

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The only terrestrial exoplanets whose atmospheres will be spectroscopically accessible in the near future will be those that orbit nearby mid-to-late M dwarfs. We present the discovery from TESS data of LTT-1445Ab, a terrestrial planet transiting an M dwarf only 6.9 parsecs away, making it the closest known transiting planet with a small-star primary. Remarkably, the host stellar system is composed of three mid-to-late M dwarfs in a hierarchical configuration, which are blended in a single TESS pixel. We use follow-up observations from MEarth and the centroid offset from the TESS data to determine that the planet transits the primary star in the system. The planet has a radius 1.35 times that of Earth, an orbital period of 5.36 days, and an equilibrium temperature of 428 K, and the mass should be readily measurable with radial velocity observations in the coming months. The system is particularly favorable for ground-based observations to advance the study of the atmospheres of terrestrial exoplanets: Such observations are typically performed using multi-object spectrographs on large telescopes, but previous studies have been limited by the need to use blue field stars to calibrate telluric variations, which have provided a poor color match to the red target stars. Here, the companion stars provides an ideal telluric calibrator, namely one of nearly equal brightness and similar spectral type located only 7 arcseconds from the target.

This work is supported by grants from the National Science Foundation and the John Templeton Foundation.

100.04 — Evidence for an additional planet in the β Pictoris system.

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With its well resolved debris disk of dust, its evaporating exocomets, and an imaged giant planet orbiting at about 9 au, the young (∼23 Myr) β Pictoris system is a unique proxy for detailed studies of planet formation and early evolution processes as well as planet-disk interactions. We have studied 10 years of ESO/HARPS high resolution spectroscopic data on the star. After removing the δ Scuti pulsations, a ∼1200 days periodic signal is observed. Within our current knowledge, we can only attribute this signal to a second massive planet orbiting at ∼2.7 au from the star (Lagrange et al, 2019, Nat. Astron., under minor revisions). To our knowledge, this is the first system hosting a planet detected in imaging and one detected with indirect technics. I will present the evidence for this additional planet, and analyse the impact of this result on previous results, including previous analysis of GAIA astrometric data, the system dynamical stability, the exocomets activity.

100.05 — Absence of a thick atmosphere on a terrestrial exoplanet

Laura Kreidberg[1]; Daniel D. B. Koll[2]; Caroline Morley[3]; Renyu Hu[9]; Laura Schaefer[4]; Drake Deming[5]; Kevin Stevenson[6]; Jason Dittmann[2]; Andrew Vanderburg[3]; David Berardo[2]; Xueying Guo[2]; Keivan Stassun[7]; Ian Crossfield[2]; David Charbonneau[1]; David Latham[1]; Abraham Loeb[1]; George Ricker[8]; Sara Seager[2]; Roland Vanderspek[2]

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I will present a thermal phase curve measurement for a terrestrial exoplanet recently detected by the TESS mission. The planet is in a short period orbit around a nearby M-dwarf star. The phase curve is the first such measurement for a planet smaller than 1.6 Earth radii, the size below which the existence of an atmosphere is unknown a priori. The amplitude of the phase variation puts strong constraints on the planet's atmospheric properties, which I will discuss.

100.06 — Recent Microlensing Results: Individual Systems and Demographic Frontiers

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Over the past several years, the field of gravitational microlensing has made myriad advancements with regard to characterizing individual planetary systems, exploring relatively unknown demographic regimes, and developing tools and resources for community use. Here I will highlight a handful of results that lead to precise planet masses for microlensing planets, including (A) measuring the microlens parallax effect (e.g., Street+ 2016); (B) using high-resolution photometry to constrain the flux of the lens (e.g., Bhattacharya+ 2018); (C) complementing microlensing photometry with astrometric and spectroscopic data (Han+ 2019); and (D) deriving the Einstein radius through interferometry (Dong+ 2019). I will also discuss recent demographic studies, including (i) constraining the frequency of free-floating planets (e.g., Mróz+ 2017, 2018; Poleski+ 2014); (ii) determining the Galactic distribution of exoplanets via a multi-year *Spitzer* program (cf. Yee+ 2015); and (iii) understanding and contextualizing the planet-star mass-ratio distribution (Suzuki+ 2016, 2018; Pascucci+ 2018). Finally, I will conclude by describing the public tools and data provided, in particular by the *WFIRST* Microlensing Science Investigation Team, to allow for the larger exoplanet community to get involved with immediate science and also help prepare for the *WFIRST* microlensing survey.

101 — Direct Imaging

101.01 — Frequency of Massive Wide-orbit Planets vs. Stellar Mass: SPHERE SHINES on the ESO VLT

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We describe the SpHere INfrared Exoplanet (SHINE) survey, a key part of the SPHERE GTO Program on the ESO VLT, and present new statistical analyses of the frequency of gas giant planet occurrence as a function of host star mass. Constraining the frequency of the most massive planets, as well as the lowest mass brown dwarf companions, at wide orbital separations vs. host star mass, enables us to discern the mean outcomes of planet formation, thus defining what is extreme in the context of planetary architectures. In addition, our data provides a strong test of predictive theories of star and planet formation. This high contrast imaging survey has discovered and characterized dozens of very low mass companions (1-76 $M_{Jupiter}$), on wide orbits (10-1000 AU) around a range of host star masses (0.3-3 M_{SUN}). Three papers in preparation (Desidera et al.; Langlois et al.; Vigan et al.) describe the survey sample and strategy, data reduction and analysis techniques, and the first statistical results. Our survey, constraining the frequency of gas giants 1-10 $M_{Jupiter}$, as well as brown dwarf companions, from 10-100 AU, suggests: 1) the frequency of gas giants around FGK (and other) stars peaks between 1-10 AU; 2) the gas giant planet mass function appears to be a universal power-law relative to host star mass, explaining the trend of gas giant detection rate of with star mass; 3) the brown dwarf companion mass function is consistent with extrapolation from a universal stellar companion mass ratio distribution down to the minimum mass for fragmentation; and 4) some, but not all, relevant predictions made by D.N.C. Lin are thankfully inconsistent with these data.

101.02 — Population-Level Eccentricity Distributions of Imaged Exoplanets and Brown Dwarf Companions

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The dominant formation channel of long-period directly imaged exoplanets and brown dwarf companions has been challenging to unambiguously constrain with observations because of their low occurrence rates, limited composition measurements, and degeneracies among theoretical predictions. Eccentricities offer a robust tool to assess the origin of these populations because they directly trace the dynamical imprint after formation and any subsequent orbital evolution.

In this talk I will discuss new results on the underlying eccentricity distributions of directly imaged exoplanets and brown dwarf companions. We have carried out homogeneous orbit fits based on new high-contrast imaging observations together with a compilation of astrometry from the literature to assess the individual and population-level eccentricity distributions of over two dozen long-period giant planets and brown dwarfs between 5-100 AU using hierarchical Bayesian modeling. Each companion traces out a small orbit arc which typically results in a broad constraint on its individual eccentricity, but together as an ensemble these systems provide valuable insight into their collective underlying orbital patterns.

The population-level eccentricity distributions for the subset of giant planets (2-15 M_{jup}) and brown dwarf companions (15-75 M_{jup}) are significantly different and provide compelling dynamical evidence for distinct formation pathways. As a population, long-period planets preferentially have low eccentricities, suggesting formation within a disk. The brown dwarf subsample is dynamically hotter with a broad peak at high eccentricities, which is qualitatively similar to binary stars. Larger samples and continued astrometric orbit monitoring will help establish whether these eccentricity distributions correlate with other parameters such as stellar host mass, multiplicity, and system age.

101.03 — Two giant Exomoons around two low-mass Brown Dwarf companions detected with SPHERE

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It is still unclear if brown dwarfs companion detected with the direct imaging technique were formed as stars or planets. The analysis of their multiplicity can provide clues on their formation mechanism. In this context, we analyzed the residuals around brown dwarf companions observed with SPHERE during the SHINE/GTO with the technique of negative fake planets to look for features around them. We found an extended source around one of the brown dwarf in the sample that would suggest the presence of a disk and two candidate companions, massive gaseous exomoon-like objects, bound to other two brown dwarfs. These latter would represent the first triple systems ever discovered with two substellar companions, one in the planetary regime and the second just above the deuterium burning limit.

101.05 — PDS 70 b: Evidence for a circumplanetary disc around the fIrst directly imaged protoplanet

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The observed properties of the major moons of Jupiter — and of other gas giants — have suggested that they formed within a circumplanetary disc. This prediction has been supported by theoretical calculations and numerical simulations of increasing complexity over the past few decades. Despite intensive search, circumplanetary discs had until now eluded detection. In this talk, I will present the first observational evidence for a circumplanetary disc, around recently imaged protoplanet PDS 70 b. Our detection is based on a new near-IR spectrum acquired with VLT/SINFONI. We tested several hypotheses (atmospheric emission alone, variable extinction, combination of atmospheric and circumplanetary disc emission) to explain the spectrum and show that models considering atmospheric emission alone consistently underpredict the longward portion of the spectrum. Our best fit is obtained with a combined atmospheric and circumplanetary disc model, with emission from the circumplanetary disc accounting for the apparent excess IR emission.

101.06 — A Pan-STARRS and TESS Search for Distant Planets

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Several lines of evidence, both theoretical and observational, indicate that additional planets in the outer solar system remain to be discovered. We recently developed a novel technique to search for solar system bodies (Holman et al. 2018). This method is particularly well-suited to very slow-moving objects, even those for which the motion within a day might be to small to detect. We present the results of our use of this method to search for distant planets and minor planets in existing Pan-STARRS and TESS data. Perhaps even more important than the search itself is a detailed, quantitative analysis of the survey's detection limits and biases. This information is essential for the rigorous interpretation of these survey results. Such simulators have been developed for CFEPS/OSSOS, NEOWISE, and other surveys, leading to detailed results on the small body populations throughout the solar system. We have developed a high-fidelity survey simulator for Pan-STARRS and have extended it to TESS. This simulator takes positions, magnitudes, and rates of motion calculated from a solar system model (Grav et al 2011) at the times and locations of individual exposures. It then inserts synthetic detections into the resulting exposure source catalogs, accounting for the details of the camera, photometric zero point, and other essential details. The source catalogs, including synthetic detections, are then run through our full search pipeline. This approach allows a clear, quantitative statement about the prevalence of distant planets, as seen by Pan-STARRS and TESS.

101.07 — Studying the Interior Structure of an Extremely Eccentric Hot Jupiter via Deep VLT Imaging

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I will describe how our group at Exeter has used the VLT-SPHERE instrument to place constraints on the internal structure of HD 20782b, a Hot Jupiter with the most extreme eccentricity known to date (e$\sim$0.96). In the dynamically-driven migration scenario (e.g. Kozai-Lidov cycles combined with tidal dissipation), a Jupiter mass planet is dynamically excited to a high eccentricity by a third body, and its orbit subsequently shrinks and circularizes through tidal dissipation. Our deep observations of the HD 20782 system rule out any additional (third) companions with masses in the range 20-60 Jupiter masses at orbital separations $\sim$10-60 AU that might be responsible for exciting the extreme eccentricity of the inner planet. Our lack of detections of any additional companions in the system indicates that the eccentricity of the planet was gained early on and has persisted until the present. The apparent failure of the tidal dissipation mechanism in this system means that we can place strong constraints on the tidal quality factor "Q" of HD 20782b. Specifically, our models of planetary tidal evolution suggest a remarkably high value for the planet's tidal Q factor of $10^7 - 10^8$: two to three orders of magnitude higher than that measured for other extrasolar planets, as well as members of our own solar system. Our result suggests a possible structural difference between HD 20782b and other giant planets inside and outside our solar system. If time allows, I will discuss how our approved 52-hour JWST Early Release Science Program will pave the way for future observations of additional systems with extremely eccentric planets starting in 2021. JWST will illuminate the interior structures of many more eccentric Jovian mass planets going forward, or possibly even image the extremely eccentric planets themselves.

102 — Radial Velocities

102.01 — HARPS and HARPS-N solar telescopes: the key to extremely precise radial-velocity measurements

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Detecting and measuring the masses of planets in the presence of stellar signals is the main challenge we are facing when using the radial-velocity (RV) technique. Even in the TESS era where planetary periods are known, obtaining a precise mass, which is critical to constrain further planetary composition and thus planetary formation, is challenging.

Critical to a better understanding of RV variations induced by stellar signals and finding correction techniques is RV data with a sampling sufficient to probe timescales ranging from minutes to years. To address this challenge, our team built two solar telescopes that feed sunlight into HARPS-N and HARPS, which allows us to obtain Sun-as-a-star RVs at a sub-m/s precision.

In this talk, I will present the data that obtained during the last 4 years with HARPS-N and nearly a year with HARPS. I will show how the two datasets match at a level of 40 cm/s within a day, which allows to characterize p-modes, granulation signal, and stellar activity on the rotation timescale of the Sun, which we know are the main limitations to precise RVs.

With these data, we start to improve our understanding of how stellar signals affect RVs: - CCF-line shape variability correlates with RVs with a significant time-delay that prevents using shape variations directly as a proxy for stellar activity. - RV correlates strongly with total magnetic field strength, which makes sense as magnetic regions are at the origin of most stellar signal. - With the extreme SNR that we reach on the Sun, we see that when analyzing the RV of individual spectral lines, some are much more sensitive to stellar activity than others, due to differing formation height in the stellar photosphere.

All these new insights into stellar signals give us the key to develop the techniques capable of mitigating their impact down to a level that will allow the detection and characterization of Earth-twins using the RV technique.

102.02 — Rocky planets from the CARMENES Survey

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Since the first discovery, more than 800 exoplanets have been detected through the radial velocity method, the majority orbiting solar-like stars. Although M-stars are the most frequent stars, very few planets have yet been found around M-stars of late spectral type.

CARMENES, operated since 2016, is a high-resolution visible-near-IR spectrograph dedicated to search for such low-mass planets around low-mass stars and already doubled the number of known planets with host stars below 0.2 M_{Sun}. Not surprisingly, also this stellar parameter range has its surprises in terms of planetary system architectures. We will give an overview of exoplanet detections (published and unpublished) from the CARMENES survey and then concentrate on the low-mass planets, including the very recent detection of two Earth-mass planets around Teegarden's star highlighting the capability of CARMENES. The planetary system is special since Teegarden's star is only one out of three planet host stars with an effective temperature below 3000K. Its two planets are within the optimistic and conservative habitable zone, respectively. Notably, the Earth, as well as other Solar System planets are currently or in near future in the transit visibility zone see from Teegarden's star.

102.03 — A low-mass planet candidate orbiting Proxima Centauri at a distance of 1.5 au

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By analyzing ∼17 years of radial velocity data of Proxima Cen collected with the UVES and HARPS spectrographs, we detected a signal of period P∼5 years that could be explained by the presence of a second planet, Proxima c, with minimum mass m sin i∼6. Earth masses. Together with the low-mass temperate planet Proxima b, this candidate planet would make Proxima the closest multi-planet system to the Sun. We will present the properties of the new RV signal and investigate the likelihood that it is related to a magnetic activity cycle of the star. We will discuss how the existence of Proxima c can be confirmed, and its true mass determined with high accuracy, by combining Gaia astrometry and radial velocities. Proxima c would be a prime target for follow-up and characterization measurements, especially with next generation direct imaging instrumentation due to the large maximum angular separation of ∼1 arcsecond from the parent star. Since the orbit would be beyond the original location of the snowline, Proxima c would challenge the models of the formation of super-Earths. Presently, this study is under review by Science Advances.

102.04 — New insights into the keystone WASP-107 system: shedding light on the formation and chemistry of WASP-107b using Spitzer eclipse spectroscopy and a clue to unveiling its dynamics history from the detection of an outer companion with Keck/HIRES

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With the radius of Jupiter, the near-Neptune-mass planet WASP-107 presents a major challenge to planet formation theories. Meanwhile, the system's brightness and planet's low surface gravity makes it a keystone target for spectroscopic characterization, especially in the poorly-probed low-temperature (T_{eq} < 800 K) regime. In this talk, we will present the main results of an extensive follow-up program of WASP-107b using over 2 years of Keck/HIRES radial velocities as well as >60 hours of Spitzer observations. The radial velocity data reveal an even lower planetary mass than previously thought. The inferred 1.8 Neptune mass indicates an extraordinarily high H/He mass fraction of 80% accreted by a core of only 7 ± 3 Earth masses. The resulting lower surface gravity means that all the transmission spectroscopy for this planet has to be reinterpreted. With Spitzer, we furthermore detect the thermal emission of this 720K exoplanet at 3.6μm, indicating substantial eccentricity ($e = 0.129^{+0.028}_{-0.011}$) and making it the best target for eclipse observations with JWST in this temperature regime. A puzzling brightness temperature contrast between the 3.6 and 4.5μm bandpasses presents direct evidence for disequilibrium chemistry, and makes WASP-107b a keystone target to unveil the underlying mechanisms of quenching and atmospheric dynamics. We show that the non-zero eccentricity of WASP-107b could result from the presence a second planet in the WASP-107 system on a highly eccentric ($e = 0.56^{+0.11}_{-0.14}$) and wide (~2000d) orbit, which we also detect in the radial velocity data. Overall, the joint constraints from the secondary eclipse and RV observations shed unprecedented light on the rich dynamics history of this peculiar planetary system offering an intriguing possibility for the origin of close-in exo-Neptunes like WASP-107b.

102.05 — Radial Velocity Discovery of an Eccentric Jovian World Orbiting at 18 au

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We announce the discovery of the longest-period planet with a well-constrained orbit discovered with radial velocities (RVs). HR 5183 b, with P = 75 ± 30 yr, e = 0.84 ± 0.04, and M sin i = 3.23 ± 0.14 M_J, was detected independently in more than two decades of data from Keck/HIRES and McDonald/Tull. The highly eccentric orbit takes the planet from within the orbit of Jupiter to beyond the orbit of Neptune over one period. Because of this high eccentricity, orbital information density is strongly peaked around periastron, which occurred in January 2018. By observing this periastron passage event with high cadence, we were able to place tight constraints on the orbital parameters without witnessing an entire orbital period.

In terms of semimajor axis and mass, HR 5183 b is most similar to a typical directly imaged planet, but its advanced age, extreme eccentricity, and solar-type primary star differentiate it from this population. This discovery probes a previously unexplored population of exoplanets, highlighting the value of long-baseline RV surveys and raising interesting questions about the long-term evolution of planetary systems with massive planets.

102.06 — First Results from the SPIRou Legacy Survey

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SPIRou is the infrared high-resolution echelle spectropolarimeter currently in operation on the Canada-France-Hawaii telescope, an instrument specifically designed and optimized to achieve precision radial velocity at infrared wavelengths. SPIRou features a unique polarimetric capability, high resolving power (70,000) and a very broad simultaneous wavelength coverage between 0.98 to 2.5 microns. SPIRou has two main science goals: detect small planets around nearby low-mass stars and explore the impact of magnetic field of star/planet formation. SPIRou has been allocated a 300-night Legacy Survey over a period of 4 years that was initiated in February with the following main science objectives: 1) search for small planets around low-mass stars, 2) provide mass measurements for new transiting planets from TESS and other transit surveys and 3) observe a large sample of pre-main sequence stars to detect and characterize hot Jupiters at early evolutionary stages and to investigate planet formation and planet/disc interactions. Thanks to its wide wavelength range, SPIRou is also a very powerful capability for atmospheric characterization of transiting exoplanets. This talk will present an overview of the instrument and its on-sky performance along with a highlight of the first science results obtained so far as part of the Legacy Survey.

103 — Transits

103.01 — Expectations vs. Reality: The Exoplanet Yield in the TESS Full-Frame Images

Adina Feinstein[1]*; Benjamin Montet*[1]*; Nicholas Earley*[1]

[1] *Astronomy & Astrophysics, University of Chciago (Chicago, Illinois, United States)*

During its two year prime mission, the Transiting Exoplanet Survey Satellite (TESS) will perform a time-series photometric survey for 80% of the sky, observing 26 24x96 degree sectors of the sky each for 27 days. The primary objective of TESS is to find transiting planet candidates around 200,000 pre-selected stars for which fixed aperture photometry is recovered every two minutes. However, TESS is also recording and delivering Full-Frame Images (FFIs) of each detector at a thirty minute cadence. Using the *eleanor* pipeline, which creates light curves for all stars in the FFIs, we have begun a uniform transit search for targets in multiple sectors. In this talk, I will highlight several of the current findings within the FFI data. I will discuss our reduction and vetting processes, specifically highlighting the most common false positives found within the data, how we identify them, and how we remove them from the final data set. As TESS has already proven a successful mission and has been awarded an extended mission, we will continue to search the FFIs for new planet candidates to further our understanding of the exoplanet population, especially those of longer periods, and its implications for finding new planets in this data set

103.02 — Newly Formed Planets within the Debris Disk of the Nearest Pre-main-sequence Star AU Mic

Peter Plavchan[1]

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We report a two-planet system orbiting a young star with a debris disk, one inner planet discovered using data from NASA's TESS mission and a second planet with multi-wavelength radial velocities. The two newly identified planets in this system can be used to investigate disk-planet interactions and inform the planet formation and migration process.

103.03 — Identifying Exoplanets with Deep Learning: New Discoveries and Progress towards Planet Occurrence Rates in Kepler, K2, and TESS

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Deep learning, a cutting edge machine learning technique, is leading to remarkable advancements in fields ranging from biomedical imaging to linguistics. Our team is leveraging this technology to discover new exoplanets and characterize their populations. We have built and tested neural networks to classify and vet transiting planet candidates from Kepler, K2, and TESS and identified new exoplanets from large sets of unclassified signals. Our discoveries include two super-Earths from the K2 mission, a new planet in a five-planet resonant chain around Kepler 80 and an eighth planet around Kepler 90, making this the most extreme solar system known in number of planets. I will give an overview of deep learning, describe our newly discovered planets, and discuss the path forward to using these deep learning classification tools to measure planet occurrence rates in Kepler, K2, and TESS.

103.04 — The HD 21749 System: A Temperate Sub-Neptune, an Earth-sized planet, and Who Knows What Else

Diana Dragomir[1]*; Chelsea X. Huang*[3]*; Stephen Kane*[2]*; Paul A. Dalba*[2]*; Maximilian N. Günther*[3]

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Our understanding of multi-planet systems has been dominated by Kepler discoveries, our understanding of multis is nowhere near complete. With TESS we have the opportunity to fill in missing pieces, like precise masses and orbital eccentricities of planets in multis, and to search for non-transiting planets with radial velocity measurements.

I will present the recent discovery of HD 21749 (jointly enabled by TESS and existing ground-based observations), a multi-planet system with an intriguing architecture. It includes an unusually dense (7 g/cm^3) sub-Neptune in a mildly eccentric 35.6-day orbit, and a 0.9 Earth radius planet with a period of 7.8 days, around a K dwarf star located 16 pc away from the Sun. A similar architecture (in terms of periods, and non-zero eccentricity of the outer planet) has surfaced in four other systems known to host small/low-mass planets. The host stars of HIP 57274, HIP 7924 and HIP 69830 are also K dwarfs, but these systems are not known to transit so only lower limits are available on their masses, and no radius measurement. The periods of the two known low-mass planets in the K2-18 system (9 and 33 days) are very similar to those of HD 21749 b and c, but while K2-18b has a radius and a mass measurement, planet c does not transit and only has a lower mass limit. Moreover, the host star is a M dwarf, and thus planet formation probably differed between those two systems. With prospects for a mass measurement of planet c in the near future, HD 21749 is poised to become the best characterized system with this emerging architecture.

We have continued monitoring this system with Magellan-PFS radial velocities, leading to improved constraints on the orbital eccentricity of planet b, and on the presence and properties of additional planets in the system. I will also show results from a dynamical analysis of the system, which provide an independent constraint on the mass of planet c and on islands of stability where other planets could orbit. Lastly, I will explore a few exciting follow-up avenues within reach, including prospects for atmospheric characterization and orbital obliquity measurements.

103.05 — Detecting Magnetic Fields in Exoplanets with Spectropolarimetry in the Helium Line at 1083 nm

Antonija Oklopcic[1]; Christopher Hirata[2]; Paulo Montero Camacho[2]; Makana Silva[2]

[1] *Harvard University (Cambridge, Massachusetts, United States)*

[2] *Ohio State University (Columbus, Ohio, United States)*

Most planets in the solar system have or previously had a global magnetic field, yet not much is known about magnetic fields in exoplanets. Information about the presence of a magnetic field and its strength could give us valuable insights into the interior structure and thermal evolution of an exoplanet. Furthermore, a global magnetic field on an exoplanet could have important consequences for the extent, composition, and evolution of its atmosphere, by controlling atmospheric escape and its interaction with the stellar wind. In this talk, I will present a new method for detecting magnetic fields in the atmospheres of close-in exoplanets, based on spectropolarimetric transit observations at the wavelength of the helium line at 1083 nm. Strong absorption signatures (transit depths on the order of a few percent) in the 1083 nm line have recently been observed for several close-in exoplanets. Most of the work so far has been focused on measuring and interpreting the effects of extended or escaping planetary atmospheres on the radiation intensity at 1083 nm; however, a wealth of information can be stored in radiation polarization as well. I will describe how linear and circular polarization signals in the helium 1083 nm line arise in the presence of an external magnetic field due to atomic level polarization induced by anisotropic stellar radiation, and the combined action of the Zeeman and Hanle effects. This phenomenon has been well established in solar physics as a means to probe the magnetic field properties of the solar chromosphere and corona, and I will demonstrate how the diagnostic power of this method can be extended to the field of exoplanets. Assuming exoplanetary magnetic fields with strengths comparable to the magnetic fields observed in the solar system planets, polarization signals in the helium 1083 nm line should be detectable with modern high-resolution spectropolarimeters operating at these wavelengths.

103.06 — The Most Metal-Poor Planets Around the Oldest Stars in Milky Way

Ji Wang[1]

[1] *Astronomy, The Ohio State University (Comlubus, Ohio, United States)*

The Gaia-TESS synergy opens up a new window to peer through planet formation in the galactic context. We can finally answer the following question: when and how did the first planet form? By selecting ~27,000 halo stars, the oldest stellar population in the Milky Way, via their galactic kinematics provided by Gaia, we conduct the most conprehensive study on chemical abundance of halo stars using SDSS/APOGEE spectra, and the search for the most metal-poor planets using TESS data. The study leads to discoveries of a few planet candidates through TESS sector 9 and the characterization of their stellar enviroment. We will report the exciting discoveries, the follow-up observations for planet confirmation and validation, and the implications on planet formation in extremely metal-poor enviroment in the infant universe.

103.07 — TESS Discovery of the First Ultra Hot Neptune, LTT9779b

James Jenkins[1]
[1] *Universidad de Chile (Santiago, Chile)*

In this talk I will discuss the discovery of a super Neptune orbiting the bright and metal-rich star, LTT9779. The planet was first detected as a candidate in data from Sector 2 of the Transiting Exoplanet Survey Satellite (TESS), and subsequent ground-based photometric and spectroscopic follow-up confirmed its reality and constrained its mass. With an orbital period of only 19 hours, this world is the first Neptune-like ultra short period planet, and with an equilibrium temperature greater than 2000 K, it can be classed as the first Ultra Hot Neptune. I will discuss the detection and confirmation of this new planet, possible origins, and highlight the unique opportunities it presents for atmospheric characterisation and further follow-up. Finally, I will briefly discuss additional small planet candidates from TESS that we are actively following up in Chile, both to confirm them as bonafide planets and also to constrain their radii, masses, and bulk densities.

200 — Dynamical Evolution

200.01 — Low-Eccentricity Formation of Ultra-Short Period Planets in Multi-Planet Systems

Dong Lai[1]*; Bonan Pu*[1]
[1] *Astronomy, Cornell University (Ithaca, New York, United States)*

Recent studies suggest that ultra-short period planets (USPs), Earth-sized planets with subday periods, constitute a statistically distinct sub-sample of Kepler planets: USPs have smaller radii (1-4 Earth radii) and larger mutual inclinations with neighboring planets than nominal Kepler planets, and their period distribution is steeper than longer-period planets. We study a ”low-eccentricity” migration scenario for the formation of USPs, in which a low-mass planet with initial period of a few days maintains a small but finite eccentricity due to secular forcings from exterior companion planets, and experiences orbital decay due to tidal dissipation. USP formation in this scenario requires that the initial multi-planet system have modest eccentricities ($\sim$0.1) or angular momentum deficit. During the orbital decay of the innermost planet, the system can encounter several apsidal and nodal precession resonances that significantly enhance eccentricity excitation and increase the mutual inclination between the inner planets. We develop an approximate method based on eccentricity and inclination eigenmodes to efficiently evolve a large number of multi-planet systems over Gyr timescales in the presence of rapid (as short as 100 years) secular planet-planet interactions and other short-range forces. Through a population synthesis calculation, we demonstrate that the ”low-e migration” mechanism can naturally produce USPs from the large population of Kepler multis under a variety of conditions, with little fine tuning of parameters. This mechanism favors smaller inner planets with more massive and eccentric companion planets, and the resulting USPs have properties that are consistent with observations.

200.02 — Relaxation of Resonant Two-planet Systems and their TTVs

Rosemary Mardling[1]
[1] *School of Physics and Astronomy, Monash University (Clayton, Victoria, Australia)*

Many two-planet systems reside near or inside first-order resonances, while many multi-planet systems form resonant chains. These are normally the product of planet-disk interactions during the time of formation, with eccentricity damping and migration resulting in a relaxed system with fewer degrees of freedom than for an arbitrary two-planet system. Are most multi-planet systems in this state? Even if they reside ‘far’ from resonance? A simple formulation describing two-planet systems will be presented which is valid inside, across and outside resonance. We will show that all such systems are governed by a single two-parameter ordinary integro-differential equation, and that all system information (variation of eccentricities, orbital frequencies, resonance angles, apsidal orientations, transit timing variations or TTVs) can be derived from its solution. An expression for the TTVs can be easily inverted to solve for the planet masses (and other system parameters) when both planets transit; if no valid inversion is possible (given sufficient signal to noise for the TTVs), it is possible to infer the existence of additional non-transiting planets, the signature of which will be imprinted on the signal.

200.03 — Signatures of Hidden Friends to Multiplanet systems

Smadar Naoz[1]
[1] *Physics and Astronomy, University of California, Los Angeles (Los Angeles, California, United States)*

Multiplanet systems seem to be abundant in our Galaxy. These systems typically feature tightly packed multiple super-Earths or sub-Neptunes with periods less than a few hundred days. Moreover, these systems seemed to be dynamically calm, with nearly co-planar and circular orbital configurations. In contrast, a significant fraction of single, close in, planets found by Kepler, have larger orbital eccentricities. Is the single planet population a result of the instability episode of the multiplanet population? If so, what triggered the instability?

A possible cause for instability is gravitational interactions with a distant companion. Radial velocity surveys found a population of giant planets and companions at far distances from their host star (e.g., Knutson et al. 2014; Bryan et al. 2016). Moreover, distant (few AUs) planetary and stellar companions were identified to orbit some specific tightly packed multiplanet systems (e.g., Uehara et al. 2016, Bryan et al. 2019, Mills et al. 2019). These companions co-exist with their inner multiplanet system and do not trigger dynamical instability. Thus, we ask, what are the allowable orbital configurations that friends for stable multiplanet systems?

I this talk I will present an analytical criterion that specifies the possible orbital configuration of a far away companion to a multiplanet system. I will also provide a set of predictions for the possible distant companion's orbital architecture of existing systems, such as Kepler-56, Kepler-448, Kepler-88, Kepler-109, and Kepler-36. Finally, I will show that a distant companion can affect the planets' obliquity with respect to their orbital angular momentum. In turn, this has a unique observable signature on the planets' flux incident at the top of the atmosphere as a function of orbital phase.

200.04 — In-Situ Excitation of Warm Jupiter Eccentricities: Implications for Dynamical Histories & Migration

Kassandra Anderson[1]*; Dong Lai*[1]*; Bonan Pu*[1]
[1] *Astronomy, Cornell University (Ithaca, New York, United States)*

Warm Jupiters (giant planets with orbital periods 10-300 days) are a major topic in exoplanetary dynamics, given their possible links to hot Jupiters, and unresolved puzzles regarding their dynamical histories and migration. Many planets show hints of a violent past, with substantial eccentricities. High-eccentricity tidal migration is a natural mechanism for producing eccentric warm Jupiters, but struggles to reproduce other characteristics of the warm Jupiter population. This talk discusses alternative dynamical mechanisms for raising eccentricities, starting from a low-eccentricity state consistent with either a disk migration origin or in-situ formation. First I discuss eccentricity growth due to secular perturbations from an external giant planet companion, through an apsidal precession resonance (for low-inclination systems), or Lidov-Kozai cycles (for highly-inclined systems). Taking the sample of warm Jupiters with characterized giant planet companions, I evaluate the prospects for secular eccentricity excitation, and find that high mutual inclinations (at least 40-50 degrees) are typically needed to produce observed eccentricities. The results of this work place constraints on possibly unseen external companions to eccentric warm Jupiters. Next I discuss the possibility of producing eccentric warm Jupiters due to in-situ formation of three giant planets, followed by planet-planet scattering. Scattering at sub-AU distances from the host star results in a combination of planet collisions and ejections, producing comparable numbers of one-planet and two-planet systems. Two-planet systems arise exclusively through planet-planet collisions, and tend to have low eccentricities/inclinations and compact configurations. One-planet systems arise through a combination of ejections and collisions, resulting in much higher eccentricities. The observed eccentricity distribution of solitary warm Jupiters is consistent with roughly half of systems having undergone in-situ scattering, and the remaining having experienced a quiescent history.

200.05 — Signatures of a Planet – Planet Impacts Phase in Exoplanetary Systems Hosting Giant Planets

Renata Frelikh[1]*; Hyerin Jang*[1]*; Ruth Murray-Clay*[1]*; Cristobal Petrovich*[2]
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Giant planets are often found on substantially non-circular, close-in orbits. An important clue for their dynamical histories has not yet been explained in theories for the origins of their eccentricities: most planets with high eccentricities (e>0.6) tend to also be planets of higher mass (m>1 MJ). This is surprising: the orbits of the lower-mass planets in a system are typically the most easily excited. Furthermore, these eccentric planets are preferentially found around stars that are metal-rich. We propose that these eccentricities arise in a phase of giant impacts, during which the planets scatter each other and collide, with corresponding mass growth as they merge. We numerically integrate an ensemble of systems with varying total planet mass, allowing for collisional growth, to show that (1) the high-eccentricity giants observed today may have formed preferentially in systems of higher initial total planet mass, and (2) the upper bound on the observed giant planet eccentricity distribution is consistent with planet-planet scattering.

200.06 — AMD-stability of Planetary Systems

Jacques Laskar[1]; Antoine Petit[1]
[1] *IMCCE, Observatoire de Paris (Paris, France)*

Due to the increasing large number of discovered planetary systems, it becomes important to set up some framework for a rapid understanding of the dynamics of the discovered systems, without the need of computer intensive numerical simulations. This has been the goal of our recent work on AMD-stability.

In a planetary system, the AMD (Angular Momentum Deficit) is the difference between the planar circular angular momentum and the total angular momentum. This quantity is conserved between collisions in the average system, and decreases during collisions.

This leads to the concept of AMD-stability. A planetary system is AMD-stable if the AMD in the system is not sufficient to allow collisions. The advantage of this notion is that it becomes possible to verify very quickly whether a newly discovered planetary system is stable or potentially unstable, without any numerical integration of the equations of motion. These principles have been applied to the 131 multiple planetary systems of the exoplanet.eu database whose orbital elements are sufficiently well determined (Laskar and Petit, 2017a).

AMD-stability, based on the secular evolution, addresses to long time stability, in absence of mean motion resonances. On the other hand, criterions for short term stability have been established on the basis of Hill radius (Marchal & Bozis 1982; Gladman 1993; Pu & Wu 2015) or on the overlap of mean motion resonances (Wisdom 1980; Duncan et al. 1989; Mustill & Wyatt 2012; Deck et al. 2013). Both long and short time scales can be combined owing some modification of the AMD-stability criterion (Petit, Laskar & Boué, 2017b). Finally, Hill stability can be expressed in a very effective and simple way in the AMD framework (Petit, Laskar, Boué, 2018).

Ref: Laskar, J. and Petit, A.C., 2017a, AMD-stability and the classification of planetary systems, A&A, 605, A72 Petit, A.C. Laskar, J. and Boué, G., 2017b, AMD-stability in presence of first order mean motion resonances, A&A, 607, A35 Petit, A.C. Laskar, J. and Boué, G., 2018, Hill stability in the AMD framework, A&A, 617, A93

201 — Ultrashort Periods and Planet-Star Interactions

201.01 — Remote Sensing of Extreme Worlds: High-Resolution Spectroscopy of Exoplanet Atmospheres

Ray Jayawardhana[1]; Ernst J.W. De Mooij[2]; Jake Turner[1]; Emily Deibert[3]; Miranda Herman[3]; Andrew Ridden-Harper[4]; Abhinav Jindal[3]; Raine Karjalainen[5]; Marie Karjalainen[5]
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High-resolution spectroscopy, combined with the Doppler cross-correlation technique, is emerging as a powerful and robust probe of exoplanet atmospheres. Here we will report on our wide-ranging observational program targeting Jovian-mass worlds, sub-Saturns and super-Earths using a suite of frontline instruments in the optical as well as the near-infrared. In particular, we will present new findings and on-going work related to two of the hottest gas giants and a very hot terrestrial planet. With a dayside at ~4000K, KELT-9b is a so-called ultra-hot Jupiter with a temperature akin to those of dwarf stars. Transmission spectra reveal a host of metal lines in its atmosphere. With new Calar Alto/CARMENES observations, we not only confirm strong Hα in its extended exosphere, but also report robust detections of the resolved CaII triplet for the first time (paper in prep.). We have also observed two transits and portions of six phase curves of WASP-33b (~3000K), with Keck/HIRES and CFHT/ESPaDOnS to obtain transmission and emission spectra at high spectral resolution, to detect molecular signatures of TiO and water vapor (paper in prep.) Finally, we report a sensitive new search for water vapor and TiO in the atmosphere of the nearby very hot super-Earth 55 Cancri e (∼2700 K) using a combination of data from Gemini/GRACES, Subaru/HDS and CFHT/ESPaDOnS (paper submitted). Our findings suggest that unless the signal is suppressed significantly by clouds/haze, this planet may well be bone-dry. Moreover, we have recently obtained high-resolution near-infrared spectra of 55 Cnc e from CARMENES at Calar Alto as well as the brand-new SPIRou instrument on the CFHT, and expect to present first results at ESS IV.

201.02 — Stellar Systems at Low Radio Frequencies: The Discovery of Radio Exoplanets

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For more than thirty years, radio astronomers have searched for auroral emission from exoplanets. With LOFAR we have recently detected strong, highly circularly polarised low-frequency (144 MHz) radio emission associated with a M-dwarf — the expected signpost of such radiation. The star itself is quiescent, with a 130-day rotation period and low X-ray luminosity. In this talk, I will detail how the radio properties of the detection imply that such emission is generated by the presence of an exoplanet in a short period orbit around the star, and our follow-up radial-velocity (RV) observations with Harps-N to confirm the exoplanet's presence. Our study highlights the powerful new and developing synergy between low-frequency radio astronomy and RV observations, with radio emission providing a strong prior on the presence of a short-period planet. I will conclude the talk detailing how the radio detection of an star-exoplanet interaction provides unique information for exoplanet climate and habitability studies, and the extension of our survey to other stellar systems.

201.03 — Mass Loss from the Exoplanet WASP-12b Inferred from *Spitzer* Phase Curves

Taylor James Bell[1]; Michael Zhang[2]; Patricio Cubillos[3]; Lisa Dang[1]; Luca Fossati[3]; Kamen O. Todorov[4]; Nick B. Cowan[1,5]; Drake Deming[6]; Robert T. Zellem[7]; Kevin Stevenson[8]; Ian Crossfield[9]; Ian Dobbs-Dixon[10]; Jonathan Fortney[11]; Heather Knutson[12]; Michael Line[13]

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As an exoplanet orbits its star, the thermal radiation coming from the planet varies roughly sinusoidally, with a peak occurring when the hottest hemisphere of the planet faces the observer. A Spitzer Space Telescope phase curve of the ultra-hot Jupiter WASP-12b from 2010 showed an unexplained anomaly in the data; unlike every other planet observed to date, the infrared signal from WASP-12b showed *two* maxima per planetary orbit, rather than one (Cowan et al. 2012). Stranger still, this was only seen at a wavelength of 4.5 μm, while the phase curve at 3.6 μm showed only one maximum. At the time, the authors dismissed this finding as being the result of detector systematics.

We present new work which robustly confirms the findings of Cowan et al. (2012) through the analysis of new *Spitzer* phase curves taken in 2013, as well as the reanalysis of their original data. We obtain consistent results at both epochs using three independent analyses. We rule out the possibility of detector systematics, nor can tidal distortion of the planet or star explain these variations. We then show that these observations require the planet to be undergoing mass loss, likely in the form of a gas stream flowing directly from the planet to the star. While mass loss has been predicted for WASP-12b, our inferred flow geometry is unanticipated. We also find strong evidence for atmospheric variability, with the offset in the phase curve maximum at 3.6 μm changing by more than 6σ between the two sets of observations.

Our findings provide an independent confirmation of past claims of mass loss from near-ultraviolet transit observations. We also show that our observations provide new constraints on the composition, flow geometry, and temperature of the gas stripped from the planet. For example, the wavelength dependence of the gas emission may suggest that the gas is rich in CO. Finally, many of the past findings regarding the atmosphere of WASP-12b, one of the best-studied exoplanets, will need to be reconsidered in light of the contamination from the escaping gas.

201.04 — Observations of Tidal Orbital Decay of Hot Jupiters

Joshua Winn[1]

[1] *Astrophysical Sciences, Princeton University (Princeton, New Jersey, United States)*

Soon after the discovery of 51 Peg b, Rasio et al. (1996) and Lin et al. (1996) realized that tidal interactions between hot Jupiters and their host stars may lead to significant orbital evolution. In particular, the orbits of almost all of the known hot Jupiters should be shrinking due to tidal orbital decay. The timescale for tidal decay is unknown and depends on the mechanism by which tidal oscillations of the star are dissipated as heat, a longstanding source of uncertainty in stellar astrophysics. The best opportunity to detect orbital decay directly is through long-term transit timing. I will present the results of search for orbital decay among the dozen most favorable hot Jupiters, some of which have now been observed for more than a decade. WASP-12 shows a clear decrease in the transit period which seems likely to be caused by either tidal orbital decay or apsidal precession. I will present two new seasons of transit observations, and four new Spitzer observations of eclipses, that help to distinguish between these possibilities. In addition to WASP-12, two other candidates for orbital decay have been identified, but the evidence is not compelling and further observations are needed. I will also discuss the prospects for detecting orbital decay using data from the Transiting Exoplanet Survey Satellite.

201.05 — Tidally-Induced Radius Inflation of Sub-Neptunes

Sarah Millholland[1]*; Gregory Laughlin*[1]

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Recent work suggests that many short-period super-Earth and sub-Neptune planets may have significant spin axis tilts ("obliquities"). When planets are locked in high-obliquity states, the tidal dissipation rate increases by several orders of magnitude. This intensified heat deposition within the planets' interiors should generate significant structural consequences, including atmospheric inflation leading to larger transit radii. Using up-to-date radius estimates from *Gaia* Data Release 2 and the California-*Kepler* Survey, we show evidence for larger average radii of planets wide of first-order mean-motion resonances, a population of planets with theorized frequent occurrence of high obliquities. We investigate whether this radius trend could be a signature of obliquity tides. Using an adaptation of the Modules for Experiments in Stellar Astrophysics (MESA) stellar evolution toolkit, we model the evolution of the H/He envelopes of sub-Neptune-mass planets in response to additional internal heat from obliquity tides. The degree of radius inflation predicted by the models is indeed consistent with the observations, suggesting that these planets have likely been inflated. We present several case studies that are particularly strong candidates for having undergone this process. Broadly speaking, we find that tidal dissipation can affect a sub-Neptune's radius to first order, yet it has not been included in previous interior structure models. This must be accounted for if the valley in the super-Earth/sub-Neptune radius distribution is to be fully understood.

201.06 — The Life Expectancy of Hot Jupiters

Benjamin Montet[1]

[1] *Astronomy and Astrophysics, University of Chicago (Chicago, Illinois, United States)*

Short period giant planets are theorized to spiral into their host stars on relatively short timescales, with the exact rate of inspiral dependent on the strength of tidal forces on main sequence stars. Thus, by measuring the occurrence rate of hot Jupiters as a function of time, one can effectively measure the strength of stellar tidal dissipation. For this, one must measure the ages of stars. I will discuss two avenues through which we can accomplish this for planet hosts. The first is an analysis of the NGC 6791 cluster, an old (8 Gyr), metal-rich ([Fe/H] ~ +0.3) cluster observed throughout the Kepler mission. While this cluster is too crowded for planet searches through traditional pipelines, we (have) developed a PSF modeling scheme to search for and find transiting planets in and toward this cluster. I will present the results from this search and the implications for the destruction of hot Jupiters in time.

We can also understand the ages of planet hosts when they are associated with other, well-characterizable stars. Gaia is now providing us with data on widely separated, co-moving systems across the sky, including in the Kepler and K2 fields. With two stars, we can use isochronal or gyrochronological information on the non-planet hosting star in the system to understand the system age, without worrying about potential tidal spin-up from the existing hot Jupiter. I will present how this method is helping us understand the ages of field stars, the rate of tidal spin-up by hot Jupiters on their host stars, and the long-term evolution of these planetary systems. I will also examine how data from Kepler and K2 can be useful for understanding the prevalence of lithium-rich red giants across the sky, potentially answering a longstanding question in stellar physics.

201.07 — Key Planets for Exogeology in the 2020s: Discoveries from the Dispersed Matter Planet Project

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HST revealed a complete lack of chromospheric emission from extreme hot Jupiter (hJ) host star WASP-12. We since found ~40% of hJ hosts have anomalously low chromospheric emission in Ca II H&K. We attribute this to absorption in diffuse circumstellar gas, originiating from the highly irradiated planets. Archival spectra of ~6000 bright, nearby stars revealed 39 main sequence field stars with similar deficits in the Ca II H&K line cores. These 39 targets were not known planet hosts; we hypothesized they harboured, close-in, mass-losing, low mass, small planets. The Dispersed Matter Planet Project (DMPP) makes high precision, high cadence RV measurements to find ~Earth-mass planets in short period (<~6 d) orbits. We have found planets wherever we have more than 60 RV measurements. We will present DMPP-1, a compact multi-planet system containing multiple super-Earths in short period orbits; DMPP-2, a hot Saturn mass planet orbiting a pulsating star; and DMPP-3. DMPP-3AB is a K dwarf and a star just above the minimum mass for Hydrogen burning in an e=0.59, 500d orbit. DMPP-3Ab is a super-Earth planet in a 6 d orbit. DMPP-3 is the most compact known S-type planet host. Angular momentum considerations suggest the mass lost from the ablating planets will be concentrated in the orbital plane of the ablating planet(s), so these systems are likely to transit. Indeed DMPP was partly motivated by the search for bright, nearby analogues of Kepler 1520b; the transiting dust in Kepler 1520b must co-exist with metal-rich circumstellar vapour which would absorb in the resonance lines of abundant elements, producing absorption exactly like the Ca II H&K line core deficits we use to select DMPP targets. The dispersed gas in the DMPP systems has a large scale-height compared to a terrestrial planet atmosphere, and is hence amenable to transmission spectroscopy techniques exploiting azimuthal column density variations to reveal the composition of the ablating planetary surface. Thus the DMPP systems offer unprecedented opportunities to directly measure the mass-radius-composition relationship(s) for rocky planets outside our Solar System.

202 — Stellar Spins and Obliquities

202.01 — New developments on the obliqueness of exoplanet systems

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The angle between the rotation axis of a star and its orbital angular momentum – its obliquity – conveys information about the formation and evolution of the star and its planetary system. Here I report on new trends and results we have recently obtained and their possible interpretations. Our results give new indications about which mechanisms are responsible for generating large obliquities in some systems, and whether tidal alignment is an important factor in shaping obliquity distributions.

(1) We have found that high eccentricities and high obliquities are linked, suggesting that close-in giant planets can be separated into dynamically cool and dynamically hot populations, in line with other recent results.

(2) Observations of protopanetary disks as well as some models suggest that protoplanetary disks need not be well-alighed with the stellar equator. However, out of the ten obliquity measurements in multi transiting systems (tracing the disk plane) only one has coplanar planets on an oblique orbit. And even in this exceptional system, Kepler-56, the large tilt may be caused by a fourth body, not primordial misalignment. We have also tentatively identified a multi-transiting system in which the planets appear to travel on retrograde orbits. Additional transit observations are scheduled for June and should clarify the situation.

(3) Tidal alignment has been invoked to explain the observed dependence of the obliquity distribution on the host star's effective temperature, the planet-star mass ratio, and the orbital separation. However, theoretical and observational counterarguments exist. We report on two new trends that suggest tides are indeed important: (i) Stars with retrograde planets have a lower projected stellar rotation speed than prograde stars. (ii) Effective temperature is a better predictor of high obliquity than stellar mass. We show that the current sample of 140 systems with reliable obliquity measurements is generally consistent with a picture of tidal alignment.

202.02 — The Spin-Orbit Misalignment Distributions of Hot Jupiters

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Many hot Jupiters have orbits that are highly misaligned with respect to the stellar rotation; most misaligned planets orbit stars above the Kraft break, which is generally though to be the result of less efficient tidal damping in hotter stars. Many mechanisms have been proposed to generate misaligned orbits, but previous observational constraints have been unable to definitively distinguish among these mechanisms. We present initial results from an extensive program to address this problem using statistical analyses of the spin-orbit misalignments of hot Jupiters around A and early F stars, and correlations with other parameters of the systems.

We demonstrate that there is not a sharp break in the spin-orbit misalignment distribution at the Kraft break as typically assumed, but rather a more gradual transition; a significant population of well-aligned planets exists up to at least Teff$\sim$6600 K, and early F stars' planets require a two-population model. Less massive and longer-period planets tend to have more misaligned orbits, consistent with expectations from tidal damping, suggesting that the tidal damping of obliquities around these stars may be stronger than previously assumed. There is no correlation between metallicity and misalignment, contrary to expectations from planet-planet scattering.

We present results from new Keck NIRC2 non-redundant aperture masking interferometry observations, coupled with archival high-resolution imaging and Gaia DR2 astrometry, to perform a comprehensive survey for stellar companions to these stars from a few to tens of thousands of AU. Such companions could drive migration and misalignments via the Kozai-Lidov mechanism. We tentatively find that hot Jupiters with stellar companions have more misaligned orbits than those that do not, contrary to previous results.

We are also leveraging Gaia DR2 parallaxes and TESS light curves to measure these stars' densities and radii and thus infer their ages and the orbital eccentricities. We demonstrate that we are typically able to measure their ages to a precision of 500 Myr, much better than is typically possible for field stars. We present initial results from this work.

202.03 — Tilting short-period planetary systems in photo-evaporating disks.

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The current sample of nearly a dozen Neptune-mass planets with stellar obliquity measurements reveals a surprising population that move on nearly polar orbits (4 planets with obliquities of $\sim$90 degrees, e.g., GJ 436b, HAT-P-11b). The absence of stellar companions and the likely presence of nearby planetary companions in these systems makes the current proposals to drive large obliquities in hot Jupiter systems (e.g., primordial disk misalignments or high-eccentricity migration) inapplicable to these sub-Jovian planets. In this talk, I will show that large stellar obliquities in short-period planetary systems are naturally excited by a distant (>1 AU) Jovian companion embedded in a photo-evaporating disk. This excitation is the result of secular resonances and often leads to polar planetary systems, even if the primordial tilts are small ($\sim$5 degrees), revealing that: (i) the disk dispersal phase plays a major role at shaping the architecture of planetary orbits; (ii) large obliquities might be intimately linked to the observed misalignments between inner and outer disks in many transitional disks. Beyond the small sample of sub-Jovian planets with obliquity measurements, we show that our proposed mechanism fits well within the observed trends of obliquities with stellar metallicities and orbital separations found in the Kepler sample. Finally, we provide with predictions from this mechanism that can be immediately tested by ongoing follow-up campaigns with TESS, as well as future Gaia's astrometric measurements.

202.04 — Nearly Polar orbit of the sub-Neptune HD3167 c : Constraints on a multi-planet system dynamical history

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We present the obliquity measurement, that is, the angle between the normal angle of the orbital plane and the stellar spin axis, of the sub-Neptune planet HD3167 c, which transits a bright nearby K0 star. We study the orbital architecture of this multi-planet system to understand its dynamical history. We also place constraints on the obliquity of planet d based on the geometry of the planetary system and the dynamical study of the system. New observations obtained with HARPS-N at the Telescopio Nazionale Galileo (TNG) were employed for our analysis. The sky-projected obliquity was measured using three different methods: the Rossiter-McLaughlin anomaly, Doppler tomography, and reloaded Rossiter-McLaughlin techniques. We performed the stability analysis of the system and investigated the dynamical interactions between the planets and the star. HD3167 c is found to be nearly polar with sky-projected obliquity, λ = -97 ± 23 degrees. This misalignment of the orbit of planet c with the spin axis of the host star is detected with 97% confidence. The analysis of the dynamics of this system yields coplanar orbits of planets c and d. It also shows that it is unlikely that the currently observed system can generate this high obliquity for planets c and d by itself. However, the polar orbits of planets c and d could be explained by the presence of an outer companion in the system. Follow-up observations of the system are required to confirm such a long-period companion.

202.05 — Precision Rossiter-McLaughin Observations of M-Dwarf Planets in the Near-Infrared with the Habitable-zone Planet Finder

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Significant progress has been made in recent years in measuring the sky-projected obliquity distribution of FGK planet hosting systems via precise Rossiter-McLaughlin (RM) effect observations. However, currently only one M-dwarf system, GJ 436 has a published obliquity constraint via the RM effect—which interestingly is observed to be misaligned. With only one published measurement, key questions remain about the dynamical histories of M-dwarf planets. The advent of stabilized extremely precise RV spectrographs in the near-infrared (NIR) is opening the doors to answering these questions, capitalizing on the large RM-effect amplitudes—large compared to their Doppler RV amplitude—produced by transiting exoplanets orbiting around rapidly-rotating M-dwarfs. In this talk, we will discuss recent precision RM effect observations of fully-convective M-dwarfs with the Habitable-zone Planet Finder (HPF), a stabilized NIR spectrograph recently commissioned on the 10m Hobby-Eberly Telescope at McDonald Observatory. We will discuss recent RM effect observations of the fully-convective M-dwarfs K2-25b, and TRAPPIST-1b, early results of which favor aligned and misaligned orbits, respectively, yielding important insights into the formation history and evolution of these systems.

202.06 — Constraints on the 3D Angular Momentum Architecture of a Planetary System

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Studying 3D architectures of planetary systems presents a unique window into their formation histories. A full description of a system's geometric orientation requires measuring the stellar spin, planetary spin, and orbital angular momentum vectors. In the past, studies have focused on just one or two of these vectors, namely the orbital plane and the stellar spin axis. For instance, measurements of projected spin-orbit alignment have found a number of hot Jupiter systems that are misaligned, raising the possibility that the misalignments resulted from high-eccentricity migration and dynamical interactions between planets. In addition, while discoveries of multi-planet compact coplanar systems indicate smooth disk migration, a handful of these systems exhibit spin-orbit misalignment, suggesting the disk itself was tilted relative to the stellar spin axis. While these partial views of 3D architectures provide an important perspective on planet formation, we can learn even more about system formation histories by characterizing all three angular momentum vectors. Here we present our study characterizing the three angular momentum vectors of the directly imaged single-planet system 2M0122-2439. In this study we measure for the first time projected spins for both star and planet from our NIR high-resolution Keck/NIRSPEC spectra. We combine these with our new stellar photometric rotation period measurement from TESS data and with a previously published planetary rotation period to obtain spin axis inclinations for both objects. We fit multiple astrometry epochs, including two unpublished epochs, to constrain the companion's orbital inclination. With these pieces needed to measure the three angular momentum vectors, we provide first measurements of the planetary obliquity, stellar obliquity, and relative inclinations between star/planet spin axes, allowing us to place new constraints on this system's formation history.

203 — Transiting Multi-planet Systems

203.01 — A Family of Newborn Planets Transiting a Young Solar Analog at 20-30 Myr

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Compact, multi-planet systems are one of the defining discoveries of the *Kepler* mission. These planetary systems are ubiquitous in the galaxy yet much about their nature remains a mystery, including whether they formed *in situ* and what their architectures were when the protoplanetary disk dispersed. Theoretical models suggest that close-in *Kepler* planets had radii that were roughly 2 to 10 times larger at the time of disk dispersal. With the recent discoveries of exoplanets transiting young stars (<100 Myr), it is now possible to put these models to the test and study close-in planets at a stage when contraction, cooling, and initial atmospheric loss are still underway. To date, only a few exoplanets have been discovered transiting pre-main sequence stars, all of which are currently single-planet systems. I will discuss the recent detection of four transiting planets larger than 5 Earth radii orbiting within ~0.5 AU of a young solar analog aged between 20-30 Myr. The inner planets are larger than Neptune and expected to be actively losing envelope mass through photoevaporation. The outer planets are both Jupiter-sized and, with separations >0.15 AU, they are expected to be largely shielded from the effects of photoevaporation. Consequently, the outer planets may be particularly valuable benchmarks, with properties that may more closely reflect the initial conditions of *Kepler* planets. In a single system, we thus have the opportunity to study proto-*Kepler* planets across a range of insolation fluxes shortly after the accretion of envelopes and at a time when stellar X-ray emission is near its peak.

203.02 — Higher Compact Multiple Occurrence Around Metal-Poor M-Dwarfs

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The planet-metallicity correlation provides a potential link between exoplanet systems as we observe them today and the effects of bulk composition on the planet formation process. Many observers have noted a tendency for Jovian planets to form around stars with higher metallicities. However, there is no consensus on a trend for smaller planets. In this talk I will discuss my recent work investigating the planet-metallicity correlation for rocky planets in single and multi-planet systems around Kepler M-dwarf stars. M-dwarfs are too dim to easily make direct elemental abundance measurements using spectroscopy, so we instead used a combination of parallaxes and photometry to find relative metallicities. We used color-magnitude diagrams to show that compact multiple systems prefer metal-poor M-dwarfs, with 73% of compact multiple systems, compared to 55% of single-planet systems, in orbit around a star more metal poor than the average star in the M_K vs. G_{BP}–G_{RP} plane. This trend is broadly consistent with other choices of color and magnitude. Our conclusion is that metallicity plays a role in the architecture of rocky planet systems. Compact multiples either form more readily, or are more likely to survive on Gyr timescales, around metal-poor stars.

203.03 — Unlocking the Interpretation of Transiting Multiplanet Systems using High Impact Parameters

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Multiplanet systems in which all the planets transit offer clean individual solutions and precise parameter constraints. In this talk, we discuss new ideas and results regarding planetary systems in which some of the members transit with high impact parameter: they enable even better solutions. Moreover, computing multiplanet statistics with impact parameters results in a clear global view of the population and can infer the existence or absence of non-transiting planets. We discuss one individual system in detail: K2-146. In campaign 5 of K2, one planet was known to transit with large transit timing variations (TTVs). In campaigns 16 and 18 we found its perturber to transit also. The two planets form a 3:2 resonance, and the fast precession of the nodes and periastra caused the outer planet's impact parameter to decrease from 0.99 to 0.89 in the ~3 years spanned by K2 observations, tripling its observed transit depth. Interpreting the transit shape variations along with TTVs allows us to measure the most precise masses (M_p/M_{Earth} = 5.77±0.18 and 7.50±0.23) for any super-Earth or sub-Neptune (R_p/R_{Earth} = 2.04±0.06 and 2.19±0.07, respectively). We further infer that these values support photoevaporation models. Zooming out to the population of transiting planetary systems of high multiplicity, we define statistics for mass partitioning (based on radii), spacing complexity (based on periods), and system flatness (based on impact parameters through durations and stellar densities). For the first time, we find the three to be correlated: if a multiplanet system has similar-sized planets that are laid out regularly in period, then it tends to be extremely flat with mutual inclinations <1 deg. We can turn this argument around and infer more rigorously than before that some systems have non-transiting planets — we identify eight systems of 3 planets with conspicuous gaps, where a 4th planet would complete an evenly-spaced set. Far from a blind application of Titius-Bode's rule, our inference of additional planets derives from system layouts actually observed in the population.

203.04 — The Intrinsic Distribution of Planetary Systems: Modeling the Impact of Clustering on Planetary Architectures

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The Kepler Mission discovered thousands of exoplanet candidates and hundreds of multi-transiting systems, enabling detailed population studies. We present a forward model for generating populations of exoplanetary systems, modeling the Kepler detection pipeline, comparing simulated planetary systems to those observed by Kepler, and performing statistical inference on *planetary system architectures*, and not just the distribution of individual planets. We show that models assuming independent planet sizes and orbital periods do not adequately reproduce the observed population and can lead to inaccurate inferences about the intrinsic distributions of multiplicities, period ratios, and mutual inclinations. In contrast, our model allowing for the clustering of planet sizes and periods within each system provides a significantly improved description of the

Kepler multi-planet systems, especially in modeling the observed multiplicity and period ratio distributions. Our results are consistent with previous studies finding that the observed multiplicity distribution implies two populations of planetary systems, a majority coming from a low mutual inclination (∼1°) population with low eccentricities (∼0.01) and a second population of systems with high mutual inclinations (or isolated planets) making up ∼40% of all systems. However, we find that a large fraction of stars do not harbor any planets (with $R_p > 0.5\ R_{Earth}$ and $10\ d < P < 300d$). Those that do tend to have many. Our model makes predictions for the distribution of additional non-transiting planets that can inform observing strategies for the follow-up of TESS discoveries and can be tested by the findings of upcoming radial velocity campaigns. We provide large simulated catalogs drawn from our models for testing whether apparent trends in the Kepler catalog could be due to observational biases or are evidence of patterns in the true distribution of planetary systems' physical properties. We provide a public code for simulating both intrinsic and Kepler-observed catalogs of planetary systems enabling comparisons between planet formation models and observations.

203.05 — Linguistic Modeling of Kepler's Exoplanets

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Planets belonging to the same system are related: formed from the same protoplanetary disk around the same star, and in general, size-ordered, with correlated radii and dynamically organized spacing. As a consequence, the individual planets in a system inform upon each other, and upon their yet-unobserved siblings.

Here, we apply the techniques of natural language processing to the problems of (i) classifying planets into maximally informative categories, analogous to parts of speech; and (ii) predicting the next unobserved planet orbiting a star. In the case of text interpretation, we expect a word's context to inform upon the word itself; for example, the incomplete sentence "The plane landed in ____ yesterday" contains enough information to limit the set of sensible missing words to a relative handful.

We treat planetary systems as "sentences" made up of planet "words," ordered from the star outward. By our analogy, we expect the properties of a planet's host star and neighboring planets to inform us of the likely properties of the planet itself, and we apply the technique of maximizing mutual information (MMI) to model the relationships between these properties.

203.06 — Compact Multi-Planet Systems With Planets That are "Way Out of Line"

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The Kepler Mission led to the discovery of hundreds of multi-planet systems. Remarkably, these systems tend to have relatively flat architectures (less than a few degrees), much smaller than the misalignments seen in our own Solar system. Recently, however, using observations from the K2 mission, we have discovered a compact six-planet system of sub-Neptunes orbiting a nearby (78 pc) K-star, K2-266. Interestingly, this system contains an ultra-short-period (USP) super Earth that is significantly misaligned (>12 degrees) to the other five planets. More recently, we discovered a system of up to five planets around an early K-star TOI 125 using data from the TESS mission. . Similar to K2-266, TOI-125 has a USP planet candidate, that if confirmed, would be misaligned to the rest of the system by ∼17 degrees. To date, these systems are the most exoplanet discovered in one system by K2 and TESS, respectively. As a result of their close proximity to their host stars, the USPs in each system actually transit along our line-of-sight. One explanation for the misalignments is that an additional unseen companion resides in each system. In this scenario, the strength of its dynamical coupling could vary between each of the inner planets, potentially resulting in a difference in the evolution of each planet's inclination, causing the observed misalignment. We will present the discovery and characterization of each systems, and provide a range of parameters for the unseen companion that could explain the misalignment seen in the K2-266 system.

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300 — Planet Formation

300.01 — Results from the New Horizons encounter with 2014 MU69 and what they tell us about planetary formation

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On January 1, 2019, NASA's New Horizons mission flew past the cold classical Kuiper Belt Object, 2014 MU69 [1]. This was the furthest encounter of a solar system object and our first close-up look at a cold classical Kuiper Belt Object (CCKBO). As a CCKBO with a circular, low-inclination orbit, 2014 MU69 likely formed at the same heliocentric distance from the protoplanetary disk about 4.5 billion years ago.

From the encounter, we learned that this object is a bilobed object composed of two ellipsoidal components. The two lobes are distinct and show no sign of significant disruption at the margin between them indicating that they formed from a low-velocity merger of the two components. The larger component is lenticular in shape with dimension of ~22 × 20 × 7 km while the smaller component is less flattened (~14 × 10 × 10 km). The two lobes have their long axis aligned which would be consistent with the two ellipsoidal parent bodies being tidally locked before their merger. From the color and compositional data collected on the spacecraft, we find no significant differences in average color and no obvious compositional differences between the two lobes. The low-velocity merger and homogeneity of the lobes are consistent with objects forming in pebble cloud gravitational collapse models.

In order for the two objects to merge, the system would have needed to lose angular momentum. Preferred mechanisms for this are either (1) interacting with other small bodies in the vicinity and/or (2) gas drag from the protoplanetary disk.

Acknowledgements: We thank the New Horizons mission for supporting this work.

References [1] Stern, S.A., et al. Initial results from the exploration of 2014 MU69, a small Kuiper Belt Object, Science, V364, 2019.

300.02 — Why super earths are of a similar size — observational signatures of a limiting pebble accretion mass scale

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We propose a novel mass scale at which growth by pebble accretion ceases, which has far reaching ramifications for both modeling and observation of planetary systems. By noting that, at scales of order the nascent planet's atmosphere, the flow of nebular gas is altered by the presence of the planet, we demonstrate that particles that require impact parameters for accretion smaller than this atmospheric scale are inhibited from accreting. Not only does this process determine the smallest particle sizes that be captured via pebble accretion, but at terrestrial and super-Earth masses this "smallest" particle size is often larger than the maximal sizes present in the disk, naturally shutting off pebble accretion. This mass scale, which we term the "flow isolation mass," is particularly salient due to the rapid growth timescales via pebble accretion for planets of terrestrial and super-Earth masses. Taken at face value, these rapid rates would predict that few planets end their growth in this mass regime; instead planets either "stall" before this scale, or continue their growth and become gas giants. Flow isolation resolves this problem, allowing close-in planets to naturally finish their growth at super-Earth mass scales. We demonstrate that flow isolation can explain several observed features of the transiting planet population. In particular, recent work indicating that super-Earths in the same system are correlated in size, and that the super-Earth population can be produced by a single characteristic core mass, both point to the existence of a limiting core mass scale. For reasonable fiducial disk parameters, the magnitude of the flow isolation mass and its dependence on stellar mass and semi-major axis agree well with these observations.

300.03 — The Boundary between Gas-rich and Gas-poor Planets

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Sub-Saturns straddle the boundary between gas-rich Jupiters and gas-poor super-Earths/sub-Neptunes.

Their large radii (4–8R_{earth}) suggest that their gas-to-core mass ratios range ~0.1–1.0. With their envelopes as massive as their cores, sub-Saturns are just on the verge of runaway gas accretion; they are expected to be significantly less populous than gas giants. Yet, the observed occurrence rates of sub-Saturns and Jupiters are comparable within ~100 days. We show that in these inner regions of planetary systems, the growth of sub-Saturns/Jupiters is ultimately limited by local and global hydrodynamic flows — runaway accretion terminates and the formation of gas giants is suppressed. Within a finite disk lifetime ~10 Myrs, massive cores (>10M_{earth}) can become either gas-poor or gas-rich depending on when they assemble but smaller cores (<10M_{earth}) can only become gas-poor. This wider range of possible outcomes afforded by more massive cores may explain why metal-rich stars harbor a more diverse set of planets. We also speculate on the origin of the fast rise in the occurrence rate of gas-rich planets towards longer orbital periods.

300.04 — Forming rocky super-Earths with realistic collisions

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Recent data on rocky super-Earths shows that they have a wider distribution of Fe/Mg ratios, or core to mantle ratios, than the planets in our Solar System. We show that this range is too large to be explained by the Fe/Mg ratios of the stars that host them. Instead, we demonstrate that realistic collisions, which alter the composition of the colliding bodies by preferentially stripping debris from the mantle, can explain much of this spread. Planet formation simulations have only recently begun to treat collisions more realistically in an attempt to replicate the planets in our Solar System. We investigate planet formation more generally by simulating the formation of rocky super-Earths with varying initial conditions using a gravitational N-body code that incorporates realistic collisions. We track the maximum plausible change in composition after each impact. The final planets span a wider range of Fe/Mg ratios than the Solar System planets, but do not completely match the distribution in super-Earth data. The most iron-rich planets are similar in Fe/Mg ratio to Mercury, and the most iron-depleted planets are found at lower masses. This indicates that further work on our understanding of planet formation is required to explain planets at the extremes of this Fe/Mg distribution.

300.05 — Atmospheric mass loss due to giant impacts: the importance of the thermal component for hydrogen-helium envelopes

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Systems of super-Earths and mini-Neptunes display striking variety in planetary bulk density and composition. Giant impacts are expected to play a role in the formation of many of these worlds. Previous works, focused on the mechanical shock caused by a giant impact, showed that these impacts can eject large fractions of the planetary envelope, offering a partial explanation for the observed compositional diversity. I will describe the thermal consequences of giant impacts, and show that the atmospheric loss caused by these effects can significantly exceed that caused by mechanical shocks for hydrogen-helium (H/He) envelopes. During a giant impact, part of the impact energy is converted into thermal energy, heating the rocky core and envelope. We find that the ensuing thermal expansion of the envelope can lead to a period of sustained, rapid mass loss through a Parker wind, partly or completely eroding the H/He envelope. The degree of atmospheric loss depends on the planet's orbital distance from its host star and its initial thermal state, and hence age. Close-in planets and younger planets are more susceptible to impact-triggered atmospheric loss. For planets where the heat capacity of the core is much greater than the envelope's heat capacity (envelope mass fractions ≤4 percent), the impactor mass required for significant atmospheric removal is $M_{imp}/M_p \sim \mu/\mu_c \sim 0.1$, approximately the ratio of the heat capacities of the envelope and core. Conversely, when the envelope dominates the planet's heat capacity, complete loss occurs when the impactor mass is comparable to the envelope mass. Because of their stochastic nature, giant impacts may provide a natural explanation for the observed range of super-Earth and mini-Neptune densities.

300.06 — The diversity of Super-Earths and a new Super-Earth-class formed from high-temperature condensates

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Super-Earths do not follow a simple mass–radius trend, but rather reveal a diversity of mass–radius relationships that are usually associated with compositional and structural differences. We hypothesise that differences in the temperatures at which rocky material condensed out of the nebula gas can lead to differences in the composition of key rocky species (e.g., Fe, Mg, Si, Ca, Al, Na) and thus planet bulk density. Such differences in the observed bulk density of planets may occur as a function of radial location and time of planet formation. In this talk we show that the predicted differences are on the cusp of being detectable with current instrumentation. In fact, for HD 219134, the 10 % lower bulk density of planet b compared to planet c could be explained by enhancements in Ca, Al rich minerals. However, we also show that the 11 % uncertainties on the individual bulk densities are not sufficiently accurate to exclude the absence of a density difference as well as differences in volatile layers. Besides HD 219134 b, we demonstrate that 55 Cnc e and WASP-47 e are similar candidates of a new Super-Earth class that have no core and are rich in Ca and Al minerals which are among the first solids that condense from a cooling proto-planetary disc. Planets of this class have densities 10-20% lower than Earth-like compositions and may have very different interior dynamics, outgassing histories and magnetic fields compared to the majority of Super-Earths.

302 — Planet Detection — Transits Poster Session

302.01 — One Hit Wonders: recovering the longest period TESS planets

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TESS is searching for transiting planets around bright, nearby stars across nearly the entire sky. With a 27-day observing cadence, TESS will only be sensitive to close-in planets with periods of less than 14 days over the majority of the sky. We estimate TESS will observe a single-transit for approximately a thousand planets during its initial two-year mission but, with largely unconstrained periods, these planets will be difficult to follow-up. The One Hit Wonders surveys will use an autonomous half-meter telescope to observe subsequent transits of the TESS single-transit planets in the North. Each night, up to a dozen targets with expected transits will be monitored at long-cadence; real-time data reduction will detect potential transits and trigger short-cadence, continuous observations. Simulations suggest approximately twenty planets may be recovered per observing year. Once confirmed, these planets will populate a previously sparse parameter space: long-period planets transiting bright host stars. This will make these planets excellent candidates for atmospheric characterization of cool planets, with refractory elements condensed out of the upper atmosphere, as well as serve as a bridge between hot Jupiters and the solar-system gas giants,

302.02 — TESS Science Processing Operations Center Pipeline and Data Products

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TESS launched 18 April 2018 to conduct a two-year, near all-sky survey for at least 50 small, nearby exoplanets for which masses can be ascertained and whose atmospheres can be characterized by ground- and space-based follow-on observations. TESS just completed its survey of the southern hemisphere, identifying >600 candidate exoplanets and unveiling a plethora of exciting non-exoplanet astrophysics results, such as asteroseismology, asteroids, and supernova. The TESS Science Processing Operations Center (SPOC) processes the data downlinked every two weeks to generate a range of data products hosted at the Mikulski Archive for Space Telescopes (MAST). For each sector (~1 month) of observations, the SPOC calibrates the image data for both 30-min Full Frame Images (FFIs) and up to 20,000 pre-selected 2-min target star postage stamps. Data products for the 2-min targets include simple aperture photometry and systematic error-corrected flux time series. The SPOC also conducts searches for transiting exoplanets in the 2-min data for each sector and generates Data Validation time series and associated reports for each transit-like feature identified in the search. Multi-sector searches for exoplanets are conducted periodically to discover longer period planets, including those in the James Webb Continuous Viewing Zone (CVZ), which are observed for up to one year. Data products also include cotrending basis vectors (CBVs) and calibration files, such as the Pixel Response Functions across the field of view of each of TESS's four cameras. To maximize the usability, the TESS science data products are modeled after those for *Kepler*, including Target Pixel Files and Light Curve files.

In this talk, I describe the SPOC pipeline and the chief differences between the TESS and the *Kepler* pipelines, and the major updates to the SPOC pipeline (4.0) available now to the community at MAST. I also discuss the documentation available to the community to help them in properly interpreting and analyzing the TESS data products.

The TESS Mission is funded by NASA's Science Mission Directorate as an Astrophysics Explorer Mission.

302.03 — Confirming transiting exoplanets with TraCS

Christian Obermeier[1]

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The number of exoplanet candidate detections by the transit method is increasing every year. Following up each target traditionally by spectroscopy is both expensive and, in some cases, infeasible due to the faint host star or shallow transit depth. One way to alternatively confirm the planetary nature of those targets is multiband photometry, where the planet's transit color signature allows to disentangle stellar limb darkening from other parameters. We have built on this and expanded it with the three-channel multiband camera 3KK, mounted on the 2.1m Wendelstein telescope located in the Bavarian Alps. Thanks to its near-infrared capabilities, it enables us to observe the secondary eclipse as well to put constraints (or measure) the planet candidate's effective temperature. I will then showcase this technique by two recently confirmed exoplanets that orbit faint (V<15mag) stars.

302.04 — Observing transits of Hot Jupiters from Baker Observatory

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Our project involves observing transits from our local observatory. Baker Observatory has three modest telescopes with virtually unlimited access for our group with approximately 200 clear nights per year. In this poster, we will show some of our preliminary transit observations.

We are observing Hot Jupiters and seeking to measure transit timing variations (TTVs) and transit duration variations (TDVs). From the measurements, our goals are to improve orbital periods, find non-transiting objects, determine eccentricities and inclinations.

While Hot Jupiters represent a small portion of all exoplanets, how they arrived at their current orbits can be used to determine if they likely migrated or were scattered by other objects. Additionally, there is the issue of other, likely smaller, planets in longer orbits, which have yet to be discovered. These issues address solar system formation scenarios and so are important for the field.

Our observatory contains a PlaneWave CDK20, a Meade LX200GPS, and a Celectron C14 telescopes, all equipped with Apogee Alta CCDs. We could potentially observe transits for nine different star-planet combinations during any one night.

We are members of ExoFOP and ExoFOP-TESS and are actively seeking collaborations for focused observations of targets of interest.

302.05 — Exoplanet Characterization using Phase Variations Observed by *TESS*

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The field of exoplanets has progressed beyond planet detection to characterization of planetary systems. This includes planetary structure and atmospheres, studies of exoplanet host star properties, and measurement of planet masses. While the precision photometry from the Transiting Exoplanet Survey Satellite (*TESS*) is primarily directed towards the detection of planetary transits, it can also be utilized for a variety of additional science applications. In particular, a phase modulation present in the photometry can be used to study the planetary mass and albedo, potentially providing insights into the atmospheric properties of the planet. We have developed an analysis program designed to detect phase variations caused by the beaming, ellipsoidal, and reflection (BEER) effects. In particular, we focus on the phase variations of *TESS* Objects of Interest (TOIs) that were observed during Cycle 1, which currently includes $\sim$100 known planetary systems and $\sim$500 new planet candidates. Our analysis provides estimates for the companion mass and albedo, and potentially identifies false positives in the list of *TESS* planetary candidates. In addition to the masses being useful for characterizing known and candidate planets, we also use the companion mass measurements to search for contaminating stellar binaries in the planet candidate catalog based on their characteristic light curve shapes and evidence for a secondary eclipse. Therefore, our phase variation analyses complement the planet candidate catalog by identifying high-priority TOIs for spectroscopic planet confirmation. From the albedo measurements, we infer atmospheric characteristics and determine planetary habitability more accurately than using the distance from the host star alone. Finally, we emphasize that BEER modulations encapsulate a specific type of phase variation. Our analysis additionally identifies phase variations that cannot be naturally explained by the BEER effects and are not necessarily well-understood. By identifying several systems with similar unusual phase variation shapes, we begin to explore possible astrophysical mechanisms behind these characteristic signals.

302.06 — Unbiased Determination of Planetary Masses and Orbital Precession from Kepler Transit Variations

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The exquisite accuracy of exoplanetary transits measured by Kepler allows detection of deviations from periodicity in the light-curves. Here we develop and apply a global fitting approach to the light-curve data that allows constraining a smaller number of relevant degrees of freedoms describing the orbital variations. The approach enables uniform and precise determinations of the masses of the perturbing planets. This avoids the necessity of having individual transits precisely determined and thus increases the sensitivity to lower TTV amplitude, shorter orbital period, and shallower transit depth, removing past biases in these variables. We fit for the eccentricity *difference* between interacting planets, reducing the parameter space by two dimensions, and alleviating the intrinsic mass-eccentricity degeneracy. Taken together, these allow us to successfully determine exoplanetary masses for more- and ever smaller- planets, and in particular for planets in the 1 Earth radius regime. Additionally, we developed a technique for detecting secular variations in the orbit by measuring and fitting transit variations beyond those seen in the mid-transit time. Detecting such dynamical scenarios provides information regarding the possible existence of non-transiting planetary companions, or the non-spherical mass distribution of the host star. The variations may imply forces out of the orbital plane, and thus probe mutual inclinations among components of the system. Because secular precession occurs about the system's invariable plane, we translate these orbital elements to sky-plane variables, and derive an analytic description of the transit parameters. By applying a non-linear search for the best-fit parameters, we constrain the dynamical scenarios that may be responsible for the light-curve variations, and show results for synthetic and Kepler data.

302.07 — Detecting astrophysical events in TESS data using deep learning

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One of TESS' primary objectives is to discover and characterize 50 Earth-like planets and it is the hope that these planets will be found among the 200,000 preselected targets observed with a cadence of 2 minutes. The standard routines for automatic planet detection (e.g., the box least squares (BLS; Kovács et al. (2002)) method) are excellent at picking out planets (both Earth-sized and bigger) transiting multiple times and orbiting stars with modest variability, they are not as well suited for detecting the oddballs like evaporating planets, single transiting planets (monotransits), etc. An oddly shaped transit or any other atypical astrophysical phenomenon is traditionally (and often easily) identified by a trained human eye. These events are naturally very interesting, however, eyeballing all stars is a daunting task, especially as the TESS data is not only comprised of the 200,000 stars observed in 2 minute cadence, but also a set of full-frame images (FFIs) covering the entire field of view (FOV) for a given sector, yielding light curves for millions of stars observed with a cadence of 30 minutes. This is why an automatic way of characterizing these systems is desirable. We are therefore training a *convolutional neural network* (CNN). It identifies the oddballs and will support traditional detection algorithms (such as BLS). It will label a light curve as one of the following: planetary candidate, eclipsing binary, variable star, oddball (i.e., a weirdly shaped or monotransit), or seemingly featureless. Here we present our results for the available TESS data and highlight some particular systems.

302.08 — New Discoveries and high precision photometric follow-up from NGTS

Oliver Turner[1]
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The Next-Generation Transit Survey (NGTS) is a wide-field photometric survey designed to discover transiting exoplanets of Neptune-size and smaller around bright stars (magnitude V<13) from the ground. These objects will be intensely interesting for detailed follow-up as they will allow us to increase our understanding of the mass-radius relation for smaller planets and the brightness of their host stars will make them accessible to present day and upcoming instruments for atmospheric characterisation. Thanks to it's versatility and high photometric precision NGTS now boasts several follow-up programs too which synergise with TESS discoveries.

We present a number of new discoveries all of which occupy the current fringes of parameter space. NGTS-4, a sub-Neptune planet orbiting a K-star with the smallest transit signal discovered from the ground, It orbits in the so-called Neptune desert, where it is thought strong stellar irradiation would cause significant mass loss. NGTS-6 is an ultra short period (~21 hours) hot-Jupiter which, models suggest, should have lost around 5% of its gaseous atmosphere since its formation. By the time of the conference we expect will be a detailed analysis of at least 3 additional systems.

In addition, we will present the new follow-up activities of NGTS, in particular the synergies available to us via the (soon) completed TESS southern hemisphere survey. NGTS is ideally situated to confirming a number of the current mono-transit, and therefore long period, TESS candidates. We have also recently demonstrated the ability to reach exceptional photometric precision (of the order 150 ppm/30 min) which will allow us to follow-up even shallow TESS detections from the ground.

302.09 — Exoplanets and the KESPRINT collaboration

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KESPRINT is a collaboration of around 50 exoplanetary researchers, located in some 20 institutes covering a large part of the world. This group concentrates on carrying out follow-up observations of data from space missions dedicated to the observation of exoplanetary transits. The importance of a ground based follow-up program (FuP) when interpreting such results can not be overstated. The verification of the existence of the exoplanet through detection of radial velocity variations or through validation by excluding all other sources (typically background binaries) through e.g. Adaptive Optics imaging, need to be carried out. It is also required to know the fundamental parameters of the host star with very high precision in order to discern the planetary data. Recently, asteroseismology have also started to play a key role. Here we briefly describe the work of this collaboration and highlight an important result — The characterization of one of the oldest planets in our Galaxy.

302.10 — Searching for transiting cold Jupiters around bright stars with ASTEP South at Dome C, Antarctica

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Much of our understanding of gas giant exoplanets come from those transiting in front of bright stars at small orbital separations (P ∼ 3 days, a ∼ 0.05 au). These hot Jupiters are coupled to their host star: stellar irradiation impacts the chemistry and temperature structure of their atmospheres and tidal interactions affects the orbital dynamics and may even impact the star itself. In contrast, gas giant exoplanets with long orbital periods and large separations (P > 30 days, a > 0.2 au) are much less coupled to their host star and provide ideal benchmarks to study gas giant planets in general. However, only a few transiting "cold Jupiters" orbiting bright stars are known to date. In the past years, we conducted the ASTEP experiment (Antarctica Search for Transiting ExoPlanets) to search and characterize transiting exoplanets from Dome C, Antarctica and to qualify this site for photometry in the visible. One instrument, ASTEP South, is a 10 cm diameter lens equipped with a CCD camera in a thermalised box pointing continuously towards the celestial South pole. We analysed four winters of data collected with this instrument and identified about 30 transit candidates around relatively bright stars (9 < V < 13) with orbital periods up to 80 days. We performed photometric follow-up with the Las Cumbres Observatory (LCO) 0.4m telescopes to investigate these signals. Most of these stars are also observed by TESS and their lightcurves can be extracted from the full frame images. In this poster, we present our set of candidates, the first results of the photometric follow-up, and discuss the use of TESS data to investigate these objects.

302.11 — MASCARA and bRing, finding bright transiting planets and synergies with TESS

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In this talk, I will discuss the current state of the MASCARA and bRing networks, and go into detail on how our observations can be combined with TESS to search for long period transiting exoplanets. These networks have discovered four exciting transiting exoplanets which are ideal for follow up atmospheric characterization surveys. The near continuous observations of these networks provides a unique synergy with TESS, where our long-term monitoring of all stars brighter than 8.4 magnitudes in the sky will provide information needed to find long period transiting systems when combined with the shorter term TESS data. The MASCARA and bRing networks are composed of a set of observatories in the northern and southern hemispheres with the aim of finding Hot Jupiters around bright stars using photometry. They are composed of four stations, two main MASCARA stations located in La Palma, the Canary Islands and La Silla, Chile, and two smaller bRing stations in Sutherland, South Africa and Siding Springs, Australia. Each MASCARA station is equipped with five interline CCD cameras, and observes the local sky down to an airmass of around 2. The smaller bRing stations are equipped with only two interline CCD cameras, and observe the declination range of -30 to -90 degrees down to an airmass of around 10. The bRing stations are combined with the southern MASCARA station, and allows for at least one station observing at any given time for much of the year in the bRing declination range, provided weather permits. With five minute exposures, we obtain photometric observations of tens of thousands of bright stars over years with a window function which is unprecedented for ground-based observatories. All MASCARA data will soon be freely available through the ESO database.

302.12 — The case for transiting warm giant exoplanets: from TESS discoveries to atmospheric characterization with JWST

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Transiting warm giant exoplanets (planets with equilibrium temperatures below 1000 K, or periods longer than about 10 days) are fundamental objects to study, as they are ideal laboratories for tests on planet formation and evolution, which might not only provide distinct signatures to their much better characterized hotter counterparts, but also constrain our understanding of giant (exo)planet interiors and their accretion history through, e.g., mass-metallicity relations. Their detection and characterization, however, is very challenging due to their longer periods (which makes them hard to detect from ground-based transit surveys) and cooler nature (which implies smaller scale-heights and, thus, smaller signals in transmission). In fact, only about 40 of these systems have been discovered to date, with only a handful of them being optimal for atmospheric characterization. In this talk, I will present the state-of-the-art on our understanding of warm giant exoplanets both from a population and from an interior modelling perspective, emphasizing how the study of these exoplanets can help us understand previously unconstrained properties and predictions of gas giant exoplanets. With this motivation at hand, I will then present the ongoing work of the Chile-MPIA collaboration, a multi-institutional effort focused on the systematic search of these long-period systems using data from the Transiting Exoplanet Survey Satellite (TESS) and several ground-based facilities. Emphasis will be given both in the methodology of the search and on the most exciting and recent results of the collaboration, including a handful of transiting systems with the longest periods discovered by the mission yet. Finally, I will focus on the unique capabilities the upcoming James Webb Space Telescope (JWST) has for characterizing the atmospheres of these exciting systems, and how together with current ground-based facilities, this promising observatory will allow us to get a panchromatic view of these distant worlds, which will in turn enable the first tests of key predictions from structure modelling and planet formation.

302.13 — A Spitzer search for transiting exoplanets around ultra-cool dwarf stars viewed equator-on

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Exoplanet population studies indicate that small rocky planets may be common around very low-mass stars and brown dwarfs: "ultra-cool" dwarfs. Temperate rocky planets around ultra-cool dwarf stars could be the best targets for detecting the atmospheric signatures of extrasolar life with the James Webb Space Telescope: because of a favourable star-to-planet contrast ratio and very short orbital periods in the habitable zone that allow frequent observing opportunities. The seven-rocky-planet planet system around the ultra-cool dwarf TRAPPIST-1 is the best — and so far only — such known example. With James Webb launching in two years and with a nominal mission lifetime of only five years, we urgently need to discover more temperate planets around nearby ultra-cool dwarfs.

We are conducting a large Spitzer Space Telescope program to search for exoplanets around 15 ultra-cool dwarfs. Our sample is optimized for transit planet discoveries by including only stars inferred to rotate nearly equator-on. The observed near-ubiquitous spin-orbit alignment between the host stars and the planets in multi-planet systems dictate that any planetary systems around our selected ultra-cool dwarfs should also be oriented nearly edge-on. We will describe our survey and will present preliminary findings.

302.14 — The Occurrence Rate of Planets around K2's Ultracool Dwarfs

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Over its 19 campaigns, the K2 mission has observed more than 450 spectroscopically confirmed ultracool dwarfs. Using this data, we determine the occurrence rates of planets around such stars. To that end, we build an automatic detrending and transit-search pipeline, and we determine its completeness with injection recovery modelling.

Our results place upper bounds on the occurrence rates of planets larger than ~2 earth radii (sub-Neptunes and giant planets), suggesting they are relatively rare (less than ~0.1 per star). For super-earths and planets such as those in the TRAPPIST-1 system, our constraints are limited by the photometric precision of K2. However, we do not exclude the possibility that rocky planets are common.

Additionally, our Gaussian process-based detrending pipeline automatically constrains periodicity in the lightcurves. We use this to study the stellar variability and rotation patterns of the sample of ultracool dwarfs. Of particular interest is the possible correlation between flare timing and variability phase, found in previous works on TRAPPIST-1. The question still remains whether this is a feature shared by other ultracool stars.

302.15 — Classifying Exoplanet Candidates with Convolutional Neural Networks: Application to the Next Generation Transit Survey

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A key bottleneck in the discovery of transiting exoplanets is the large number of false positives produced by existing detection algorithms. Currently the solution to this problem is to vet the candidates by hand, however this is time consuming and can be inconsistent. Recently convolutional neural networks (CNNs), a type of 'Deep Learning' algorithm, have been shown to be effective at this task [Shallue+19]. Not only can CNNs reduce the man hours required to vet candidates, but they have helped to identify planets which otherwise had been missed [Shallue+19, Datillo+19]. As the number of planetary candidates pile up from missions like TESS, reducing the false positive rate (FPR) is crucial for maximising the yield of small planets and making the best use of follow-up time. Additionally, lowering the FPR, is also important for improving measurements of occurrence rates to better constrain the underlying distribution of exoplanets.

Here I will present results from the on-going effort to automate the Next Generation Transit Survey (NGTS) candidate vetting process using a CNN. Currently we are able to exclude ~50% of false positives, while recovering ~90% of our manually identified candidates and all currently known planets in the NGTS dataset [Chaushev+19, in prep]. On-going work is focused on reducing the number of false positives further, by searching for novel CNN architectures and by adding additional information to the network. A key goal of the project is to understand and improve the network performance in the lowest signal to noise regimes. In this regard, NGTS provides a unique dataset as it has been continually pushing to find planets on the edge of detectability, leading to the discovery of NGTS-4b, the shallowest transit discovered from the ground to date [West+19]. This makes NGTS an ideal testing ground for CNNs and improvements made in the techniques here can readily be applied to space based data from K2 and TESS currently, and PLATO in the future.

302.16 — KELT is up to the TESS: The Ongoing Search for Transiting Planets in Longer Periods and around Hotter Stars

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The Kilodegree Extremely Little Telescope (KELT) transit survey was designed to find planets transiting stars from roughly 7th to 10th magnitude, filling in the gap between brighter RV surveys and previous transit surveys targeting fainter stars. To date, KELT has discovered 25 planets, many of which are bright enough to for detailed follow-up and characterization. In particular, KELT has found many of the transiting planets now known to be orbiting hotter (B/A) main-sequence stars, including KELT-9b, the hottest known exoplanet and KELT-5b, the first planet transiting a hot, pulsating star in a prograde orbit. We have also found the brightest host star with a massive transiting Jupiter, KELT-24b.

KELT overlaps with a large fraction of the TESS sky footprint and magnitude rangewith time baselines of up to 15 years. While the TESS cadence and sensitivity means that TESS is very complete in detecting transits as they occur, the 27-day duration of TESS observations in most of the sky will not provide the ephemerides for planets with periods greater than about 13.5 days. The combination of short duration and high precision TESS observations and the KELT baseline means that existing KELT planet candidates can be found in the TESS data, and that TESS planet candidates can be identified in KELT data enabling precovery of single transit TOIs.

302.17 — Studying the Diversity of Exoplanets with LUVOIR

Eric D. Lopez[1]
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LUVOIR is powerful and flexible observatory designed to revolutionize our view of the universe. In addition to searching for signs of life on habitable worlds, LUVOIR will be capable of detecting and characterizing hundreds of non-habitable exoplanets orbiting nearby stars dramatically advancing the field of "comparative exoplanetology". Operating at L2, with a large aperture of 8-15 m and a sophisticated instrument suite, LUVOIR will allow for fantastic characterization of planets across parameter space both with direct imaging and transmission spectroscopy. At FUV wavelengths the LUVOIR Ultravoilet Multi Object Spectrograph (LUMOS) will obtain high signal to noisetransmission spectra at high spectral resolution, allowing us to detect transiting planetary exospheres and constrain the physics of atmospheric escape. Meanwhile, High Definition Imager (HDI) instrument we can obtain high signal to noise, medium resolution spectra from the NUV to the NIR, allowing us to constrain the properties of clouds, map absorption from alkali metals, and measure abundances for a wide range of molecules including H2O, CO2, and O2. Finally, direct imaging and spectroscopy with the ECLIPS coronograph will enable a systematic investigation of system architectures and the diversity of exoplanet atmospheres at wide orbits.

302.18 — Exoplanet Science Using University of Wyoming Observatories

Hannah Jang-Condell[1]*; Cristilyn Gardner*[1]*; David Kasper*[1]*; Henry Kobulnicky*[1]*; Michael Pierce*[1]*; Catherine Pilachowski*[2]
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[2] *Indiana University (Bloomington, Indiana, United States)*

The University of Wyoming is home to the 2.3-m Wyoming Infrared Observatory (WIRO) and the 0.6-m Red Buttes Observatory (RBO). These facilities enable research in exoplanet detection and characterization. Transit observations at RBO have led to the discoveries of KELT-9b and KELT-21b. Multi-band photometry of HD 189733b at WIRO has helped to characterize its atmosphere. New instrumentation under construction at WIRO include installation of diffusers for better PSF control and an echelle spectrograph (FHiRE: Fiber-fed High Resolution Echelle). FHiRE is poised to become a precision radial velocity measurement instrument for long-term RV monitoring of candidate exoplanet host stars. As TESS identifies new planet candidates, our facilities will make significant contributions toward exoplanet discovery and characterization.

302.19 — Searching for Long-Period Planets in TESS

Steven Villanueva[1]*; Diana Dragomir*[2]*; Chelsea X. Huang*[1]*; Paul A. Dalba*[3]*; Dax Feliz*[4]*; Scott Gaudi*[5]*; Arvind Gupta*[9]*; Stephen Kane*[3]*; Belinda Nicholson*[8]*; Josh Pepper*[6]*; Joseph E. Rodriguez*[7]*; Daniel Joseph Stevens*[9]*; Xinyu Yao*[6]
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[6] *Lehigh University (Bethlehem, Pennsylvania, United States)*
[7] *Center for Astrophysics | Harvard & Smithsonian (Cambridge, Massachusetts, United States)*
[8] *University of Southern Queensland (Darling Heights, Queensland, Australia)*
[9] *Astronomy & Astrophysics, The Pennsylvania State University (University Park, Pennsylvania, United States)*

I will discuss the progress in confirming and characterizing TESS long-period (P > 20 days) planets, specifically those identified as single-transit events (STE). I will discuss the efforts to identify and vet STEs, including an overview of our identification pipeline. STEs require more careful planning and lengthier follow-up campaigns for confirmation than multiply transiting or short-period planets, but can yield some of the longest-period planets that TESS can find. I will discuss some of the strategies and challenges specific to confirming STEs, and I will give an overview of the known STEs and give an update on their status.

302.20 — NGTS-6b: An Ultra Short Period Hot-Jupiter Orbiting an Old K Dwarf

Jose Ignacio Vines[1]
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We report the discovery of a new ultra-short period hot Jupiter from the Next Generation Transit Survey. NGTS-6b orbits its star with a period of 21.17 h, and has a mass and radius of $1.330^{+0.024}{}_{-0.028}$ M_J, and $1.271^{+0.197}{}_{-0.188}$ R_J respectively, returning a planetary bulk density of $0.805^{+0.498}{}_{-0.283}$ g cm^{-3}.

Conforming to the currently known small population of ultra-short period hot Jupiters, the planet appears to orbit a metal-rich star ([Fe/H] =+0.11 ± 0.09 dex). Photoevaporation models suggest the planet should have lost 5% of its gaseous atmosphere over the course of the 9.6 Gyrs of evolution of the system. NGTS-6b adds to the small, but growing list of ultra-short period gas giant planets, and will help us to understand the dominant formation and evolutionary mechanisms that govern this population.

302.21 — A transiting circumbinary planet from TESS

Veselin Kostov[1]
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We report the TESS detection of a transiting circumbinary planet. At the time of writing, the target was observed in 11 sectors of long-cadence data and in 8 sectors of short-cadence data. The host eclipsing binary exhibits prominent primary and secondary eclipses, the planet produced two transits of different durations, and is expected to produce another transit in Sector 13. We combined the precision photometry from TESS with ground-based observations in a numerical photometric-dynamical model to reproduce the observed planet transits and stellar eclipses. The system demonstrates the discovery potential of TESS for circumbinary planets, and provides further understanding of the formation and evolution of planets orbiting binary stars.

303 — Planet Detection — Radial Velocities, Poster Session

303.01 — Search for Earth analogues in the habitable zone around solar type stars: radial velocity or astrometry?

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Stellar activity is currently a major limitation to the detection of very low mass planets around solar type stars using radial velocity techniques. Various techniques have been implemented to mitigate this problem, without allowing to reach one M_{earth} planets for stars similar to the Sun yet. It is therefore crucial to estimate precisely the effect of activity on exoplanet detectability using realistic time series for various types of stars to overcome this problem. I will describe the basic processes at work and how we extended a realistic solar model to build representative time series of radial velocity, photometry, astrometry and chromospheric emission variability. We built coherent sets of stellar parameters covering a large range in effective temperature (K4-F6) and average activity levels. Such simulations are extremely useful to better understand the relationship between RV, astrometry and activity indicators and the limitations of correction techniques. I will present the impact of activity on the detectability of Earth mass planet in the habitable zones of those stars using radial velocity and high precision astrometry and discuss their respective performance.

303.02 — Stellar activity and wavelength-dependent radial velocity measurements

Maksym Lisogorskyi[1]*; Hugh R.A. Jones*[1]*; Fabo Feng*[2]*; R. Paul Butler*[2]
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The Alpha Centauri system is the primary target for planet search as it is the closest star system. Here we look at contaminating signals from telluric lines and activity sensitive lines across the spectrum in HARPS observations of Alpha Centauri B. We compile and quantify the behaviour of 345 spectral lines with a wide range of line shapes and sensitivity to activity and investigate its effect on radial velocity using observations from UVES. Removing parts of the spectrum that contain activity-sensitive lines removes a radial velocity trend reaching 8 m/s. The differential velocity can be used as an indicator for contaminating signals and can benefit greatly from careful selection of "active" and "inactive" echelle orders.

303.03 — An Expanded Catalog of Long-Period Exoplanets, Discovered with HIRES, Lick-Hamilton, and APF

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The California Planet Search team has been conducting a radial velocity survey of almost 800 nearby F/G/K stars for the past three decades, using the

HIRES instrument on Keck I, and the Hamilton spectrograph and Automated Planet Finder at the Lick observatory. We describe a systematic search of this dataset for previously undetected periodic signals and long-term trends, and present a catalog of dozens of newly-detected planet candidates, ranging from warm sub-Neptunes to cold gas giants.

303.04 — The Beginning of the Strategic Large Exploration for Exoplanets Orbiting Nearby Late-M Dwarfs with the InfraRed Doppler (IRD) Spectrograph on the Subaru Telescope

Masayuki Kuzuhara[9,1]; Bun'ei Sato[2]; Motohide Tamura[6,9]; Takayuki Kotani[9]; Nagayoshi Ohashi[1,3]; Masashi Omiya[9,1]; Teruyuki Hirano[2]; Hiroki Harakawa[3,9]; Wako Aoki[1,5]; Norio Narita[9,1]; Yasunori Hori[9,1]; Akitoshi Ueda[1,5]; Akihiko Fukui[4]; Hiroyuki Tako Ishikawa[5,1]; MASATO ISHIZUKA[6]; Takashi Kurokawa[9,7]; Nobuhiko Kusakabe[9,1]; Tomoyuki Kudo[3,9]; Eiichiro Kokubo[1,5]; Mihoko Konishi[8]; Tadashi Nakajima[9,1]; Jun Nishikawa[1,5]; Masahiro Ogihara[1]; Takuma Serizawa[7]

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The observations of the *Kepler* space telescope suggest that small planets are abundant around cool main-sequence stars, among which late-M dwarfs (LMDs) represent the coolest objects. LMDs are the great targets for the exoplanet search with the radial velocity (RV) technique due to their relatively low masses and inner habitable zones. However, LMDs are so faint especially at optical wavelengths that the RV technique for LMDs needs the infrared spectrograph available on a large-aperture telescope with a stable calibration system of RV measurement. We have developed and operated the InfraRed Doppler (IRD) spectrograph that can be utilized with the adaptive optics of the Subaru Telescope. IRD observes a laser frequency comb simultaneously with an object spectrum, enabling the stable RV calibration comparable to 2 m s^{-1} at ~1.0–1.7 μm. Since February of 2019, we have started a strategic campaign to explore planets around LMDs using IRD, which is planned to go on until 2024 with the total allocation of 175 nights. This is the first large-scale survey dedicated to LMDs that is achieved by the precision RV measurements in the infrared. The IRD survey is expected to discover habitable planets that can be characterized in detail with next generation telescopes. Also, the monitor of LMDs over a few years can reveal the population of rocky to ice-giant planets inside and outside of snow lines. We have listed 150 targets based on the literature and our pre-selection spectroscopic observations to filter out active LMDs unsuitable for precision RV measurements. In addition, the rapid rotators and close-separation multiple stars are removed through the first-year IRD observations, selecting the best 60 LMDs for extensive RV measurement. In parallel with the science observations, we are testing the precision and stability of our RV measurements by observing RV-stable stars and planet-host stars such as GJ 699 and GJ 436. We here present the strategy of the IRD planet survey and its latest progress, as well as the results of the performance verification.

303.05 — The Magellan TESS Survey (MTS): Probing the Formation and Evolution of Small Planets with a Statistically Robust Survey

Xuesong Wang[1]; Johanna Teske[1]; Angie Wolfgang[2]

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[2] *Penn State (State College, Pennsylvania, United States)*

We present the design, execution, and latest results of the Magellan TESS Survey (MTS), a systematic radial velocity (RV) follow-up program using the Planet Finder Spectrograph (PFS) on the 6.5m Magellan II telescope in Chile. We will characterize a statistically robust sample of ~30 super-Earths and sub-Neptunes discovered by TESS.

There are several features that make our survey unique: (1) We designed our survey to be most effective in addressing three specific science questions: How do planetary bulk densities depend on stellar insolation? How do planetary bulk densities depend on host star composition? How do planetary bulk densities depend on system architecture? (2) We have a clearly defined target selection function and observation cadence design formula, enabling more powerful statistical/population studies using our sample. (3) We will publish all RV results regularly (~ once per year) and at the end of our study, including non-detections and upper limits. We have already been making our observing schedules public on Exo-FOP.

On behalf of the MTS team, I will present: (1) The design and execution of our program, including a description of our target selection and cadence coverage schemes, as well as the observation queue management, which is uniquely challenging for first-year

follow-up observations of TESS targets. These would be of general interest to groups that are running or will run similar programs. (2) The latest highlights and lessons learned from the first 10 months of MTS, including our battles with stellar jitter and several uniquely interesting planetary systems (from recent publications and papers in preparation).

303.06 — Radial Velocity Follow-up Program with FIES (Nordic Optical Telescope)

Andreea Gornea[1]; Lars Buchhave[1]
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The high resolution Fiber-fed Echelle Spectrograph (FIES) at the Nordic Optical Telescope (NOT) is going under instrumental developments in 2019 to prepare it for a large radial velocity (RV) follow-up program for TESS. The wavelength calibration for FIES will be improved with the installation of a Fabry-Pérot calibration source. The grating of the spectrograph will be enclosed with a pressure chamber which will decrease the variations caused by the atmospheric changes. Increasing the precision and stability of the instrument will make it suitable for the RV follow-up program that will yield mass measurements for the exoplanet candidates that the TESS mission discovers. With support from NASA and MIT the program will consists of up-to 200 nights.

303.07 — Results of the SOPHIE search for Neptunes and Super-Earths around bright solar-type stars

Nathan Hara[1]; François Bouchy[1]; Isabelle Boisse[2]; Luc Arnold[3]; Alexandre Santerne[2]
[1] *Université de Genève (Versoix, Switzerland)*
[2] *Laboratoire d'astrophysique de Marseile (Marseille, France)*
[3] *Observatoire de Haute Provence (Saint-Michel l'Observatoire, France)*

The SOPHIE spectrograph search for Neptunes and Super-Earths around bright solar-type stars began in 2011. We present the analysis of the 124 systems observed, with more than 7000 data points in total. The first part of the presentation will be dedicated to new signal processing techniques, regarding the correction of the drift of the instrument, the selection of detection thresholds and the analysis of the time series, in particular the l1-periodogram. In the second part, we will present the ten new planets that have been discovered, most of which are detectable by TESS.

303.08 — Analysis of Exoplanetary Systems as WFIRST Targets

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As part of the WFIRST Coronagraph Science Investigation Team (WFIRST-C SIT) to study exoplanets around nearby stars, we aim to characterize nearby exoplanetary systems and provide a list of stars that would be suitable targets for WFIRST to carry out exoplanet direct imaging mission. To achieve that, we will be addressing two primary issues: characterization of stellar and orbital properties of nearby exoplanets. Having a better understanding of host star characteristics and the Keplerian orbit properties of the known nearby exoplanets are crucial in determining exoplanet targets for WFIRST direct imaging. These two aspects give us important insights such as the presence of stellar and substellar companion in the system, planet-star separation, reflected light from planets, background star fields etc. We use ExoCat as well as other online sources such as Simbad, Vizier, and Gaia DR2 to provide the best possible stellar parameters for nearby exoplanet host stars. We provide a strategy to conduct precursor radial velocity observations to refine orbital ephemeris of nearby potential WFIRST exoplanet targets by the use of major telescopes such as the Automated Planet Finder. The combined effort will allow us to progress towards the completion of target selection for WFIRST exoplanet observing program.

303.09 — Exoplanets orbiting giants stars: 10 years observations of the *EXPRESS* program

Matias Jones[1]
[1] *European Southern Observatory (Santiago, Chile)*

Evolved stars (subgiants and giants) are suited targets for precision radial velocity studies by two main reasons: 1) they are cooler and rotate slower than their former main-sequence progenitor, which allow us to achieve a radial velocity precision at the m/s level for intermediate-mass stars , and 2) we can use them to study the dynamical evolution of planetary orbits due to the interaction with the expanding stellar envelope. Since 2009, we have been conducting a radial velocity survey called EXPRESS (*EX*o*P*lanets a*R*ound *E*volved *S*tar*S*) aimed at studying the population of planets orbiting giant stars. We have obtained multi-epoch spectroscopic data for a sample of 166 bright giant stars, resulting in the *detection of*

~*30 planetary systems* (some of these in common with the Pan-Pacific Planet Search), *2 brown dwarf candidates in the desert and 24 spectroscopic binaries*, two of them with an astrometric orbit resolved using Hipparcos data. Additionally, we have found that the *planet-metallicity correlation is valid for giant stars* and we have also confirmed previous results showing that the *giant planets formation efficiency increases with the stellar mass* (up to ~ 2.0 M_{sun}). In this talk I will describe our project and present the main results after 10 years of observations. Finally, I will discuss our findings in the context of planetary formation.

303.10 — A New Tool for Simulating Spectra Spectra & Validating Machine Learning Models for Exoplanet Discovery

Eric B. Ford[1,2]; Michael Palumbo[1]; Johannes Löhner-Böttcher[3]; Suvrath Mahadevan[1]; Jason Wright[1]

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Currently, the planet detection sensitivity of state-of-the-art Doppler RV spectrographs is limited by intrinsic stellar variability for most target stars. Multiple groups are developing improved spectroscopic indicators (e.g., Jones et al. 2017, Zechmesiter et al. 2017, Dumusque 2018, Wise et al. 2018) and powerful, but complex statistical models (e.g., Rajpaul et al. 2015; Jones et al. 2017) to mitigate stellar variability. These methods need to be validated and compared, in order to make robust and credible detections of rocky planets in or near the habitable zone of Sun-like stars. Recent results appear promising for mitigating stellar variability originating from active regions rotating across the disk, as long as observing campaigns obtain dense time sampling and high spectral resolution/signal-to-noise. However, it is unclear if these same methods will be effective for stars dominated by granulation, which has a much shorter timescale than rotationally-linked variability.

We present a new tool for generating synthetic high-resolution stellar spectroscopic timeseries. While previous tools (e.g., SOAP, StarSim) have focused on modeling stellar activity, our tool focuses on exploring the effects of convection and granulation on measured radial velocities. Generating synthetic datasets that include these effects is critical for evaluating the performance of strategies for mitigating the stellar variability problem for Sun-like stars. Thus, our tool will play an important role in validating machine learning algorithms and comparing the efficacy of various approaches for mitigating the effects of intrinsic stellar variability on Doppler planet surveys. Additionally the results are likely to have important implications for target selection in upcoming Doppler surveys. We will describe our model and show a movie of the line-profile variations in our simulated data. We will evaluate the apparent radial velocities perturbations predicted by our new model and discuss the implications for upcoming Doppler planet surveys and TESS follow-up campaigns.

303.11 — Distinguishing planets from stellar variability with machine learning

Christian Gilbertson[1]; Eric B. Ford[1]; David Jones[3]; David Stenning[4]; Tom Loredo[2]

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[4] *Mathematics, imperial College London (London, United Kingdom)*

The radial velocity method is one of the most successful techniques for the discovery and characterization of exoplanets. Current RV surveys are sensitive to planetary signals of 1 m/s or less, but the variability of stellar spectra (caused by star spots, pulsations, convective motions, granulation, etc.) can mimic and obscure true planet signals at the same level. A data-driven approach for detecting planetary RV signals amidst stellar activity has recently been proposed by Rajpaul et al. (2015) and refined by Jones et al. (2017). This approach uses a physically motivated multivariate Gaussian process (GP) to jointly model the apparent RV and multiple indicators of stellar activity, allowing the planetary RV component to be separated from the total RV signal. Our statistical framework combines spectroscopic and temporal information to reconstruct the apparent RV perturbation and improve sensitivity to low-mass planets. In this work, we build on previous studies by simulating higher-fidelity active solar spectra time series (e.g., distribution of active region sizes, rise and decay timescales, latitudes, and differential rotation) and compare the performance of several different GP kernel functions. Our early results suggest specific alternative kernel functions that are likely to improve the model and make it more sensitive to detecting low-mass planets. We will describe simulated datasets (which may be valuable for research groups testing their own approaches to mitigating stellar variability), demonstrate the features of our statistical model, and share our most recent results on the impact of the choice covariance kernel on sensitivity to low-mass planets and the implications for planning RV surveys and follow-up campaigns. The success of current and upcoming planet-hunting instruments hinges on the community's ability to overcome the stellar variability challenge. This research represents important steps on the path toward developing, validating and applying powerful machine-learning tools and a robust statistical framework for discovering and characterizing low-mass exoplanets in the presence of stellar variability.

303.12 — New Astrophysical Insights into Radial Velocity Jitter

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For nearly 20 years, the California Planet Search (CPS) has simultaneously monitored precise radial velocities and chromospheric activity levels of stars from Keck observatory to search for exoplanets. This sample provides a useful set of stars to better determine the dependence of RV jitter on magnetic activity and stellar convection. For ~650 stars covering a wide range of stellar parameters (effective temperature, surface gravity, and activity, among others), there are enough RV measurements to distinguish this astrophysical jitter from accelerations due to orbital companions. To properly isolate RV jitter from these effects, we first remove the RV signal due to these companions. We present some new results from our analysis of the CPS data, highlighting empirical evidence of two regimes of RV jitter – activity-dominated and convection-dominated – and the resulting "jitter minimum". A more thorough understanding of the various sources of RV jitter and the underlying stellar phenomena that drive these intrinsic RV variations will enable more precise jitter estimates for RV follow-up targets such as those from the K2 or TESS missions.

303.13 — Exoplanet Imitators: A test of stellar activity behavior in radial velocity signals

Chantanelle Nava[1]; Mercedes Lopez-Morales[1]; Raphaëlle Haywood[1]; Helen Giles[2]

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Effects from stellar activity are the largest barrier to detecting radial velocity signals of low-mass exoplanets. Radial velocity (RV) signals due to stellar activity are primarily caused by stellar magnetic active regions on the rotating stellar surface. Current methods to identify activity signals assume that the maximum peak in a RV periodogram will occur at the stellar rotation period or a related harmonic. In this talk, we present results of simulations to test the effect of non-perfectly periodic activity signals in typical RV observations. We simulate RVs with quasi-periodic signals that account for the evolution and migration of magnetic active regions. As test cases, we apply our analysis to two known exoplanet hosts, Kepler-20 and K2-131. Our simulations show the maximum peak in the RV periodogram occurring at a period unrelated to the stellar rotation period in 85% and 72% of iterations, respectively for K2-131 and Kepler-20. We also show that in datasets with observational sampling typical of current RV surveys, signals from stellar activity can imitate those of exoplanet candidates with orbital periods many days away from the stellar rotation period and any of its harmonics. These new results not only apply to small exoplanet detection, but also have broad implications for the general interpretation of periodic signals in stellar RVs.

303.14 — Two massive planets orbiting HD 25723 and 17 Sco and two planet candidates around 3 Cnc and 44 UMa

Marcelo Tala Pinto[1]; Sabine Reffert[1]; Andreas Quirrenbach[2]

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More than hundred exoplanets have been discovered around K and G giant stars, and their properties differ considerably from those of the planets found orbiting late-type main-sequence stars. This allows us to study the properties of planetary systems after the host star has evolved off the main-sequence, and helps us to constrain planetary formation and evolution models. Our aim is to confirm the long-period radial velocity variations observed in four giant stars of the Lick survey as caused by orbiting planets, and to study the properties of the planet population as a function of stellar evolutionary stage. We analyze twelve years of precision radial velocity data for four stars of the Lick sample. In addition, we compare the planet occurrence rates as a function of evolutionary stage for two surveys, Lick and EXPRESS, based on the evolutionary stages derived by the Bayesian Inference method. We report the detection of two new exoplanets and two candidates orbiting giant stars. The best Keplerian fits to the data predict minimum masses of 2.3 m_J and 4.3 m_J for the planets orbiting HD25723 and 17 Sco, respectively. The minimum masses of the planet candidates around 3 Cnc and 44UMa would be 20.7 m_J and 12.1 m_J, respectively. In addition, we computed planet occurrence rates for the Lick and EXPRESS samples as a function of evolutionary stage. For the Lick sample the planet occurrence rates are 5.3% and 4.3% for horizontal branch and red giant branch stars, respectively. For the EXPRESS sample the horizontal branch and red giant branch planet occurrence rates are 11.1% and 9.9%, respectively.

304 — Planet Detection — Microlensing, Poster Session

304.01 — Precise Mass Measurements of Cold Planets Discovered by Microlensing: Cold planet Mass Function and Spatial Distribution in Our Galaxy

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Microlensing is probing the unique population of cold planets down to Earth mass orbiting around any kind of star, at any distance towards the galactic center. Relative physical parameters are known to good precision from the modelling of the light curves, but it is necessary to combine the result of light curve modeling with lens mass-distance relations from additional observations and/or perform a Bayesian analysis with a galactic model. Often, physical parameters are determined to 30-50 %. Recently, two kinds of constraints on masses have been extensively used, coming from ground-space parallax Spitzer observations and high angular resolution observations with adaptive optics or HST. Our team has shown that we can derive physical parameters on known systems to 10 % or better with mass-distance relations obtained from high angular resolution observations, either by detecting the lens flux and/or resolving source and lens and measuring the amplitude and direction of their relative proper motion. This work is also a pathfinder of the mass measurement method to be applied to WFIRST and Euclid microlensing programs.

We will report the results from our large observing program with KECK and HST over 40+ planetary systems. We revised the stellar and planetary masses and distances for these systems, and often found significant differences, even despite the initial large error bars. We also show some tensions with the constraint from ground-space parallax Spitzer data, where Spitzer lightcurves photometry seems to be plagued by under estimated systematics for the faint targets in very crowded field. We will discuss the impact of our analysis on the cold planet mass function. With our revised distances, we found that the systems we re-visited so far tend to be located in the Sagittarius or Scuttum-Crux arms, or at the tip of the bar.

304.02 — A blind search for free-floating planets in K2 Campaign 9

Iain McDonald[1]; Eamonn Kerins[1]

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Free-floating planets may be as frequent in the galaxy as stars, and act as tracers of the dynamism of planetary systems. However, their occurrence rate, particularly for low-mass planets, is very poorly known. We have conducted a blind search for microlensing signatures caused by free-floating planets over the contiguous K2 Campaign 9 field, towards the Galactic Bulge. This has revealed a number of candidate microlensing planets. I will present the latest analysis of the Campaign, and reflect on its shortfalls and the lessons to be learnt for future surveys.

304.03 — Determining the NIR Microlensing Event Rate at |b| < 2 with the United Kingdom Infrared Telescope

Savannah Renee Jacklin[1]; Yossi Shvartzvald[2]; Geoff Bryden[4]; Sebastiano Calchi Novati[2]; Keivan Stassun[1,6]; B. Scott Gaudi[3]; Kiri Wagstaff[4]; Selina Chu[4]; Calen Henderson[5]; Matthew Penny[3]; Chas Beichman[2]

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With the mid-2020s launch of the Wide Field Infrared Survey Telescope (WFIRST) fast approaching, it is becoming increasingly imperative to understand the optimal spatial region for microlensing event detection. The Galactic center (i.e. where $|b| < 2$) which has the highest density of potential source stars in the Milky Way, has been historically understudied due to the obscuring properties of its high volume of gas and dust. The United Kingdom Infrared Survey Telescope (UKIRT) microlensing project has succeed in mitigating some of the reddening effect of Galactic dust by observing in the near-infrared over a baseline from 2015-2018. Observations in the K and H NIR bands in unique fields have yielded hundreds of microlensing events detected via our UKIRT data reduction pipeline. We combine our microlensing detections with image-level mock event injections in order to determine our survey's detection efficiency, and subsequently aim to derive the NIR microlensing event rate per observed square degree. Here we discuss the methodology of our pipeline as well as preliminary results for the NIR microlensing detection efficiency and event rate. Understanding the intrinsic NIR microlensing event rate at low Galactic latitude is crucial for informing mission design and field specifications for WFIRST.

304.05 — UKIRT Microlensing Survey as a Pathfinder for WFIRST

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Exoplanet microlensing surveys generally neglect the very center of the Galaxy due to the very high optical extinction. The future NASA flagship mission, WFIRST, however, will operate at near-IR wavelengths, such that its optimal target fields may be located in more central regions of higher stellar density. To test this, we are using UKIRT's wide-field near-IR camera to survey the galactic bulge all the way to the center. We will present our 2017-2018 survey results, both the raw number of event detections and the corresponding event rate maps, after correcting for the detection efficiency.

304.06 — Mass Measurements of Wide Orbit Exoplanets

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The original prediction of the core accretion theory was that planet formation was dominated by wide orbit planets that grew beyond the snow line. The discovery of a large number of planets in short period orbits by the transit and radial velocity methods may have changed these expectations somewhat, but an understanding of the wide orbit planet population is needed to advance our understanding of the panet formation process. The gravitational microlensing method has unique sensitivity to wide orbit planets down to an Earth mass, beyond the snow line, so it is our most promising method to study the demographics of wide orbit planets over a large mass range. However, microlensing light curves usually reveal only the planet-star mass ratio and not the planet or host star mass. (Masses are rarely measured for wide orbit radial velocity planets, but the host star mass is almost always knwon.) I present new results on the measurement of microlens planet and host star masses using the microlensing parallax method and high angular resolution follow-up observations, and show how this difficulty will be resolved for microlens planetary systems discovered by ground-based surveys and WFIRST.

305 — Planet Detection — Imaging, Poster Session

305.01 — Kernel-Phase Interferometry for Super-Resolution Detection of Faint Companions

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Filling out the dearth of detections between directly imaged and radial velocity planets will test theories of planet formation across the full range of semi-major axes, connecting formation of close to wide separation gas giants, and also substellar companions. Direct detection of close-in companions is notoriously difficult: coronagraphs and point spread function (PSF) subtraction techniques are significantly limited in separation and contrast. Non-redundant aperture masking interferometry (NRM or AMI) can be used to detect companions well inside the PSF of a diffraction limited image, though the technique is severely flux-limited since the mask discards $\sim$95% of the gathered light. Kernel-phase analysis applies similar interferometric techniques to an *unobscured* diffraction limited image. Kernel-phases are constructed by simulating a redundant interferometer as a grid of subapertures superimposed on the full telescope aperture and calculating phase-like observables (similar to closure-phases used with NRM). I have developed a new faint companion detection pipeline which analyzes kernel-phases utilizing Bayesian model comparison. I break open the black box of interferometry by demonstrating the use of this pipeline on archival *HST/NICMOS* images of nearby brown dwarfs. I refine astrometry of previously known companions and search for new companions, in order to constrain formation models at au scales. I also present contrast curves to demonstrate the strength of this technique at separations inaccessible to classical imaging techniques. Using this method, it is possible to detect companions down to flux ratios of $\sim 10^2$—reaching the planetary-mass regime for young targets—at half the classical λ/D diffraction limit while using a fraction of the telescope time as NRM. I am now preparing to use this technique to search for planetary mass companions using *HST/ACS* imaging of the young star-forming regions of Taurus and Upper Scorpius. Since *JWST* will be able to perform NRM and unobscured imaging, further development and characterization of kernel-phase analysis will allow efficient use of competitive *JWST* time.

305.02 — Direct imaging of exoplanets in the mid infrared with VISIR

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Direct imaging is a tried and tested method of detecting exoplanets in the near infrared, but has so far not been extended to longer wavelengths. Large ground-based telescopes are capable of routinely producing diffraction limited images at mid-IR (8-20 micron) wavelengths. We have used the VISIR instrument on the VLT to image the close vicinity of the young stars HD 100546 (10 Myr) and HR 8799 (60Myr) systems in the mid infrared at 8.7micron. We use two different methods to reduce the data, angular differential imaging and the subtraction of a circularised psf, and present the best mid-IR images to date of the disk around HD 100546. We derive the most stringent upper limits to date for the 8.7 micron flux of planets in both systems.

305.03 — Initial results from BEAST: The B-star Exoplanet Abundance Study

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In the last decade, a large number of direct imaging surveys have targeted hundreds of young and nearby stars in the near-infrared, looking for self-luminous giant planets at separations >10AU. These observations have proven that substellar companions on wide orbits are rare, but seem to be more common with increasing host stellar mass. However, the more massive B-type stars (>3M_{Sun}) have not been studied to the same level of scrutiny as AFGKM types, and it is not clear whether this trend holds for the most massive stars or there is an overturn, as suggested by the indirect methods at short separations. To address this issue, the B-star Exoplanet Abundance Study (BEAST) survey has recently been started with the goal of detecting giant planets, brown dwarfs and disks around 83 B-type stars in Scorpius Centaurus with SPHERE. Here, we describe the layout of the survey and the current status of the initial exploratory observations. We also present the first result yielded by BEAST, the discovery of a ~20 M_{jup} circumbinary brown dwarf in Upper Scorpius with a mass ratio <1%, i.e., consistent with being formed through a planet-like mechanism. We will discuss the spectral properties of this object and the importance of common proper motion when claiming physical association.

305.04 — Pushing the Limits of Exoplanet Discovery via Direct Imaging with Deep Learning

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Further advances in exoplanet detection and characterisation require sampling a diverse population of extrasolar planets. One technique to detect these distant worlds is through the direct detection of their thermal emission. The so-called direct imaging technique, is suitable for observing young planets far from their star. These are very low signal-to-noise-ratio (SNR) measurements and limited ground truth hinders the use of supervised learning approaches. In this paper, we combine deep generative and discriminative models to bypass the issues arising when directly training on real data. We use a Generative Adversarial Network to obtain a suitable dataset for training Convolutional Neural Network classifiers to detect and locate planets across a wide range of SNRs. Tested on artificial data, our detectors exhibit good predictive performance and robustness across SNRs. To demonstrate the limits of the detectors, we provide maps of the precision and recall of the model per pixel of the input image. On real data, the models can re-confirm bright source detections.

305.05 — New Spatially Resolved Observations of the SR 21 Transition Disk

Stephanie Sallum[1]; Andy Skemer[1]; Josh Eisner[2]; Nienke van der Marel[3]; Patrick Sheehan[4]; Laird Close[2]; Michael Ireland[5]; Jared Males[2]; Katie Morzinski[2]; Vanessa Bailey[6]; Runa Briguglio[7]; Alfio Puglisi[7]
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We present new 0.6 - 4 micron imaging of the SR 21 transition disk from Magellan / MagAO and Keck / NIRC2. The protoplanetary disk around SR 21 has a 30 - 40 AU dust clearing first inferred from its spectral energy distribution and later confirmed in submillimeter imaging. The gas and small, micron-sized dust grains are known to have a different morphology, with a truncation in CO at ∼ 7 AU and H band scattered light detected within the millimeter clearing. The observations presented here probe tighter angular separations than previous studies, placing new constraints on the geometry of the small-grain disk. Reproducing the imaging data requires a misaligned inner disk or azimuthal asymmetries in the dust distribution. Furthermore, reconciling the imaging with the spectral energy distribution may require grain growth to ∼2-5 microns. These features can be connected to dynamical shaping by an unseen, giant-planet mass companion, a situation supported by previous observational and theoretical studies.

305.06 — Giant planet formation in the near-infrared: single large telescopes are not enough

Jens Kammerer[1,2]; Alexander Wallace[1]; Michael Ireland[1]
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Giant planets are thought to form at large orbital separations (>3 au), which is why direct imaging is crucial to detect young gas giants and study their formation process. PDS 70 b remains the only fascinating case of such an object for which accretion is clearly evident.

Using Keck/NIRC2, we search for companions around 33 members of the ∼1 Myr old Taurus star-forming region. Fourier plane imaging (kernel phase) and PSF subtraction allow us to probe a large range of orbital separations down to Solar System scales (∼6 au = 0.5 λ/D), which has not been possible before in the near-infrared. Together with our simulation of giant planet formation via core accretion and the latest planet distribution from radial velocity surveys, our observations put some constraints on the peak luminosity and the timescale of the runaway accretion.

Considering future observations, we show that even with optimistic assumptions, the number of "normal" core accretion giant planets detectable by 8-10 m telescopes is of order 1. This is due to evidence for a turnover in planet frequency at ∼3 au, the small number of ∼solar-mass young stars harbouring gas disks within 200 pc, and the insufficient brightness of truly "Jovian" planets. We make the case that in order to probe the formation of planets like Jupiter, a high-contrast interferometric instrument (such as Hi-5/VIKiNG) is required.

305.07 — PDS70, witnessing a young solar system analog in formation

Dino Mesa[1]
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PDS70 is a young (∼5 Myr) star hosting a known transition disk with a large gap resolved with observations at NIR and (sub-)millimiter wavelengths with SMA and ALMA. Recent observations with SPHERE allowed us to detect a planetary companion (5-9 M_{Jup}) at a separation of ∼22 au (PDS70b), well inside the disk gap. This companion was then confirmed by observation with other instruments (e.g. MagAO, SINFONI, MUSE) which furthermore revealed ongoing accretion on PDS 70 b. In addition, recent Hα observations with MUSE also suggested the presence of a second planetary companion at larger separation from the star. Re-analysis of archive SPHERE data and new data taken with this aim allowed us to confirm and to characterize this object (PDS70c). Furthermore, we reporton the tentative dtection of a third source (PDS70d) located at shorter separation than PDS70b. Its spectrum is compatible with the presence of dust and therefore the existing data do not allow to confirm its planetary nature. We will present here some hypothesis on its nature. Finally, we will describe the possible structure of the PDS70 planetary system as emerging from our current knowledge. PDS70 is a unique case where the properties of a planetary system can be characterized during its formation stage.

305.08 — Thermal-Infrared spectroscopic studies of planets and protoplanets with ALES

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Understanding the physical state of gas-giant exoplanet atmospheres is challenging due to persistent degeneracies between effective temperature, cloudiness, and dis-equilibrium chemistry. Broad wavelength spectroscopic studies are essential to break these degeneracies, yet, until recently, all extreme adaptive optics systems focused on 1-2.5 micron sensitivity. To break model degeneracies and improve our understanding of gas-giant atmospheres, we built an adaptive optics-fed integral field spectrograph with sensitivity out to 5 microns — the Arizona Lenslets for Exoplanet Spectroscopy (ALES). I will present initial results including 2.8-4.2 micron spectra of gas-giant exoplanets. I will also provide an update on the status of recent instrument upgrades including increased spectral resolution and the addition of high-performance coronagraphic technologies.

305.09 — How to Detect Long-Period Neptunes through Direct Imaging

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Modeling of the gap structures in protoplanetary disks revealed by the Atacama Large Millimeter Array suggests that sub-Jupiter-mass planets may be common at large orbital separations. If true, this imposes fundamental constraints on theories of planet formation to both form giant planet cores quickly at large orbital separations, and to sufficiently suppress runaway gas accretion to yield the inferred planet mass function. Unfortunately, while future high-contrast instruments will push toward detecting ever-smaller planets closer to their host star, directly imaging this putative population of distant sub-Jupiters at typical contrast ratios of 10^{-10} - 10^{-12} will remain out of reach for the foreseeable future.

However, building on models of circumplanetary debris disks (CPDDs) by Kennedy & Wyatt (2011), we show that debris from collisions between irregular satellites can increase young planets' contrast ratios by several orders of magnitude. Dozens of irregular satellites are found around each of our own giant planets, and they indeed represent the most collisional evolved population in the solar system, betraying bright CPDDs in the past. We find that exoplanetary CPDDs would have been below the detection threshold of the GPIES direct imaging survey. However, depending on irregular satellites' capture mechanism and efficiency, we show that by optimizing the target selection for finding such structures, the CPDDs of this population of long-period, Neptune-mass planets may be detectable with current instrumentation, and demonstrate that it should be an important science case for the next generation of direct imaging with ELTs and WFIRST coronography. We argue that such structures can be unambiguously identified through their strong polarization signatures and discuss their implications for our understanding of not only planet formation but also our own Solar System's history.

306 — Planet Detection — Other, Poster Session

306.01 — How to detect forming planets?

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Giant- and immediate mass planets are surrounded by their circumplanetary disk during the last stage of their formation. In order to detect nascent planets, therefore, we need to understand the characteristics of this disk, since this is what we are going to observe. The planet is embedded within the circumplanetary disk, therefore we would not be able to see that directly, as simulations show. I create mock observations on various wavelengths by combining 3D radiative hydrodynamic simulations and Monte-Carlo radiative transfer to create synthetic images, and spectral energy distributions (SEDs). In my talk I will show how these images look like at sub-mm and radio wavelengths, at near/mid-infrared and at polarized scattered light for the various current and near-future instrumentation, such as ALMA, SPHERE/GPI, ERIS/NaCo etc. The spectral energy distribution of the circumplanetary disk will be also discussed and compared with the circumstellar disk SED, in order to identify the wavelength range where the best contrast can be achieved to detect the circumplanetary disk and the forming planet. Finally, I will talk about what line fluxes we can expect regarding detecting H-α from these sources. I will try to give an answer why previous attempts of detection of circumplanetary disks often failed, what are the difficulties to face with, and what systems we could detect with current/near future instrumentation based on my simulations. To understand how forming planets should look like on observations, also help us distinguishing forming planets from other circumstellar disk features. I will highlight, that in the formation phase, unfortunately we cannot estimate the planet mass based on the observed brightness, because the fluxes are always contaminated by the circumplanetary disk contribution, and therefore the brightness will depend mainly on the disk properties (temperature, dust-to-gas ratio, density, viscosity, etc.), less about the planet luminosity.

306.02 — Astrometric orbits of tight substellar binaries

Johannes Sahlmann[1]
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We present new results from the high-precision astrometric monitoring of nearby very-low-mass stars brown dwarfs with Gemini/GMOS and VLT/FORS2. The goals of these projects are the characterisation of known spectral binaries and the discovery of companions down to sub-Jupiter mass, respectively. We will give an overview of the program, report on the orbit determination of spectral binaries, and present an update on our planet-search results. We will put these results into the context of efforts to determine the tight binary fraction of ultracool dwarfs and to explore the occurrence of planets around these objects.

306.03 — What we'll see when we've seen what we see that we can see

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Improving instrumental precision is like a receding tide, revealing the geological shapes underneath the water's surface. New signals rise out of the noise, take shape and gain familiarity, until it is hard to imagine ever not having known them.

Out-of-transit effects — tides, beaming and reflections in particular — are one such family of signals which will transition from near-invisible to commonplace. As photometric precision drops from 100s of parts per million to 10s and below, these signals will go from being occasional to ubiquitous in light curves, especially for massive, close-in or eccentric planets.

We can leverage these signals as tools for constraining planetary properties, confirming candidates and detecting new planets — but doing so requires a detailed, intuitive and accurate theoretical understanding of the physics at play and the observational signatures.

Here we present analytic models of these effects, of sufficient simplicity to allow easy intuition and calculation, whilst encoding a full physical picture able to capture the behaviour of the broad exoplanet zoo.

306.04 — The potential of direct detection of exoplanets by optical interferometry

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With over 4000 exoplanets discovered, the focus of exoplanet research progressively shifts from census to characterization. Direct imaging targets a different planet population than transit spectroscopy: it is possible to obtain spectra of young, far-out exoplanets. And in that field, optical interferometry is on the verge of playing a major role: with baselines of hundred meters, its spectral and differential imaging capacities surpass by order of magnitudes those of single dish telescopes. During this talk, I will present the interferometric technique which enables direct observations of exoplanets. I will present the detection of HR8799e by the GRAVITY instrument, and discuss the capability of the technique for future detections.

306.05 — Alkaline Signatures of an Active Exomoon

Apurva V. Oza[1]; Robert E. Johnson[2]; Emmanuel Lellouch[3]; Carl Schmidt[4]; Nick Schneider[5]; Chenliang Huang[6]; Diana Gamborino[1]; Andrea Gebek[1,7]; Aurelien Wyttenbach[8]; Brice-Olivier Demory[9]; Christoph Mordasini[1]; Prabal Saxena[11]; David Dubois[10]; Arielle Moullet[10]; Nicolas Thomas[1]

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[11] *Center for Space and Habitability, Universität Bern (Bern, Switzerland)*

Exomoons are generally too small to be detected by nominal searches. By analogy to the most active body in the Solar System, Io, we describe how sodium (Na I) and potassium (K I) gas could be a signature of the geological activity venting from an otherwise hidden *exo-Io*. Analyzing a dozen close-in gas giants hosting robust alkaline detections, we show that an Io-sized exomoon can be stable against orbital decay below a planetary tidal Qp < 10^{11}. This tidal energy is focused into the satellite driving $\sim 10^5$ times more mass loss than Io's supply to Jupiter's Na exosphere, based on a simple atmospheric loss model. The remarkable consequence is that several exo-Io column densities are on average *more than sufficient* to provide the $10^{10\pm1}$Na cm^{-2}required by the equivalent width of exoplanet transmission spectra. Furthermore, the benchmark observations of both Jupiter's extended ($\sim$1000 R_J) Na exosphere and Jupiter's atmosphere in transmission spectroscopy yield similar Na columns that are purely exogenic in nature. As a proof of concept, we fit the "high-altitude" Na at WASP 49-b with an ionization-limited cloud identical to the precise Na profile about Io. Moving forward, we strongly encourage time-dependent ingress and egress monitoring along with spectroscopic searches for other volcanic volatiles.

306.06 — Detection of a New Planet in a Resonant Orbit Using Transit Timing Variations

Chris Fox[1]

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The vast amount of data from the Kepler Space Telescope has provided more than just transiting planets. By analyzing the timing of transit, the existence of more planets, as well as the properties of already known planets, can be determined. Here we look at the case of Kepler-159, a system of two transiting planets, one of which shows significant transit timing variations. Using orbital modeling and Bayesian Inference, we determine the existence of a third planet in a resonant orbit, as well as mass estimates and orbital parameters for the two interacting planets.

307 — Transit Timing, Poster Session

307.01 — Unravelling the Hidden Features of Time-Varying Signals in a Photocentric Model of Transitting Exoplanets with Moon

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There have been several attempts to use the Transit Timing Variations (TTV) and Transit Duration Variations (TDV) techniques to infer the presence of exomoons from existing observational data, but none has successfully been able to accomplish this. Part of the reasons is the unexplained deviations of signals in the theoretical sinusoidal shape, which result from light curves fitted by a photocentric model. In this work, the deviation of time-varying signals is characterised by considering the fitting of synthetic star-planet-moon light curves using a photocentric model. The magnitude of signal deviation depends on the position and length of moon transit component at different moon phases. This results in unique features in the phase evolution of TTV, TDV and effective transit depth signals in and around

the primary and secondary transits of the moon inside the planet. Taking into account the aforementioned effect and neglecting limb darkening, the dependency of features' magnitude on masses, radii and orbital separations is described for the cases of moons at large planet-moon orbital separations. For large moons with non-negligible transit components, this demonstrates that the contribution of moon transit component to the resulting TTV, TDV and effective transit depth needs to be accounted for in order to confirm exomoon detections.

307.02 — Transit Timing Variation Refinement of the Long-period Exoplanet Kepler-167e

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Kepler-167e is a long-period (P=1,071 days), Jupiter-size exoplanet that was discovered in transit observations by the *Kepler* spacecraft during its primary mission. Many properties of Kepler-167e including its eccentricity, stellar insolation, and equilibrium temperature are strikingly similar to those of Jupiter, making this exoplanet an excellent candidate for comparative planetology. *Kepler* observed only two transits of Kepler-167e, which left the existence of transit timing variations (TTVs) unknown. Many long-period exoplanets and candidates have shown TTVs of up to 40 hours in duration. Until the existence of such TTVs are constrained, follow-up transit observations (e.g., for atmospheric characterization) are extremely risky. We present new *Spitzer* observations of Kepler-167 that recover a partial transit of Kepler-167e. These observations constrain the extent of TTVs in the system, and enable accurate and precise predictions of future transits through the anticipated era of *JWST*.

307.03 — Maintenance of Transit Timing Errors using Real and Simulated Telescope Networks

Hamish Elliot Caines[1]
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The Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) will observe 1000 exoplanets spectroscopically during transit to characterise their atmospheres. Optimal use of the observation time will require accurate transit times for all of the selected targets. The current uncertainty in the transit time will propagate significantly between now and the mission launch in 2028. The calculated uncertainty at launch in many cases is too large for optimal scheduling of ARIEL observation time, and in some it is larger than the duration of the transit itself, so these transit timings are effectively lost. Therefore, ground-based follow-up to obtain more transit times for each target is required, as this reduces the amount of time the uncertainties are propagated over. In this work we determine a set of criteria that provides optimal prioritisation of transit events that maintains timing accuracy for all ARIEL targets to within seconds from today until launch. We present a telescope network simulator that will be used to evaluate potential criteria sets. The size of the network in the simulation can be adjusted, so the minimum number of telescopes required to best execute the follow-up can be also determined. In parallel, high priority targets will be observed in transit using a real network of telescopes, yielding new timing data. We present sets of real light curves and ephemerides obtained using this telescope network, and demonstrate the effect of adding observations to a data set on the timing uncertainty of a given target. In addition, we provide an estimate of the size and cost of a network able to provide the amount of telescope time needed to constrain the transit timing for all targets until and beyond launch.

308 — Stellar Spins and Obliquities, Poster Session

308.01 — Finding Waldo: The Rossiter-McLaughlin effect of π Men c hidden within stellar oscillations

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Context. The formation and dynamical evolution of super-Earths is subject to an intense debate. About 50% (70%) of FGK (M) stars host super-Earths, making them one of the most frequent types of planets. Yet, we do not understand whether the close-in super-Earths we can detect formed close to the star, or further out followed by an inwards migration process, such as dynamical scattering with an outer companion. In the latter case, the scattering process would leave an observable trace in the form of high obliquity, which can be measured through the Rossiter-McLaughlin (R-M) effect and can thus distinguish between different formation mechanisms. The first TESS planet, π Men c, offers a great test case given that the G dwarf also hosts an outer massive planetary companion on an eccentric orbit, reminiscent of past dynamical interactions within the system.

Methods. R-M observations for π Men c are challenging since its signal is expected to be dwarfed by stellar pulsations. However, the bright host star allows for short cadence observations that can resolve the oscillation frequency, yet retain the R-M signal. We have obtained spectroscopic transits of π Men c on ESPRESSO. The data show high frequency peak-to-peak variation of 4-5 m/s, masking the expected 0.7 m/s R-M amplitude. In a novel framework, we employ Gaussian processes to perform asteroseismology in the time-domain on a main-sequence star to successfully extract the dominant frequency, ν_{max}, and uncover the projected obliquity, λ. Moreover, we use TESS data to constrain the stellar rotation and extract the 3D obliquity, ψ. We verify our analysis by attempting to extract the planet-occulted light of the star for an independent retrieval of ψ.

In this talk. I will present our efforts towards the first detection of the R-M effect from a super-Earth, showing some of the first science results from ESPRESSO on the obliquity of pi Men c. In the era of extreme precision RVs, our analysis demonstrates the need for incorporating asteroseismology in the modelling of stellar variability to push R-M observations towards small planets in order to study their dynamical histories.

308.02 — Doppler Tomographic Analysis for Planetary Orbital Precession of WASP-33b

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Apparent orbital obliquity λ is one of the important parameters to understand orbital evolutions. If a planet has followed an orbital evolution like those in our solar planets, its orbit will be aligned with the stellar spin. It is called a prograde orbit ($|\lambda| <$ 90 deg) and many exoplanets orbit in this direction. However, there are few exoplanets with retrograde orbits ($|\lambda| >$ 90 deg). Doppler tomography (DT) is one of the methods to measure λ. When a planet covers part of the stellar surface during transit, a planetary shadow appears in the broadened line profile. Then, λ can be derived by the track of the shadow. Moreover, impact parameter b can be also measured by DT.

Johnson et al. (2015), henceforth as J+15, found that the transit chord of WASP-33b, which has a 1.2-day period retrograde circular orbit around a rapidly rotating and pulsating A-type star, changed slightly from 2008 and 2014. They detected its orbital precession due to its slightly flattened central star. However, only two observational epochs, from 2008 and 2014, were used in J+15. We aim to confirm and more precisely measure the precession using not only the dataset of 2008 and 2014 but also a previously unpublished dataset from 2011.

In our research, we used observational data of WASP-33 which was obtained using the High Dispersion Spectrograph (HDS) on the 8.2m Subaru telescope on 19th October 2011 (UT), as well as data sets of J+15 which has already been analyzed up to their line profiles. We got the planetary shadow showing a retrograde orbit and a component from stellar pulsations. In order to make the measurement of the planetary parameters more easily, we extracted only the planetary shadow by Fourier filtering used in J+15.

In order to make the measurement of λ and b, we adopted an MCMC analysis for the datasets with our planetary shadow model with Fourier filtering. Then we found that our measured values did not follow the equations of a long-term orbital precession from Iorio (2016). This may imply that WASP-33b's precession has a short unclear variation or our measured errors are underestimated.

308.03 — Reloaded RM with ESPRESSO: New Planet Architectures and Stellar Activity Characterisation

Heather Cegla[1]

[1] *University of Geneva (Versoix, Geneva, Switzerland)*

Stellar surface phenomena (spots, faculae, granulation etc.) alter the observed stellar spectra and can inject spurious signals into a variety of planet detection and characterisation methods. As such, our knowledge of other solar systems depends strongly on our understanding of their host stars. For these reasons, we 'Reloaded' the Rossiter-McLaughlin (RM) effect using transiting planets to directly probe stellar surfaces and 3D planetary dynamical histories. With the 'Reloaded RM', we can isolate the starlight behind the planet without making any assumptions on the local absorption line profiles, or underlying stellar radial velocities. We have successfully applied this new technique to planets orbiting GK dwarfs, pinning down 3D geometries and demonstrating that classical RM analysis may bias our planetary interpretations. Moreover, with the Reloaded

RM we have also unveiled the first planet architecture around a cool M dwarf. Here, I will present the first Reloaded RM results obtained from the ESPRESSO spectrograph, including both a planet orbiting a magnetically active K dwarf and another misaligned planet orbiting a hot F dwarf. Initial analysis reveals striking divergences from the literature, owing to the increased instrumental precession of ESPRESSO and advances from this new technique; in particular, we find evidence for significantly different star-planet obliquities and potentially contamination from starspot penumbral flows.

309 — Population Statistics and Mass-Radius Relations, Poster Session

309.01 — Threshold Radii of Volatile-rich Planets

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We use a statistical analysis to determine the characteristic maximum radii ("threshold radii") for various compositions for exoplanets with masses up to 25 Earth masses. We constructed a series of planetary models in order to characterize exoplanets by their compositions. Our models correspond to homogeneous Earth-like composition planets, planets of pure water or rock, along with planets with complex structure of a rocky core surrounded by a light atmosphere containing water. We confirm that most planets with radii larger than 1.6 Earth radii (R_e) are not rocky, and must consist of lighter elements, as found by previous studies (Rogers, 2014). We find that planets with radii above 2.6 R_e cannot be pure-water worlds, and must contain significant amounts of light gases, such as hydrogen and helium (H–He). We find that planets with radii larger than about 3 R_e, 3.6 R_e, and 4.3 R_e are expected to consist of at least 2%, 5%, and 10% of H–He, respectively. We show that the atmospheric composition, the mass fraction of H–He in the planet, and the distribution of the elements play a significant role in the determination of the threshold radius. We conclude that, although the exact planetary composition cannot be inferred from mass and radius alone, it is possible to put limits on the range of possible compositions for planets with well-measured mass and radius.

309.02 — The Typical Earth-mass Planet Discovered by Transit Surveys and Its Implications for Planet Formation and Evolution

Kevin C. Schlaufman[1]
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All mass-radius relations for low-mass planets published to date have been affected by observational biases. Since planet occurrence and primordial atmospheric retention probability increase with period, the "typical" planet discovered by transit surveys may bear little resemblance to the short-period planets sculpted by atmospheric escape ordinarily used to calibrate mass-radius relations. An occurrence-weighted mass-radius relation for the typical low-mass planets in the Galaxy observed so far by transit surveys requires the typical Earth-mass planet to have about 1% of its mass in a H/He atmosphere to explain its observed radius. Unlike the terrestrial planets in our own solar system that finished forming long after the protosolar nebula was dissipated, these Earth-mass planets discovered in transit surveys must have formed early in their systems' histories. The existence of significant H/He atmospheres around Earth-mass planets confirms an important prediction of the core-accretion model of planet formation. It also implies that such planets can retain their primordial atmospheres and requires an order-of-magnitude reduction in the fraction of incident XUV flux converted into work usually assumed in photo-evaporation models. Because the short-period planets likely to be discovered by NASA's Transiting Exoplanet Survey Satellite (TESS) are not representative of the Galaxy's planet population, it will be important to use occurrence-weighting when considering the implications for models of planet formation of the masses and radii of TESS discoveries.

309.03 — Getting Better at Measuring the Galactic Distribution of Planets with Spitzer

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Gravitational microlensing is a powerful tool that allows us to discover planets through the gravitational effect they have on light from more distant sources. Unlike most other planet detection methods, gravitational lensing does not rely on the detection of photons from the planet or its host star. Therefore, this method allows us to probe planets well outside of the Solar neighborhood. In addition, gravitational microlensing is most sensitive to detecting planets at and beyond the snowline and Solar System analogs, a category of planets that is extremely challenging to detect with other methods. Since 2015, the Spitzer team is leading a microlensing observational campaign towards the Galactic Bulge following up microlensing events alerted by ground-based surveys. Near-simultaneous observations of microlensing event from two distant observatories allow for the measurement of microlens parallax which allows us to obtain robust measurements of both the lens' mass and distances. The main scientific drive of this campaign is to build the galactic distribution on planets towards the bulge of the Milky Way. As microlensing event are mostly unpredictable, surveys toward the bulge are favorable, however, photometry extraction in crowded fields is challenging. In this talk, I will present results from this Spitzer Microlensing campaign and our efforts in obtaining exquisite level of photometric precision.

309.04 — Transiting Planets Around Red Giant Stars

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Every Sun-like star will eventually evolve into a red giant, a transition which can profoundly affect the evolution of a surrounding planetary system. The timescale of dynamical planet evolution and orbital decay has important implications for planetary habitability, as well as post-main sequence star and planet interaction, evolution and internal structure. We demonstrate how photometric surveys such as Kepler, K2, and TESS are vastly improving our understanding of evolved planetary systems. We describe results from the first estimate of planet occurrence around evolved stars using light curves, and compare the observed planet populations of evolved and main sequence stars. We then discuss the population of red giant planetary system candidates discovered by transit surveys to date, and use this population to derive constraints on the timescales of planet inflation, inspiral and engulfment. Finally, we illustrate the potential of full frame images from the full 2-year primary TESS mission to increase the known transiting planet population of red giants by more than an order of magnitude, and advocate for continued all-sky coverage at a 30 minute cadence or higher to maximize the potential to understand late-stage planetary evolution.

309.05 — "Dynamically Hot" Stars Prefer Higher Planet Fraction and Smaller Planet?

Huigen Liu[1]
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The correlations between stellar physical properties and planetary system have been explored based on Kepler planets, e.g. stellar mass, metallicity. However, the stellar velocities may reveal the dynamical history and influence the formation and evolution of planetary systems. Here we utilize the data of Gaia DR2 to calculate the motion of Kepler stars including planet hosts, to check if there is any correlations between stellar motion and the planetary systems. The KIC stars are divided into two samples according to the deviation of the stellar velocities, i.e. standard stars and "dynamically hot" stars. We find the "dynamically hot" stars have a higher planet fraction. Based on the 355 CKS multi-planet systems, the radius of the outer most planet around "dynamically hot" stars are smaller than the standard stars. To explain the interesting correlations, we compare the distribution of stellar mass and metallicity for the two star samples. The "dynamically hot" sample prefers stars with smaller masses and metallicities. Based on the MC simulations, planet fraction of Dynamically hot star have a larger planet fraction in 1-σ confidential level for Kepler samples. The conclusions induced that dynamical history of star could influence planetary formation and evolution via observations.

309.06 — The TESS Follow-up Observing Program and the Characterization of Small Planets

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Over the course of its two-year primary mission, TESS will survey most of the sky in search of small planets transiting the nearest stars, the brightness of which enables studies of planetary compositions and atmospheric properties. The efficient deployment of ground- and space-based observing facilities in pursuit of such characterization, however, requires a community effort to vet planet candidates and coordinate resources. The TESS Follow-up Observing Program (TFOP) is a mission-organized, community-driven working group, the primary goal of which is to deliver such coordination. We describe the organization of TFOP resources, summarize the scale of the community effort, and highlight opportunities for involvement in TFOP.

309.07 — A Planet Hunters study of the long-period exoplanet population around *Kepler* M-dwarfs

Emily Safron[1]; Tabetha Boyajian[1]
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M-dwarfs are the most common stars in our galaxy, and efforts to characterize the population of exoplanets orbiting them are numerous and ongoing. Among some of the most difficult of these exoplanets to study are those with long periods ($P > \sim 600$ days). Surely many single and double transit events caused by such exoplanets reside in the four years of *Kepler* lightcurves, undiscovered by traditional search pipelines, as several groups have recently come to find using deep learning techniques. In this work, we utilize a different, yet unexplored resource to comb the *Kepler* lightcurves for these signals — the brains of hundreds of thousands of volunteer citizen scientists, through the interface of the Planet Hunters website. By crowd sourcing the identification of promising transit-like features and designing careful vetting techniques, both automated and subjective, we aim to broaden the population of known long-period M-dwarf exoplanets and further constrain the statistical properties of this under-represented population.

309.08 — The Sub-Saturn Mass-Radius Relationship from K2 and a NASA-Keck Key Project

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We now know of thousands of exoplanets with sizes between that of the Earth and Saturn, thanks to the Kepler mission, which mapped out a distribution of planet radii and orbital periods. However, most of these planets do not have mass measurements, which are fundamental to understanding their compositions and formation histories. An accurate predictor of planet mass as a function of radius and host star properties will be valuable for estimating population-wide distributions from transit surveys. We have constructed a catalog of 139 exoplanets with precisely measured masses and radii between 1 and 8 R_{Earth}. This sample represents the largest and most precise catalog of small planet masses and radii, as well as orbital and host star properties. We explore a number of empirically and physically motivated models to quantify the small-planet mass-radius relationship. We use a hierarchical Bayesian modeling approach to characterize the intrinsic model scatter and parameter uncertainties. The hierarchical model naturally incorporates population-level inferences, allowing distinct sub-populations such as the super-Earths and sub-Neptunes to be distinctly characterized. We compare various models and explore the multi-dimensional dependence of planet mass on planet radius, orbital period, and various host-star properties.

309.09 — Exoplanet Population Synthesis in the Era of Large Exoplanets Surveys

Gijs Dirk Mulders[1]; Christoph Mordasini[3]; Ilaria Pascucci[2]; Fred Ciesla[1]; Alexandre emsenhuber[2,3]; Dániel Apai[2]
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[2] *University of Arizona (Tucson, Arizona, United States)*
[3] *University of Bern (Bern, Switzerland)*

The Bern planet population synthesis models (e.g. Mordasini 2018) represent a decade long effort to investigate the integrated effects of the processes at work during planet formation and make predictions for exoplanet populations, planetary system architectures, and planet compositions. Over the last few years new physical mechanisms have been incorporated and adjusted to reflect the lessons learned from Kepler, in particular on atmospheric loss shaping the planet radius distribution and N-body interactions setting the architectures of planetary systems. By comparing the synthetic planet populations to observed exoplanet systems we can constrain planet formation mechanisms to inform predictions of planetary compositions.

This poster shows simulated planet populations from the latest version of the Bern planet population synthesis model. I will make detailed, quantitative comparisons between what the synthetic population would look like compared to exoplanet survey data using the Exoplanet Population Observation Simulator (EPOS), which takes into account the unique observation biases in both transit and radial velocity surveys. While the synthetic populations reproduce many key features seen in the known populations of radial velocity giant planets and systems of close-in super-earths observed with Kepler, we also see key differences in other diagnostics. These differences inform the setup for the Next Generation of Planet Population Synthesis (NGPPS) models.

309.10 — Are Planets with Close Siblings Systematically Less Dense Than Those Without?

Angie Wolfgang[1]; Eric Ford[1]; Daniel Jontof-Hutter[2]
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[2] *University of the Pacific (Stockton, California, United States)*

Compositions of individual exoplanets inform the physical nature and possible habitability of planets orbiting other stars; population trends with composition offer a valuable window into exoplanet formation and evolution. Mass and radius measurements provide the constraints on which these trends are based, and the relationship between them describe the empirical, model-independent distribution of exoplanet compositions as a function of size or mass. In the era of TESS and Gaia, individual planetary masses and radii can be measured with unprecedented precision, yet selection effects and detection biases continue to confuse efforts to extract insight on a population-wide level. With updated mass constraints from transit timing variations observed by Kepler, I will present new results on the completeness-corrected mass-radius relationship of planets in tightly spaced multi-planet systems. In comparing these results to the typical densities of single-transiting planets, I will discuss which regions of parameter space would particularly benefit from both additional observations and a different approach to conducting radial velocity follow-up of transiting planets. Finally, I will discuss the implications of these results for the formation and evolution of low-mass planets.

309.11 — Refining the occurrence rate of inner companions to hot Jupiters using *TESS* full-frame image data

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To date, WASP-47 e and Kepler 730 c remain the only known inner companions to hot Jupiters (Becker et al. 2015, Zhu et al. 2018). This apparent scarcity is broadly in line with the hypothesis that most hot Jupiters form beyond the ice line and move inwards via high-eccentricity migration (HEM). However, statistical evidence based on the dearth of super-eccentric hot Jupiters in *Kepler* data suggests that HEM does not explain the formation of all hot Jupiters, leaving the possibility for some hot Jupiters to have close-in planets (Dawson et al. 2015). *TESS* brings a golden opportunity to study the occurrence rate of hot Jupiter companions in terms of both quality and quantity: not only does *TESS* have enough photometric precision to detect super-earths around bright stars, but its full-frame images will also provide more than double the number of high-precision light curves for hot Jupiters compared to *Kepler* and *K2* combined. Using the first eight sectors of *TESS* full-frame images, we generate light curves for ∼80 confirmed and candidate hot Jupiters brighter than the 11th *TESS* magnitude with the MIT Quick Look Pipeline. Having carefully removed the known planet signal, we perform a uniform BLS search for companions in order to derive a constraint on the occurrence rate of such planets. Combining this constraint with the ones derived from *Kepler* and *K2* hot Jupiters, we arrive at a refined upper limit on the occurrence rate of inner companions to hot Jupiters. We then discuss the implications of this newly calculated occurrence rate and how it informs current discussions on the formation theories of hot Jupiters.

309.12 — Phase Curve Analysis of a Brown Dwarf and its Stellar Host: Increasing the Aridity of the Brown-Dwarf Desert with TESS

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Observations have shown there is a paucity of brown-dwarfs found orbiting within 5 AU of solar-type stars, otherwise known as the “brown-dwarf desert”. In this study we revisit the discovery of a brown-dwarf desert member to examine the likelihood that the radial velocity signals which lead to this discovery were indeed due to the existence of a short period brown-dwarf, or if they were instead the result of stellar variability. To do this, we use time series photometry of the host star to measure the amplitude of coherent photometric variations observed by the Transiting Exoplanet Survey Satellite (TESS) and compare these measurements to the range of theoretical ellipsoidal variation and Doppler beaming amplitudes induced by the mass of the speculative brown-dwarf companion. Our preliminary re-

sults show that the observed photometric variability amplitudes are much too large to be explained by the presence of a brown-dwarf, thus strengthening the validity of the brown-dwarf desert.

309.13 — M Dwarf Planet Occurrence Rates Depend on Metallicity at all Planet Radii

Cicero Xinyu Lu[1]*; Sihao Cheng*[1]*; Kevin C. Schlaufman*[1]
[1] *Physics and Astronomy, Johns Hopkins University (Baltimore, Maryland, United States)*

There must be a threshold for the amount of solid material in a protoplanetary disk below which even small planets cannot form. Since the amount of planet-making material in a protoplanetray disk is proportional to host star metallicity and mass, the best way to search for this effect is to calculate the planet occurrence for metal-poor, low-mass stars. For late K and early M dwarfs, we have calculated the effect of stellar metallicity on planet occurrence in the DR25 Kepler KOI list. For planets in the range 2.5 $R_{Earth} < R_p < 5\ R_{Earth}$, we find that a 0.5 dex decrease in [M/H] decreases planet occurence by an order of magnitude. For planets in the range $0.5\ R_{Earth} < R_p < 2.5\ R_{Earth}$, we find that a similar decrease in metallicity decreases planet occurrence by a factor of two. This result demonstrates the importance of metallicity in the calculation of small planet occurrence rates and therefore for TESS yield calculations. We predict that for early M dwarfs at [M/H] = -1, even super-Earth planets should be rare.

310 — Multiple-Planet Systems, Poster Session

310.01 — TROY: surveying a new type of extreme planetary systems

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Theoretical works of planetary system formation and their early evolution predict the existence of co-orbital planets (two planets sharing the same orbital period) with occurrence rates up to 30% in multi-planetary systems. Trapped either in the Lagrangian points of more massive planets or in other type of 1:1 mean motion resonances, these bodies keep the dynamical and chemical properties of the formation of the planetary system and are thus fossils of these processes. Looking for these exotic configurations represents a new viewpoint to study planet formation and migration mechanisms. The TROY project (Lillo-Box et al., 2018a,b) is a multi-technique effort in the hunt for these celestial fossils. In this talk I will show the latest results of the project regarding the valuable data provided by TESS and by our own new, dedicated, re-analysis of the Kepler data. In particular, I will discuss the results presented in Leleu et al. (2019) on the analysis of similar-period planet candidates detected by both TESS and Kepler, with a special focus on the co-orbital candidate TOI-178. Three planets were detected in this system, with the external two components practically sharing the same orbital period. I will also show the latest results on other TESS candidates and the Bayesian analysis of the full set of Kepler light curves in a dedicated search for these bodies accounting for different co-orbital configurations. The results of this analysis provides, for the first time, statistically significant and observational measurements of the occurrence rate of a new type of extreme planetary systems: two planets sharing the exact same orbit.

310.02 — Modeling light curves of the multi-transiting system Kepler-20 using Blender

Holger Matthias Müller[1]*; Panagiotis Ioannidis*[1]*; Jürgen H. M. M. Schmitt*[1]
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Transiting multi-planet systems can hold additional information about their orbital configurations. These systems can show multi-transits where at least two planets are eclipsing the star at the same time. If the orbital alignments are favorable, these systems also provide planet-planet occultations (PPOs). The presence or absence of these events gives constraints on the alignment of the orbits in question. We present a comprehensive study of the multi-transiting planetary system Kepler-20. The solar-like host star is orbited by six planets, while five of them perform transits. Their small sizes range from roughly 1 to 3 Earth radii, clearly detected by *Kepler*. In our approach we synthesize a grid of multi-transit light curves using the orbital parameters of planets b and c, varying the angle α between their orbits, while keeping their transit impact parameters constant. For that purpose we are the first to utilize the publically available 3D animation software Blender. This allows us to use arbitrary surface brightness distributions of the star like model limb darkening or spots. The resulting light curves show PPOs depending on the angle α, which are then compared to the *Kepler* data. In this way we are able to statistically exclude orbital geometries, and we can identify which are the most favorable. Besides the Rossiter-McLaughlin effect where spectral data is needed, this method is able to acquire orbital alignment information from the optical light curve alone.

310.03 — Towards Photodynamical Modeling of All Kepler Multi-Transiting Systems

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Kepler's 700 systems with multiple transiting planets are incredibly valuable. These systems have provided large numbers of precise exoplanetary densities by characterizing planet-planet dynamical interactions (Transit Timing Variations) caused by transiting planets. We are pursuing the most detailed analysis of these systems to date, improving on previous studies in several ways. We will fit all 700 multi-transiting systems with our new PhotoDynamical Multi-planet Model (PhoDyMM) which directly fits n-body integrations to the light curve (skipping the step of measuring individual transit times) in order to infer the most precise orbital and physical properties for all known planets. Our study will provide Bayesian posterior distributions for these properties in two sets: a homogeneous analysis of all systems to provide support for later meta-analyses and a best-case analysis of all systems that includes improved stellar parameters, and hitherto underutilized short cadence data. We will present a detailed explanation of our methods from detrending to DEMCMC and preliminary analyses demonstrating our technique.

310.04 — Chaos in Three-Planet Systems

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We describe a simple analytic theory for chaos and its onset in eccentric, three-planet systems. Previous work on this topic has relied almost entirely on numerical simulations. Here we show that by properly accounting for the overlapping of mean motion resonances and resonant combinations of these mean motion resonances, one can predict to surprisingly good accuracy the boundary between chaos and stability for a three-planet system.

311 — Earths and Super-Earths, Poster Session

311.01 — A water budget dichotomy of rocky protoplanets from ^{26}Al-heating

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In contrast to the water-poor planets of the inner solar system, stochasticity during planetary formation and order of magnitude deviations in exoplanet volatile contents suggest that rocky worlds engulfed in thick volatile ice layers are the dominant family of terrestrial analogues among the extrasolar planet population. However, the distribution of compositionally Earth-like planets remains insufficiently constrained, and it is not clear whether the solar system is a statistical outlier or can be explained by more general planetary formation processes. Here we employ numerical models of planet formation, evolution, and interior structure, to show that a planet's bulk water fraction and radius are anti-correlated with initial ^{26}Al levels in the planetesimal-based accretion framework. The heat generated by this short-lived radionuclide rapidly dehydrates planetesimals prior to accretion onto larger protoplanets and yields a system-wide correlation of planet bulk abundances, which, for instance, can explain the lack of a clear orbital trend in the water budgets of the TRAPPIST-1 planets. Qualitatively, our models suggest two main scenarios of planetary systems' formation: high-^{26}Al systems, like our solar system, form small, water-depleted planets, whereas those devoid of ^{26}Al predominantly form ocean worlds, where the mean planet radii between both scenarios deviate by up to about 10%.

311.02 — The Snowball Bifurcation on Tidally Locked Planets

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The ice-albedo feedback on rapidly-rotating terrestrial planets in the habitable zone can lead to abrupt transitions (bifurcations) between a warm and a snowball (ice-covered) state, bistability between these states, and hysteresis in planetary climate. This is important for planetary habitability because snowball events may trigger rises in the complexity of life, but could also endanger complex life that already exists. This raises the question of how the Snowball Bifurcation might work on tidally influenced planets in the habitable zone orbiting M and K dwarf stars. We investigate this question using analytical theory, an ocean-atmosphere global climate model, and an intermediate complexity global climate model coupled to an active carbon cycle. We find that planets locked in a 1:1 synchronous rotation state are likely to experience a smooth transition to global glaciation rather than a bifurcation. This is important because it means that tidally locked planets with an active silicate-weathering feedback loop should not tend to stay in the snowball state (they would just pop out of it if they ever entered it because weathering would go to near zero while CO2 outgassing would continue).

311.03 — Terrestrial Planets from CARMENES: Extremely Close, Extremely Interesting

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The CARMENES consortium is conducting a survey of more than 300 nearby M dwarfs (average distance only 13pc), with the goal of finding terrestrial planets in their habitable zones. To make this survey possible, we have built a pair of spectrographs optimized for measuring precise radial velocities of cool stars; together they cover 520 to 1710 nm with resolution > 80,000. The instrument has been operational since January 2016 at the 3.5m telescope on Calar Alto, Spain. So far more than 13,000 spectra have been taken, covering all spectral subtypes from M0V to M7V. 22 new planets have been discovered by CARMENES, almost all of them with masses in the Super-Earth and Earth-like range. In addition, a number of previously known planets could be confirmed. Among the CARMENES discoveries are a cold Super-Earth orbiting Barnard's star, and two planets with 1.05 and 1.1 Earth masses in the habitable zone of their host star. At the other end of the mass range, Jovian planets challenge planet formation models based on the pebble accretion paradigm. Because of their proximity, the CARMENES planets offer unique follow-up opportunities with space missions and extremely large ground-based telescopes. Some CARMENES planets are easily detectable astrometrically by Gaia, and Gaia should also reveal the outer planets in those systems where CARMENES detects the inner ones. If "scaled-down" twins of the Solar System (with an M dwarf host, one or two habitable-zone Earths, and icy or gaseous planets at a few AU) are common, they should be found in the combined CARMENES and Gaia data. Among the CARMENES planets are also some of the best targets for follow-up spectroscopy, which can characterize their atmospheres. Since the stars in our survey are typically only a few pc away, their habitable zones can be resolved with adaptive optics on 30m class telescopes, making them accessible to high-resolution spectrographs coupled to coronographs. In addition, a subproject of the CARMENES survey that is performing follow-up observations of TESS planets has already discovered the transiting Earth-like planet best suited for characterization with JWST.

311.04 — A geophysical model for 55 Cancri e

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55 Cancri e is one of the closest known super-Earths, orbiting a bright host star that makes it a tantalizing prospect for observations. Measurements of the planet's phase curve and secondary eclipse suggest a possible lava world with >1000 K temperature contrast from day to night. Observations have failed to detect water vapor or signs of escaping hydrogen, consistent with a planet lacking most of the cosmically abundant volatiles. However, the mass and radius measurements likely require a relatively significant atmosphere. Observations have found hints of Na and Ca^+ in an extended exosphere, which may be consistent with the lava world interpretation, but other measurements suggest the presence of HCN, which would likely require a much more volatile-rich atmosphere. In this presentation, we will review the models that have been proposed for 55 Cnc e and which observations those models are consistent with. We will propose two preliminary models, depending on either the presence or absence of HCN, that are consistent with both mass-radius con-

straints, as well as atmospheric composition and heat redistribution properties.

311.05 — Multi-season optical modulation phased with the orbit of the super-Earth 55 Cnce

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The 55 Cancri system contains five known planets, with only one transiting the star: 55 Cnc e. With a bright host star and an orbital period of only ~17 hours, this Super-Earth is an ideal target for characterization. The planet's nature still remains largely unknown, but plausible scenarios include strong volcanism and/or a thick atmosphere. In 2011, Winn et al. (2011) detected a quasi-sinusoidal variation at the orbital period of the planet in optical-light with the MOST satellite. The amplitude of this modulation was too large to be explained by light reflected or emitted by the planet. From 2011 to 2015, we continued to monitor this target for several weeks per years, totalizing around 140 transits events. Through independent analyses, we confirm the quasi-sinusoidal variation observed at the orbital period of the planet and we detect this modulation throughout the subsequent years. Intriguingly, the amplitude and the phase of the maximum light are seen to vary from year to year. While we can only speculate about the exact nature of this optical modulation, we argue that additional observations with TESS and CHEOPS will be extremely valuable for our understanding of this mysterious planet.

311.06 — Extreme Cassini states of planets with a liquid core

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Most terrestrial exoplanets detected so far have been found in compact multiplanetary systems where interplanetary interactions are strong. The perturbed trajectories have eccentricity, mutual inclination and are subject to precession motions. Although eccentricities and inclinations in these systems are limited for stability reason, they are sufficiently large to affect the long term evolution of the spin axes (e.g., Saillenfest, Laskar & Boué 2019). This can have strong implications on the habitability of these planets. For instance, high-obliquity planets undergo severe seasonal variations (Spiegel et al. 2009) but their hability is also enhanced towards the outer limit of the Habitable zone (Colose et al. 2019).

In this paper I revisit the equilibrium configurations — known as Cassini states — of the spin-axis of planets subject to orbital precession. It is now well known that a planet can have up to three stable fixed orientation and an unstable one. This has been shown for axisymmetric bodies by Colombo (1966) and generalised for triaxial planets by Peale (1969). But in both cases, the planet is assumed to rotate as a rigid body. Here I consider the effect of a liquid core on the rotation axis of a planet mantle. In this situation the number of fixed points is much larger than in the rigid case. I will show that extreme equilibrium obliquities do exist even in systems where the classical Cassini states are marginally inclined.

311.07 — An asynchronous rotation scenario for 55 Cancri e

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The surface temperature distribution of the transiting hot super-Earth planet 55 Cancri e has recently been measured by Spitzer. The hottest point on the surface is surprisingly found to be offset from the substellar point, necessitating efficient horizontal heat transport. Suggested mechanisms include lava streams or a relatively massive atmosphere with strong lateral winds. Here we propose an alternative scenario where the planet is rotating at an asynchronous rate. In particular, we study the case where the planet is in a 3:2 spin-orbit resonance, giving a synodic rotation period of 35.4 h. From a model of the planetary surface heat distribution we find that the thermal inertia resulting from rock evaporation with subsequent condensation could be sufficient to explain the observed shift of the hot spot.The 3:2 asynchronous rotation also serves to naturally explain strong short-term variability, as the visible planetary surface will rotate by 180 degrees between subsequent eclipses.

311.08 — Two Terrestrial Planet Families With Different Origins

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We propose an oral presentation to present work submitted for publication that highlights small planets spanning the planet occurrence rate deficit reported by Fulton et al. 2017. We analyze a sample of small planets ($R < 3.5\ R_{earth}$) in a three-dimensional space, incorporating radius, density, and insolation, and identify physically motivated trends. The potentially important role of stellar irradiation in envelope removal for planets with diameters of < 2 R_{earth} has been inferred both through theoretical work and the observed bimodal distribution of small planet occurrence as a function of radius. We find, terrestrial planets divide into two distinct families based on insolation. The lower insolation family merges with terrestrial planets and small bodies in the solar system and is thus Earth-like. The higher insolation terrestrial planet family forms a bulk-density continuum with the sub-Neptunes, and is thus likely to be composed of remnant cores produced by photoevaporation. However, these potential remnant cores also have evidence for collisional processing, inferred from the positive density-mass relation for higher insolation terrestrial planets. The implication is that the average mass for the high insolation family of terrestrial planets, 4.8±1.8 M_{earth}, may represent an upper bound on the typical mass needed to produce the onset of the rapid gas accretion phase associated with envelope assembly during the planet formation process.

311.09 — Achieving Sub-Millimagnitude Precision from the Ground: the Capabilities of ARCTIC and the LHS 1140 System

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As TESS observes most stars for only 28 days, many TESS planetary candidates will require future observations by other facilities in order to be properly vetted. Ground-based observations of these candidates can reject false positives, update mid-transit times, refine planetary parameters, and provide long-term monitoring of interesting systems. Ground-based telescopes achieve these science goals in part due to their larger size compared to TESS's 0.1m diameter lens. However, most observations from the ground struggle to achieve precisions better than 1 millimagnitude. The new CCD imager ARCTIC, installed on the 3.5m Apache Point Observatory Telescope, attains extreme precision by combining its large collecting area (1000× larger than TESS) with a diffuser that spreads the stellar PSF into a stable top-hat. We test the performance of this instrument by observing multiple transits of LHS 1140b and LHS 1140c. LHS 1140 is a nearby M-dwarf orbited by two rocky, near Earth-sized planets, including one in the habitable zone. This system therefore presents a unique opportunity to study two rocky planets in very different temperature regimes around the same star. Our observations double the number of published LHS 1140b and 1140c transits, and we use these to update the ephemeris and better constrain the planetary parameters. We find ARCTIC achieves a RMS of 150ppm on LHS 1140 for data binned to 20 minute timescales. Based on our success with the LHS 1140 system, we predict that ARCTIC will prove a useful instrument for future TESS follow-up on both smaller and fainter planet candidates as TESS moves into the northern hemisphere this year.

311.10 — A Planet of Ice and Fire — Barnard Star b : Life beyond the Snowline?

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Barnard's Star (M3.5V; 5.98 ly) was recently discovered to host a super-Earth with a minimum mass of $3.23M_E$, P_{orb} = 233-d, and a = 0.40 AU (Ribas et al. 2018). Barnard b is at nearly the same distance as Mercury (0.39 AU) from the Sun. However, the M-star is faint (L/L_{sun} = 0.0033) so that the planet receives only 2% of the solar radiation received by Earth. This corresponds to the equivalent amount of radiation received at roughly ~7 AU from the Sun. Barnard b is cold (Teq ~105 ±5 K; -168°C) and orbits well beyond the M-star's liquid water habitable zone (HZ), near the snowline.

Barnard b is a probable terrestrial (rocky) planet, and if water is present, it would be ice-covered and inhospitable to most life. However, as pointed out by Guinan et al. 2018, all hope for life on Barnard b may not be lost. Ehrenreich et al. (2006) studied the possibility that geothermal energy from a cold super-Earth planet (similar to Barnard b) could be sufficient to permit liquid water under its icy surface at least while young. Although the cold icy moons Europa and Enceladus have subsurface water, they are heated primarily from tidal energy. A closer analog for Barnard b may be be here on Earth. The sub-glacial Antarctic lakes (e.g. Lake Vostok) contain large inventories of liquid water (and maybe life?) and are heated by geothermal energy from the Earth's interior.

We discuss possibilities of liquid water (and potential life) on Barnard b and on other cold rocky planets.The amount of geothermal energy depends on several factors (most of which are not well known). These include mass, radius, age and composition & internal structure of the planet. Also very important

are the concentrations of radiogenic elements such as 238-U, 235-U, 232-Th & 40-K and the primordial heat from the planet's formation. Because of its old age (~9 Gyr) and depletion of some radiogenic elements, the best chance for liquid water (and niches for life) on Barnard b would be in subsurface lakes. We report on the initial results and its applications to other cold super-Earth planets.

This research is supported by grants from *NASA* for *HST*, *Chandra* and XMM-Newton.

312 — Neptunes and Mini-Neptunes, Poster Session

312.01 — The Orbital Damping Effect on Neptunian Trojans

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Using test particle simulations, the orbital element distributions of Neptune Trojans affected by the planetary migration and the orbital damping of Uranus and Neptune was investigated. We examine the stability of primordial Neptune Trojans, objects that were initially Trojans with Neptune prior to migration and Trans-Neptunian objects captured into resonance with Neptune and becoming Neptune Trojans during planet migration. We find that most primordial Neptune Trojans were unstable and lost if eccentricity and inclination damping took place during planetary migration. With damping, secular resonances with Neptune can increase a low eccentricity and inclination population of Trans-Neptunian objects increasing the probability that they are captured into 1:1 resonance with Neptune, becoming high inclination Neptune Trojans. These suggest that the resonant trapping scenario is a promising and more effective mechanism to explain the origin of Neptune Trojans if Uranus and Neptune had orbital damping during planetary migration.

312.02 — The origin of the obliquity of Uranus due to the giant impact

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Our solar system has two ice giants, Uranus and Neptune. Those planets have similar mass and radius but different obliquity and the intrinsic luminosity. Differences between Uranus and Neptune suggest origins of those planets. Since the obliquity difference is caused by impact events, we investigate the giant impact on the ice giant to reproduce the obliquity of the planet. In this study, we use the Godunov-type Smoothed Particle Hydrodynamic simulation to calculate the giant impact simulation on the rotting planet and calculate the obliquity of the ice giant after the impact directly. We find that the obliquity of the present Uranus is able reproduced by an Earth mass impactor. Thus, the impact event disappears the rotation of the pre-impact target and give other direction of planetary spin in to reproduce the large obliquity. Moreover, we formulate the simple approximation for the obliquity variation due to the impact and calculate the probability distribution of the planetary obliquity after the impact. We also find that the slow rotating planet have an advantage to reproduce the large obliquity. If we consider the two impacts, the planetary obliquity become larger than single impact. We conclude that larger than Earth mass impactor collided on slow-rotating proto-Uranus. Our study will be useful to consider the probabillity of the large obliquity of exoplanets.

313 — Hot Jupiters and Ultra-Short Periods, Poster Session

313.01 — Transmission Spectroscopy of WASP-79b from 0.6 to 4.5 μm with Predictions for JWST Observations

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As part of the PanCET program, we have conducted a spectroscopic study of WASP-79b, a Jupiter-size exoplanet orbiting an F-type star in Eridanus with a period of 3.66 days. Building on the original WASP and TRAPPIST photometry of Smalley et al (2012), we have performed reduction and light curve fitting on HST/WFC3 (1.125 – 1.650 μm) and Magellan/LDSS-3C (0.6 – 1 μm) observations for WASP-79b, and we have conducted photometric extraction on Spitzer observations (3.6 and 4.5 μm). Additionally, we have validated our light curve against the transit depths estimated from the Sector 4 and Sector 5 TESS observations of this exoplanet. We will present our light curve results, which show indications of a water feature at 1.4 μm. Finally, we will discuss the results of an atmospheric retrieval analysis and simulated JWST data based on best-fit retrieval models for these data. The suggested water feature makes WASP-79b a target of interest for the approved JWST Director's Discretionary Early Release Science (DD ERS) program, with ERS observations planned to be the first to execute in Cycle 1. Transiting exoplanets were recently approved for 78.1 hours of data collection, and with the delay in the JWST launch, WASP-79b is now a target for the Panchromatic Transmission program. This program will observe WASP-79b for 42 hours in 4 different instrument modes over 0.8-5.0 μm, at which time WASP-79b will be the best-characterized exoplanet to date.

313.02 — Full-orbit phase curvers of known transiting systems with *TESS*

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The *TESS* Mission promises to be a watershed moment for exoplanet science. In addition to the huge yield of new planet candidates, *TESS* will provide many interesting avenues of study for known planets. Following the legacy of similar work carried out with Kepler data, we seek to take advantage of the continuous, long-baseline photometry provided by the *TESS* mission to study the full-orbit light curves of transiting systems. From these datasets, we can place constraints on such physical quantities as: (1) the planet's dayside temperature and Bond albedo, through measurement of the secondary eclipse depth in the *TESS* band; (2) the efficiency of day-night recirculation of incident stellar irradiation, via the amplitude and phase shift of the planet's atmospheric brightness modulation across the orbit; and (3) the response of the host star to the gravitational interaction with the orbiting planet, which are expressed in the phase curve signal via Doppler boosting of the star's light and tidal distortion of the stellar surface. As an exemplary demonstration case, we recently published our analysis of the phase curve of WASP-18b from *TESS* Sectors 2 and 3 (Shporer, Wong, et al. 2019), which reveals a strong secondary eclipse signal and high signal-to-noise phase curve modulations attributable to atmospheric brightness variation, ellipsoidal distortion, and Doppler boosting. Since then, we have expanded our efforts into a unified and systematic light curve analysis of all known transiting systems contained in *TESS* fields with predicted detectable secondary eclipses and/or phase curve signals. I will present the latest results from this work and discuss them in the context of emergent trends in exoplanet atmospheric dynamics and comparisons with the predictions of theoretical phase curve modeling.

313.03 — A model for Hot Jupiter with bottom thermal perturbation

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Hot Jupiters are one of the few types of planets that can currently be observationally characterized. Under strong external radiation forcing, Hot Jupiters show a variety of atmosphere circulation pattern. Due to spectrum exhibits information and our knowledge in atmosphere dynamic of the Hot Jupiter, some researchers create the atmosphere models, for understanding the observations and the physics of these planets generally, but almost all models ignore — or treat in a very simplified fashion — the interaction of the interior convection zone with the deep, thick stratified atmosphere. Here, we take the small-scale thermal perturbation into account, and import a spatially and temporally noise, which is horizonally isotropic, as forcing parameter into 3D primitive equation model for influencing the temperature at convective-radiation boundary layer. In some cases, the random thermal perturbation give limited impact on pattern — a significant temperature increase near the hot spot, while the others does not have much influence on the top layer pattern, which shows hot spot shift with super-rotation on equator at top layers, when star radiation becomes stronger.We draw a conclusion that the flow does not vary in time until the bottom perturbation is over the bottom heating rate(0.001K/sec). We assume the model relax the radiation forcing by Newtonian cooling scheme to equivalent temperature in various radiative time scale on different levels.Perhaps we predict more time variability if atmospheres are strongly enough forced by convection, and we hope get new information from spectrum to prove the result.

313.04 — High resolution transmission spectrum of ultra-hot Jupiters

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Ultra-hot Jupiter is a new class of exoplanets emerging in the recent years. Their extremely hot temperatures cause thermal dissociation of molecules and even ionisation of atoms. We have detected an extended hot hydrogen atmosphere around KELT-9b — the hottest exoplanet discovered so far. The detection was achieved by measuring the atomic hydrogen absorption during transit with the Balmer Hα line using the CARMENES spectrograph. The obtained Hα transmission spectrum has a strong extra absorption of 1.15% at the line centre. The observation implies that the effective radius at the line centre is $\sim$ 1.64 times the size of the planetary radius, indicating that the planet has a largely extended hydrogen envelope close to the size of the Roche lobe and is probably undergoing dramatic atmosphere escape.

313.05 — Insights into Terrestrial Planet Compositions and Geophysics from Observations of Magma Worlds

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There exists a remarkable population of short period transiting rocky exoplanets with temperatures >2,000 K, and masses ranging from about 8 Earth masses, such as the hot super-Earth 55 Cancri e, to that of Mercury or smaller, such as K2-22b. These planets are thought to have mineral atmospheres that are produced by the vaporisation of their magma surfaces, or large exospheres that are produced by sputtering of their atmospheres or exposed surfaces by intense stellar winds. Additionally, the smaller, low surface gravity hot rocky exoplanets have been found to be actively disintegrating and forming 'comet-like' dust tails.

Since their atmospheres and released gas and dust can be observationally constrained, these planets present the tantalising prospect of directly probing the composition of rocky planets. Sodium and calcium are promising species to detect given their low sublimation temperatures, large absorption cross-sections, likely presence in terrestrial planet compositions, and presence in Mercury's exosphere.

This poster presents the insights we gained from using high-resolution transmission spectroscopy to search for Na and Ca around 55 Cnc e and K2-22 b using several ground based telescopes. For 55 Cne e, we detected a tantilizing $\sim$5 σ signal of Ca+ on one night of observation, but a similar signal has not been detected since (despite our unprecedented limits). This may be related to variability of the star-planet system and the planet's magnetic field.

For K2-22 b, we did not detect absorption by Na or Ca+, but found lower-limits that are smaller than the expected magnitude of the signal based on the planet's estimated mass-loss rate and assuming a terrestrial composition. We attribute this non-detection to the probed gases being accelerated by the stellar wind and radiation pressure to high velocities, resulting in very broad Doppler shifted absorption signals that are hard to detect.

The implications of these results on probing rocky exoplanet compositions, constraining planetary magnetic fields, and understanding the environment around short-period rocky exoplanets are also outlined.

313.06 — MuSCAT2 validation of a USP giant-planet-sized object around an M-dwarf

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MuSCAT2 is a 4-color simultaneous camera on the Telescopio Carlos Sanchez 1.52m in the Teide observatory in Tenerife, Canaries, Spain. On behalf of the MuSCAT2 team, I present a latest result from the MuSCAT2 Consortium: a multi-color validation of a TESS planet candidate TOI 263.01.

TOI 263.01 was first released as a planet candidate in the TESS alert for the sector 3 in December 2018. According to the TESS alert, TOI 263 is a mid-M dwarf and TOI 263.01 has a period of about 13 hours and a radius of 5.22 R_{Earth}, suggesting it is a possible ultra-short-period giant planet around an M dwarf. Such a planet is extremely rare.

We immediately targeted this planet candidate with MuSCAT2. At that time MuSCAT2 could observe only in 3 bands (r, i, z_s) simultaneously as one CCD camera was removed for upgrading into a deep-depletion CCD camera. Although the host star was almost setting at the time of the TESS alert, we aimed to validate this planet candidate by taking advantage of the multi-color capability of MuSCAT2. We observed 3 full transits of TOI 263.01 with MuSCAT2 on December 18 and 19, 2018 and January 2, 2019.

The multi-color transit light curves of TOI 263.01 confirmed achromaticity of transit depths. We further utilized a code PyTransit v2 (Parviainen 2015) which models a transit with a possible light contamination from unresolved sources. Consequently, the MuSCAT2 multi-color photometry excluded such contamination, meaning transits of TOI 263.01 are not caused by unresolved eclipsing binaries. Thus TOI 263.01 is validated as an object orbiting around TOI 263.

We have constrained the radius of TOI 263.01 as 0.78 ± 0.15 R_{Jup}. The MCMC posterior distribution suggests the object is smaller than 1.5 R_{Jup} with over 99.99% confidence level. Thus TOI 263.01 is an ultra-short-period giant-planet-sized object around an M-dwarf.

At this point, we cannot say TOI 263.01 as a planet because the mass of TOI 263.01 is still unknown. The faintness of the host star (V=18.97, J=14.08) make it difficult to measure the mass of this interesting object. However, the 4-VLT mode of ESPRESSO will enable a measurement of the mass of TOI 263.01 in the future.

313.07 — On the radiative effects on the thermal bulge of a hot Jupiter

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We investigate the influence of radiative effects on the thermal bulge of an asynchronous hot Jupiter driven by the semidiurnal component of stellar irradiation. The background states of the planet are assumed to be in thermal equilibrium maintained by a uniform internal heating per unit mass. On top of an optically thick interior, we adopt the two-stream approximation to model the atmosphere in the radiative equilibrium between the incoming optical stellar irradiation and outgoing thermal infrared emission. We then apply a semidiurnal thermal forcing to the interior-atmosphere system to solve for the resulting thermal bulge. We find that while the radiative cooling damps the thermal bulge, self-absorption of thermal emissions can significantly enhance it depending on the optical and near-infrared opacities in the atmosphere.

313.08 — A comprehensive survey of exoplanet atmospheres with Spitzer/IRAC

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Studying exoplanets affords us the opportunity to understand the sheer diversity of planets in different physical regimes. We use the two IRAC bandpasses from the warm Spitzer mission and the statistical power of a transit survey to test the theoretical predictions of exoplanet atmosphere properties across a broad regime of parameter space. Our survey ranges from the coolest gas giant planets to the ultra-hot Jupiters. It spans a range of mass, radii, equilibrium temperature and differing atmospheric compositions. In particular, we probe the carbon monoxide, methane and water content of these atmospheres from emission and transmission spectra.

We classify the sample into groups and use the properties of individual planets within these groups to understand their collective diversity. We see several trends emerging in our data that hint towards different atmospheric properties and behaviors in these atmospheres. We discuss the possibilities for such trends. Ultimately, our work places new constraints on the diverse families of exoplanet atmospheres, as well as on possible formation and evolution scenarios.

313.09 — A Comprehensive Spitzer Study of GJ 436b

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GJ 436b is one the most observable transiting Neptune-sized planets, with hundreds of hours of Spitzer observations, including 16 transits and 24 eclispes over 6 photometric channels, some of which have not been published. We jointly fit all these observations, using advances in correlated-noise removal techniques to achieve the best, but realistic, signal-to-noise ratios. We then determine updated orbital parameters, atmospheric composition, and thermal structure, and discuss these results in the context of past work. Spitzer is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. This work was supported by NASA Astrophysics Data Analysis Program grant NNX13AF38G.

313.10 — Hot Jupiters are Destroyed While Their Host Stars are on the Main Sequence

Jacob Howard Hamer[1]; Kevin C. Schlaufman[1]
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On their extreme orbits, hot Jupiters represent the perfect testing ground for our understanding of tidal dissipation. While cooler giant planets are often observed with non-zero eccentricities, the small, circular orbits of hot Jupiters suggest that tidal dissipation plays a significant role in their formation. Once on these circular orbits, tidal dissipation should allow the rapidly orbiting planet to transfer angular momentum to the slowly spinning host star, which may result in the inspiral of the planet. However, we do not yet know if hot Jupiters survive the main sequence of their host stars, as the efficiency of this process is uncertain by orders of magnitude, and because tidal decay has never been unambiguously observed. If tidal decay causes hot Jupiters to be destroyed while their host stars are on the main sequence, then hot Jupiter hosts should be relatively young compared to a sample of similar field stars not hosting hot Jupiters. We use data from Gaia DR2 to show that hot Jupiter hosts have a smaller Galactic velocity dispersion than similar stars without hot Jupiters. As Galactic velocity dispersion is correlated with the age of a population, this implies that hot Jupiter hosts are a relatively younger population due to the inspiral of their planets. This observation requires that the tidal quality factor, Q'_* , be in the range $Q'_* < 10^{6.2}$.

313.11 — The Current State of Spitzer Secondary Eclipse Analyses: HD 209458 b

Kathleen McIntyre[1]; Joseph Harrington[1]; Ryan Challener[1]; Matthew Reinhard[1]; M.R. Green[1]; Zacchaeus Scheffer[1]; Cody Jordan[1]; Parker Jochum[1]; Catherine Millwater[1]
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The Spitzer Space telescope has been the workhorse for exoplanet secondary eclipse observations for more than a decade. Despite this, we are still uncovering and understanding new methods for moderating systematics in our analyses. Here we present the test case of HD 209458b, one of the most observed, published, and highest signal-to-noise exoplanets discovered to date. We compare the effect of different methods, for example, BiLinearly-Interpolated Subpixel Sensitivity (BLISS) and Pixel-Level Decorrelation (PLD), on the resulting light curves across all of Spitzer's IRAC channels. One such systematic that can mimic the features of a secondary eclipse or small primary transit is vibrations of the spacecraft that manifest as changes in the point spread function. Previously utilized metrics of interpreting noise pixel do not account for the systematic's presence when there is no accompanying increased contribution to the noise. This omission with will impact published results. Spitzer is operated by the Jet PropulsionLaboratory, California Institute of Technology, under a contract with NASA. This work was supported by NASA Planetary Atmospheres grant NNX12AI69G and NASA Astrophysics Data Analysis Program grant NNX13AF38G.

314 — Planets around Compact Objects, Poster Session

314.01 — The tidal interaction between a white dwarf and a planet

Dimitri Veras[1]
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I present a collection of 3 new papers which all model tidal interactions between a white dwarf and different types of planets (gas giants, ice giants, terrestrial planets, magnetic planetary cores). Before 2019, there was almost a complete dearth of papers whose sole focus was to model star-planet tidal interactions with a white dwarf. The models in these 3 papers are timely given the increasing evidence of major planets orbiting white dwarfs.

315 — Planets in Star Clusters, Poster Sessopm

315.01 — Destruction of circumstellar disks by surrounding stars during star clusters formation

Taku Hasegawa[1]
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Over 3500 planets have been discovered since first detection of the exoplanet. Although most stars are considered to be formed in clustering environments, only dozen of planets have been found in star clusters. In clustering environments such as star clusters, circumstellar disks can be broken by their surrounding stars due to external far-ultraviolet (FUV; 6.0-13.6 eV) radiation from their surrounding O, B-stars (photoevaporation) and dynamical disk truncation by stellar encounters. Although recent improvement of the resolution of observations enables us to investigate the efficiency of the dissipation of circumstellar disks by those two effects in detail, largeness of contribution of those effects to disk dissipation is still debatable. In addition, initial conditions of star clusters are one of the still discussed issues. Recent theories and observations showed that initial states of star clusters are dynamically cool and clumpy, but not spherical. In this study, we performed *N*-body simulations of star clusters with clustering initial conditions, constructed from the results of hydrodynamic simulations of the morecular clouds with turbulence, and investigated the destruction of circumstellar disks due to photoevaporation and dynamical truncations by stellar encounters in clustering environments. We regarded the clumps with the number of stars > 300 and the half-mass density > 100 M_{Sun} pc^{-3} as clusters and investigated the influence of the two disk dissipation effects. We also investigated the dependency of the disk truncations effect due to stellar encounters on stellar density of star clusters. We found that photoevaporation is dominant for disk dissipation, especially in the central region, in most star clusters. Only in the case that clusters experience extremely dense phase (stellar density > 10^7 pc^{-3}) in the early age, dynamical truncations contribute to disk dissipation, which affect strongly at the outside of clusters.

315.02 — The fate of planetesimal discs in young open clusters: implications for 1I/'Oumuamua, the Kuiper belt, the Oort cloud and more

Thomas Hands[1]*; Walter Dehnen*[2,3]*; Amery Gration*[2]*; Joachim Stadel*[1]*; Ben Moore*[1]
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[2] *University of Leicester (Leicester, United Kingdom)*
[3] *Universitäts-Sternwarte der Ludwig-Maximilians-Universität (Munich, Germany)*

We perform N-body simulations of the early phases of open cluster evolution including a large population of planetesimals, initially arranged in Kuiper-belt like discs around each star. Using a new, 4th-order and time-reversible N-body code on Graphics Processing Units (GPUs), we evolve the whole system under the stellar gravity, i.e. treating planetesimals as test particles, and consider two types of initial cluster models, similar to IC348 and the Hyades, respectively. In both cases, planetesimals can be dynamically excited, transferred between stars or liberated to become free-floating (such as A/2017 U1 or 'Oumuamua) during the early cluster evolution. We find that planetesimals captured from another star are not necessarily dynamically distinct from those native to a star. After an encounter both native and captured planetesimals can exhibit aligned periastrons, qualitatively similar to that seen in the Solar system and commonly thought to be the signature of Planet 9. We discuss the implications of our results for both our Solar system and exoplanetary systems.

315.03 — Observational consequences of close encounters in stellar clusters

Melvyn Davies[1]*; Daohai Li*[1]*; Alexander Mustill*[1]
[1] *Lund Observatory, Lund University (Lund, Sweden)*

The birth environments of stars are hazardous to any planets they may possess. Close encounters in stellar clusters can perturb planetary systems, destabilising them, causing orbits to cross, planets to scatter, and be ejected, leaving those behind on more bound, and eccentric, orbits. Hot Jupiters may be produced as massive planets from further out are placed on extremely eccentric orbits leading to tidal circularisation very close to their host star. In extremis, planets may collide with their host star, potentially leading to an observable enhancement in metallicity. The study of close encounters involving planetary systems enjoys a rich literature. We, and others, have previously considered the effects of encounters between planetary systems and passing stars. In this talk, we go beyond earlier work, presenting new research considering encounters between two stars where both of the stars host planetary systems. Such encounters will be relatively common when one reflects how observations reveal that a large fraction of stars possess planetary systems. Here, we present the results of extensive N-body simulations where we study fly-by encounters involving two planetary systems. We model both the initial fly-by stage but also consider the post-fly-by evolution of both planetary systems. We consider a broad range of planetary systems and host stars. Encounters are found to be damaging to a large fraction of planetary systems. Many stable planetary systems are destabilised: planets are then either ejected, placed on eccentric orbits, or collide with each other. Planets are also found to transfer from one planetary system to the other. These interlopers often destabilise the planetary system. We find that one half of the surviving captured planets are on retrograde orbits. Thus, we show that encounters between two planetary systems within stellar clusters represent an intriguing channel to place planets on wide retrograde orbits that may be detectable through astrometry or direct imaging.

315.04 — Survival rates of planets in open clusters: The Pleiades, Hyades, and Praesepe clusters

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In clustered environments, stellar encounters can liberate planets from their host stars via close encounters. The detection probability of planets suggests that the planet population in open clusters resembles that in the field. Only a few dozen planet-hosting stars, however, have been discovered in open clusters. We explore the survival rates of planets against stellar encounters in open clusters similar to the Pleiades, Hyades, and Praesepe and embedded clusters. We performed a series of *N*-body simulations of star clusters, modeling the three open clusters and embedded clusters. We find that less than 1.5 % of close-in planets within 1 AU and at most 7 % of planets with 1–10 AU are ejected by stellar encounters in clustered environments after the dynamical evolution of star clusters. We expect no significant difference between the frequency of short-period planets in open clusters and that in the field. Besides, our simulations imply that most of planets (within 10au) around FGKM-type stars are likely to survive against stellar encounters in open clusters. If a planet population from 0.01–100 AU in an open cluster initially follows the observed planet distribution in the field, the production rate of free-floating planet per star is 0.0096–0.18, where we have assumed that all the stars initially have one giant planet with a mass of 1–13 M_{Jup} in a circular orbit. These values are compatible with the observed fraction of free-floating planets, $\sim$0.25 per main-sequence star.

315.05 — TESS Planet Candidates in Open Clusters

Luke G. Bouma[1]; Joel Hartman[1]; Waqas Bhatti[1]; Joshua Winn[1]; Gaspar Bakos[1]

[1] *Department of Astrophysical Sciences, Princeton University (Princeton, New Jersey, United States)*

The TESS full-frame images of star clusters are a gold mine for stellar astrophysics and exoplanet science. Because of their known ages, exoplanets in clusters can be used to resolve questions regarding the formation, dynamical evolution, and long-term fates of exoplanets. We have made over 100,000 light curves for candidate member stars of more than 100 open clusters and moving groups, based on TESS observations of the galactic plane.

I will present the most interesting planet candidates, eclipsing binaries, and rotational variables found in these light curves. These candidates have survived numerous vetting procedures and will be made available to the community for follow-up observations. Ultimately, we hope this work will probe the exoplanet size and separation distributions for planets younger than 1 Gyr, and will shed light on the origins of close-in giant planets.

I will also describe the image subtraction and light curve processing techniques we have used to obtain precise photometry in crowded fields. The resulting light curves have many other uses — notably gyrochronology and studies of eccentricity damping in eclipsing binaries — and will be accessible for general use through MAST.

315.06 — Radial velocity confirmation of K2-100b: a young transiting hot Neptune with a likely evaporating atmosphere

Oscar Barragán[1]
[1] *University of Oxford (Oxford, United Kingdom)*

The tens of young transiting exoplanets discovered to date by K2, and those yet to be found by TESS, are valuable tests of planet formation and early evolution scenarios. However, their scientific impact so far has been limited because none of them have mass measurements. We present an exhaustive analysis of RV measurements for the star K2-100, a member of the Praesepe cluster for which K2 photometry revealed a close-in planet with a period of 1.67 days. We apply a multi-dimensional Gaussian-Processes approach to HARPS-N radial velocity and activity indicators in order to measure the Doppler signal of the planet in this active star. We detect a Doppler signal with a semi-amplitude of 10.6 ± 3.2 m/s, consistent with the transit ephemeris, and corresponding to a mass of 22.8 ± 7.0 Earth masses for the planet. This is the first mass measurement of a planet orbiting a star in a young active star. The radius of K2-100b, at 3.9 ± 0.1 Earth radii, implies a significant volatile envelope. However, the planet receives is $\sim$1900 times more heavily irradiated than the Earth, and photoevaporation is expected to play a significant role in its evolution. As the first young transiting planet with both radius and mass measurements, K2-100b provides valuable insights into the physical mechanisms that shape early planet evolution. This result also demonstrates the feasibility of RV follow-up for transiting planets around active stars, given enough measurements, and bodes well for the young planets yet to be discovered by TESS.

315.07 — Understanding the early evolution of planetary systems with the Next Generation Transit Survey

Edward Gillen[1]
[1] *University of Cambridge (Cambridge, United Kingdom)*

We present the first results from our systematic survey of nearby young open clusters with the Next Generation Transit Survey (NGTS), a wide-field photometric facility based at ESO's Paranal Observatory. Our aim is to understand the early evolution of planetary systems. By characterising young transiting planets, we can quantify timescales for migration, orbital circularisation, evolutionary cooling and atmospheric loss. I will present the NGTS young clusters program, describe how we address the evolving activity signals of young stars using dedicated Gaussian process regression models, and highlight new unpublished results from a comprehensive study of Blanco 1 ($\sim$120 Myr) and the Orion star forming region (1-10 Myr). Finally, I will conclude with an outlook towards future prospects for the survey and our understanding of young planetary systems.

316 — Planets in and around Binary Stars, Poster Session

316.01 — Orbital evolution of a circumbinary planet in a protoplanetary disk

Akihiro Yamanaka[1]*; Takanori Sasaki*[1]
[1] *Astronomy, Kyoto University (Kyoto, Japan)*

Sub-Jupiter classed circumbinary planets (CBPs) around close-in stellar binaries discovered by Kepler have orbits just beyond the dynamically unstable region, which is determined by the eccentricity and mass ratio of the host binary stars. These planets are assumed to have formed beyond the snow line and migrated to the current orbits rather than forming *in situ*. Reproducing orbits of observed CBPs have not succeeded and the origin of such orbits is yet unclear. In order to reproduce a stable orbit just over the instability boundary, we proposed a new scenario in which a planet formed beyond the snow line and migrated to the inner edge of the circumbinary disk, which was within the unstable area, and then moved to the current orbit through outward transportation. We carried out N-body simulations with a dissipating circumbinary protoplanetary disk for binary systems with different eccentricities and mass ratios. We find CBPs can maintain a stable orbit near the instability boundary if they enter the unstable area while enough amount of gaseous disk remains. CBPs are more likely to achieve a stable orbit just beyond the unstable region in binary systems with smaller eccentricities and mass ratios. These dependencies are consistent with the data from observed binary systems hosting circumbinary planets. We find CBPs' orbits just over the instability boundaries are explained by our orbital evolution scenario.

316.02 — Habitability of S-type tidally locked planets: effects of a binary companion star

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Planets in the Habitable Zones around M-type stars are important targets for characterization in future observations. Due to their proximity to the host stars, they are likely to be tidally locked in synchronous spin-orbit rotations and to have a hot dayside and a cold nightside (Kasting et al. 1993). On the cold nightside, water vapor transferred from the dayside can be frozen in ("cold trap") or the major atmospheric constituent could also condense ("atmospheric collapse") if the atmosphere is so thin that the heat re-distribution is not efficient. This is one of the serious problems for the habitability of a planet around a single M-type star (e.g., Joshi et al. 1997; Leconte et al. 2013). Motivated by the abundance of binary star systems (Raghavan et al. 2010), we investigate the effects of irradiation from a G-type companion star on the climate of a tidally locked planet around an M-type star. We calculate the surface temperature distribution through simulations of the 2D energy balance model (e.g., North 1975). While the mass difference between G-type stars and M-type stars is not so large, the luminosity of G-type stars are a few orders of magnitude brighter. This enables a G-type star to warm the cold nightside of the planet around the M-type star without destabilizing the planetary orbit. On top of it, we find that the irradiation from the G-type star is more effective at warming up the nightside of the planet than the dayside. This contributes to the prevention of the irreversible trapping of water and atmosphere on the cold nightside, broadening the parameter space where tidally locked planets can maintain surface liquid water. Tidally locked ocean planets with $\leq \sim 0.3$ bar atmospheres or land planets with $\leq \sim 3$ bar atmospheres can realize temperate climate with surface liquid water when they are also irradiated by a companion star with a separation of 1 - 4 au. We also demonstrate that the total irradiance is not a sufficient measure for the planetary climate in binary systems, as planets with given properties can be in the Earth-like temperate climate regime or in a completely frozen state under the same total irradiation.

316.03 — Understanding the Multiplicity of TESS Exoplanet Host Candidates

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While at first glance multi-star systems seem quite extreme, they are in fact the most common type of star system in our galaxy, throughout the stellar mass distribution. In particular, 40 to 50% of exoplanet host stars reside within multiple star systems. Given the degree to which initially undetected multiplicity has skewed Kepler results, high-resolution imaging of our nearby low-mass neighbors is necessary for both accurate characterization of transiting exoplanets, as well as a better understanding of stellar astrophysics. To address this frequent gap in our knowledge of exoplanet hosts, we will utilize speckle interferometry to directly image TESS exoplanet host candidates to complete our knowledge of individual star multiplicity. Our investigation will expand upon the speckle observations taken as a part of the POKEMON speckle survey of nearby M-dwarfs to better constrain the multiplicity of low-mass TESS exoplanet host candidates, and to constrain M-dwarf multiplicity by subtype across the entire M-dwarf sequence.

316.04 — Forming Polar Planets Around Binaries

Stephen Lubow[1]; Rebecca Martin[2]
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[2] *Physics and Astronomy, University of Nevada Las Vegas (Las Vegas, Nevada, United States)*

One of the key discoveries of the Kepler mission was the detection of transiting circumbinary planets. By the nature of the detection technique, these planets are preferentially found on nearly coplanar orbits with the binary. We (Martin & Lubow 2017) have shown that a mildly misaligned circumbinary protoplanetary disk can naturally evolve to a highly inclined polar orbit that is perpendicular to the binary orbital plane. Planets formed in such a disk would orbit around the semimajor axis of the binary, instead of in the binary orbital plane. Such a disk was recently discovered in HD98800 by Kennedy et al. (2019) using ALMA. We have recently extended our work to explore how the disk angular momentum and radius can affect this process (Martin & Lubow arXiv:1904.11631). We find that disk breaking and inclined nonperperdicular orientations can occur. The latter can provide a constraint on the disk mass. We will also comment on the following questions: Is the existence of such planets compatible with their lack of detection to date by Kepler? What types of binary systems are most likely to harbor polar planets?

How does the dynamics of polar disks and their accretion onto the stars differ from coplanar circumbinary disks? What would we learn about the formation of polar planets by studying the properties of their orbits?

316.05 — Instabilities in Multi-Planet Circumbinary Systems

Adam P. Sutherland[1]; *Kaitlin M. Kratter*[1]
[1] *Astronomy, University of Arizona (Tucson, Arizona, United States)*

The majority of the discovered transiting circumbinary planets are located very near the innermost stable orbits permitted, raising questions about the origins of planets in such perturbed environments. Most favored formation scenarios invoke formation at larger distances and subsequent migration to their current locations. Disk-driven planet migration in multi-planet systems is likely to trap planets in mean motion resonances and drive planets inward into regions of larger dynamical perturbations from the binary. We demonstrate how planet-planet resonances can interact with the binary through secular forcing and mean-motion resonances, driving chaos in the system. We show how this chaos will shape the architecture of circumbinary systems, with specific applications to Kepler 47 and the Pluto-Charon system, limiting maximum possible stable eccentricities and indicating what resonances are likely to exist. We are also able to constrain the minimum migration rates of resonant circumbinary planets. Furthermore, we demonstrate how circumbinary planets can be affected by tidal evolution of the binary, limiting the efficiency of tidal evolution, constraining the age of circumbinary systems, and possibly explaining the lack of circumbinary planets around short period binaries.

316.06 — On the multiplicity of TESS planet hosts: Early results from a ground-based AO follow-up campaign

Elisabeth Matthews[1]; *Ian Crossfield*[1]; *David Ciardi*[2]; *Steve Howell*[3]; *Charles Beichman*[4]; *Erica Gonzalez*[5]; *Rachel Matson*[3]; *Joshua Schlieder*[6]
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We are using 8m class telescopes to study the multiplicity of TESS planet hosts. TESS has been finding candidate planets for nearly a year, and we have been taking snapshot images of the most promising targets to identify nearby stars at separations as small as a few 10s of milliarcseconds, using both AO and speckle imaging. In the short term, this work is vital to check for the presence of blended stars which can dilute the light curve, which can bias the measured radius of the observed planet, or even be responsible for false positives (Ciardi et al. 2015). Measuring the radius correctly is crucial for accurately determining the density of small planets, and therefore fully understanding the mass-radius relationship. Although GAIA provides excellent data on visual companions that are either bright or separated by several arcseconds, it is not sensitive to the faint, close visual companions that we are able to detect. When visual companions are detected, we are working to determine whether these objects are bound, and thereby understand how binarity affects planet formation. TESS typically detects planets roughly twice as close as those identified by Kepler, and so we are able to probe for binary companions at smaller angular separations and determine the most compact binary systems where planets can be found. In this talk I will present some of our early results from the survey, where we have already identified ~15 visual companions to ~40 TESS candidate hosts, and it appears likely that many of these are bound companions. This work will facilitate a broader study of the multiplicity of TESS planet hosts, for which we plan to combine GAIA and our high resolution data.

316.07 — The Perilous Lives of Planets in Binary Star Systems

Adam Kraus[1]
[1] *UT-Austin (Austin, Texas, United States)*

The majority of solar-type stars form with binary companions, and they should profoundly sculpt the formation and evolution of planetary systems. However, most searches for extrasolar planets have concentrated exclusively on single stars, avoiding close binary systems where the companion might complicate the observations and analysis. I will discuss statistically robust samples that outline the influence of stellar multiplicity at different stages of planet formation and evolution, enabled by a high-resolution imaging technique (nonredundant aperture-mask interferometry) that opens the discovery space for binary companions on solar-system scales (5-50 AU) even around relatively distant stars (100-500 pc). From the combined census of stellar multiplicity and protoplanetary disk occurrence in star-forming regions, binary companions have a ruinous effect upon protoplanetary disks; at ages when disks are still ubiquitous among single stars and wide binaries, the corresponding disk fraction among close binaries is suppressed by a factor of 3-4. The corresponding census of stellar multiplicity and transiting planetary systems at old ages, as assessed in the Kepler sample, shows a similar suppression rate among close binaries. However, some planetary systems do survive even in very dynamically perilous configurations, and I will outline the factors that potentially contribute to planetary survival and destruction. Finally, I will discuss how these results change the interpretation of planet formation and disk dissipation around single stars, given that almost all of them appear to host disks for at least 2-3 Myr, and what this might mean for the timescales and mass budgets for assembling planetary systems.

316.08 — Understanding the Impacts of Stellar Companions on Planet Formation and Evolution: A Survey of Stellar and Planetary Companions within 25 pc

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Nearly half of all solar-type stars have at least one stellar companion, and planets around G- and K-type stars appear to be quite common. Yet the impact of stellar multiplicity on planets is not yet well understood. Stellar companions may truncate disks and destabilize planetary orbits, and may contribute to planet migration scenarios. To test these theories, we have conducted a uniform survey for stellar and planetary companions around sun-like stars within 25 pc of the Sun. This survey made use of high-resolution imaging observations from ShaneAO at Lick Observatory and speckle interferometry from DSSI at WIYN, as well as precise radial velocities from HIRES at Keck and the Automated Planet Finder at Lick. From these observations, we confirm the stellar multiplicity statistics of previous surveys and uncover several new high-contrast binary systems. We also perform a thorough investigation of the nearby giant planet sample, including the detection of several new planets. By dividing the sample based on the presence or absence of stellar companions, the planet occurrence rates can be directly compared between single and binary systems. We conclude that binary companions with separations of hundreds of AU do not seem to strongly impact the planet formation process. Follow-up work with larger sample sizes and detailed attention to observational sensitivity to planets in close binary systems is needed to address the hypothesis that binaries with separations 10 - 100 AU more strongly impact planets. Since these "close" binaries comprise over a quarter of sun-like stellar systems, this follow-up work is essential to reach a complete understanding of planet occurrence rates and distributions.

316.09 — Stability Boundary and Stopping Orbits of Circumbinary Planets

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Not only did the detection of circumbinary planets (CBPs) confirm theoretical predictions of their existence, it also revealed new findings, some of which challenging our understanding of major physical processes such as planet migration. One of these findings is the apparent clustering of CBPs at or close to the boundary of stability. It has been stated that this clustering is not a detection bias and that the stability boundary is a preferred stopping location for migrating CBPs. Given that the physical processes governing the stopping of a migrating planet and that of the appearance of the boundary of stability are unrelated, the above statement, if correct, implies that CBP migration may involve new and unknown physics. It is, therefore, imperative to understand the nature of this clustering and determine its implications. Motivated by the latter, we launched a comprehensive project on studying the stopping of migrating CBPs. A migrating planet stops where negative Lindblad torques are balanced by positive corotation torques, a process that depends on the physical properties of the disk such as its mass and viscosity. We, therefore, considered a parameter space consisting of plausible ranges for the mass, viscosity and scale-height of the disk. The boundary of orbital stability is a celestial mechanics entity that is the result of the gravitational interactions between the binary and planet. We, therefore, considered binaries with different semimajor axes, eccentricities and mass-ratios, and varied the mass of the planet, as well. We carried out close to 1000 simulations of planet migration and identified the CBP's final orbits. Results confirmed, unequivocally, that circumbinary planets stop at a variety of different orbits, and there is no logical connection between their stopping location and the boundary of orbital stability. This is a significant finding that fully agrees with

theoretical predictions, clarifies the nature of the apparent clustering, and prevents it from being mistakenly labeled as a physical characteristic of CBPs. We respectfully request time for an oral presentation to present and discuss results of our study.

316.10 — Planetary–Stellar Orbit Alignment in Binary Systems

Trent Dupuy[1]; Adam Kraus[2]; Kaitlin M. Kratter[4]; Aaron Rizzuto[2]; Andrew Mann[5]; Michael Ireland[6]; Daniel Huber[3]

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Most planetary systems only offer the possibility to measure either the initial conditions of planet formation (e.g., protoplanetary disks) or the final outcome (e.g., demographics of mature field samples). Planet-hosting binaries offer the rare opportunity to study both concurrently. We will present results from our Keck adaptive optics program to monitor the stellar orbits of KOIs that have binary companions at solar-system scales of 20–200 AU. The astrometric orbital arcs that we measure enable a fundamental test: whether or not the stellar orbits are seen edge-on and thus co-aligned with the transiting planets in the system. This orbit–orbit alignment test allows us to critically examine the possible formation pathways for these systems. We find that stellar and planetary orbits tend to be aligned, which raises the question of whether this may be one of the keys to successful planet formation and subsequent survival in the otherwise inhospitable environment of such binary systems. Projection effects and the underlying eccentricity distribution are limiting factors in our current analysis, and I will discuss how future observations will actually turn this challenge into an opportunity to jointly constrain eccentricities and semimajor axes, as well as alignment, in the sample of *Kepler* planet-hosting binaries.

317 — Planet Formation Theory, Poster Session

317.01 — Establishing the Diversity of Super-Earth Systems with a Continuum of Formation Conditions

Mariah MacDonald[1]; Sarah Morrison[1]; Rebekah Dawson-Rigas[1]

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Multi-planet systems observed by Kepler that contain super-Earths exhibit a diversity of orbital and compositional properties. Here we investigate what planetary system outcomes arise from a range of protoplanetary disk solid surface densities and dissipative conditions shortly before disk dispersal, through simulating the giant impact phase of planet formation and subsequent dynamical evolution. We also compare the orbit distributions of these outcomes to the multi- transiting systems observed by the Kepler mission. For the same degree of dissipation from a gaseous disk and with no orbital migration, we find that larger solid surface densities lead to more tightly packed, flatter systems than smaller solid surface densities. We find that the spread in mass-radius relation observed in the Kepler population can also be explained with a wide range of solid surface densities, where small solid surface densities lead to rocky, dense planets and large solid surface densities lead to larger, gaseous planets. The distributions of the period ratios, spacings in mutual Hill radii, and transit duration ratios of adjacent planets — as well as the distribution of planet multiplicity — arising from these solid surface densities in conjunction with moderate gas damping (corresponding to a protoplanetary disk depleted by a factor of 100 in mass before disk dispersal) agree with the distributions of observed systems. These disk conditions can also produce super Earth systems with resonant chains, successive pairs near and in mean motion resonances.

317.02 — Suppression of pebble accretion by planet-induced gas flow: The implication for the formation of super-Earths

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The ubiquity of short-period super-Earths remains a mystery on the planet formation, because these planets are expected to become gas giants via runaway gas accretion within the lifetime of protoplanetary disk. Super-Earths cores should be formed in the late-stage of the disk evolution to avoid the runaway gas accretion. Previous studies have found the three-dimensional (3D) structure of the gas flow around embedded planets (e.g., Ormel et al. 2015). Disk gas enters at high latitude of the Bondi/Hill sphere of the planet and exits through the midplane region. This outward gas flow was considered to suppress the accretion of ~mm—cm-sized particles, called pebbles, and delay the core growth (Kurokawa & Tanigawa 2018; Kuwahara et al. 2019).

We calculated the trajectories of pebbles accreting onto a planet in the 3D gas flow field obtained from non-isothermal hydrodynamical simulations.

The efficiency of pebble accretion is lower in the planet-induced flow than in the unperturbed Keplerian shear flow. In the midplane, pebbles coming from a window between the horseshoe and shear regions can accrete onto the core if the pebble size is sufficiently large. Otherwise the outflow prohibits pebble from accreting. Because the horseshoe flow extends well above the midplane, pebbles coming from high altitudes are also influenced. We analytically derived that the pebble accretion is suppressed when $m \geq \sqrt{(\mathrm{St})}$, where m is the dimensionless planetarty mass expressed by the ratio of the Bondi radius to the disk scale height and St is the Stokes number of pebbles (the stopping time times the Keplerian frequency). This means that, for a given St, a growing proto-core starts to suppress the accretion of those pebbles as the core reaches the mass $m = \sqrt{(\mathrm{St})}$.

We suggest a scenario for the formation of super-Earths as follows. 1. Proto-cores form in the protoplanetary disk under the influence of the flow field. Due to the planet-induced gas flow field, the growth of proto-cores may halt when $m \sim \sqrt{(\mathrm{St})}$. 2. When the growth of the proto-cores halts, they begin to migrate inward. 3. Super-Earths are formed by giant impact during disk dispersal.

317.03 — Collisional growth of organic-mantled grains and formation of rocky planetesimals

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It is believed that the collisional growth of silicate dust grains is restricted by their poor stickiness. In this study, we explore the possibility that the stickiness of silicate grains in protoplanetary disks is enhanced by organic mantles. Silicate grains coated by organics can be commonly found in interplanetary dust particles, and previous laboratory experiments (Kudo et al. 2002) showed that such organic-coated particles are sticky in warm environments. To study in more detail how the stickiness of organic-mantled grains depends on temperature and mantle thickness, we construct a simple grain adhesion model that gives the binding energy of core-mantle grains in contact. Our model shows that the stickiness of organic-mantled grains increases with temperature. This occurs because as the temperature increases, the elasticity of organic mantles decreases and the contact area increases. We find that aggregates made of organic-coated grains are able to break through the fragmentation barrier in the inner part of protoplanetary disks where temperature is above > 200 K. We also simulate the growth and radial drift of organic-mantled grains in a disk, finding that they indeed grow into planetesimal-sized objects in a warm inner region of the disk. We will discuss a new scenario for terrestrial planet formation based on our results.
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317.04 — Pebble-driven planet formation around stars of different masses

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Observational breakthrough has been achieved in characterizing the properties of protoplanetary disks and extrasolar planets in the last decade. We thus gain a better understanding on both the birth conditions and the end products of planets. Meanwhile, more advanced theoretical and numerical models are required to establish the bridge between these two based on evolving planet formation theories. We develop the pebble-driven core accretion model to study the formation and evolution of planets around stars in the range of 0.08 M_{Sun} and 1 M_{Sun}. By Monte Carlo sampling of their initial conditions, the growth and migration of a large number of individual protoplanetary embryos are simulated in a population synthesis mannar. Two hypothesis are proposed for the birth locations of embryos, at the water ice line or log-uniformly distributed over distance in protoplanetary disks. Two types of disks with different turbulent viscous parameters α_t of 10^{-3} and 10^{-4} are also investigated. The forming planet population is statistically compared with the observed exoplanets in terms of mass, semimajor axis, metallicity and water content. We find that massive planets are likely to form when the characteristic disk sizes are larger, the disk accretion rates are higher, the disks are more metal rich and/or their stellar hosts are more massive. Our model shows that 1) the characteristic planet mass is set by the pebble isolation mass. It increases linearly with the stellar mass, corresponding to one Earth mass around a Trappist-1 star and 20 Earth mass around a solar-mass star. 2) The low-mass planets up to 20 M_E can form around stars with a wide range of metallicities, while massive gas giant planets are preferred to grow around metal rich stars. 3) The super-Earth planets mainly composed of silicates with relatively low water fractions can form from the seeds at the water ice line in less turbulent disks. Altogether, the model succeeds in quantitatively reproducing several important observed properties and correlations among exoplanets.

317.06 — Unified model of formation and atmospheric evolution of super-Earths and Neptune-mass planets

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According to the theoretical study of atmospheric accretion, super-Earths and Neptune-mass planets (SENs) accumulate massive H/He atmospheres in a runaway fashion within the lifetime of protoplanetary disks. In contrast, several observational evidences suggest that most SENs avoided accretion of massive atmospheres. Many ideas have been proposed to solve this discrepancy. As a possible solution, we focus on the heating of atmospheres by pebble accretion, which would suppress the accretion of atmospheres. In addition, the accreted atmosphere can be lost by collisional erosion during late-stage giant impacts and by long-term photoevaporation due to stellar XUV. In this study, we perform unified numerical calculations for N-body simulations of the formation of SENs formation and their atmospheric evolution. In other words, using our N-body simulations, the planetary growth and atmospheric evolution can be consistently calculated. In this presentation, we will reveal whether the amount of accreted atmospheres can be limited by the above mechanisms (i.e., heating by pebble accretion, atmospheric escape). We also discuss a few other observed properties (e.g., orbital distribution, sub-Neptune desert) of SENs that can be reproduced by the results of our simulations. We can theoretically predict observable properties (e.g., orbital property, mass, and atmosphere) and their mutual correlation, which help understand the results of ongoing and future observational projects (e.g., TESS, CHEOPS).

317.07 — Formation of compact system of super-Earth via dynamical instabilities and giant impacts

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NASA's Kepler mission discovered ~700 planets that reside in multisystems containing 3 or more transiting planets, many of which are super-Earths and mini-Neptunes in compact configurations whose origins are not yet understood. Using N-body simulations, we examine the final stage assembly of multiplanet systems through the collisional accretion of protoplanets. Our initial conditions are constructed using a subset of the Kepler 5-planet systems as templates, and apply to the epoch after gas disc dispersal. Two different prescriptions for the outcomes of planetary collisions are adopted. The simulations address a number of questions: do the results depend on the accretion prescription?; do the resulting systems resemble the Kepler systems and do they reproduce the observed distribution of planetary multiplicities when synthetically observed?; do collisions lead to significant modification of protoplanet compositions, or to stripping of gaseous envelopes?; do the eccentricity distributions agree with those inferred for the Kepler planets? We find the accretion prescription is unimportant in determining the outcomes. On average, the final planetary systems look similar to the Kepler templates we adopted, but the simulations do not reproduce the observed distributions of planetary multiplicities or eccentricities, because gravitational scattering does not dynamically excite the systems sufficiently. In addition, we find that approximately 1% of our final systems contain a co-orbital planet pair in horseshoe or tadpole orbits. Post-processing the collision outcomes suggests they would not lead to significant changes of the water fractions of initially ice-rich protoplanets, but significant stripping of low mass gaseous atmospheres appears likely. Hence, it may be difficult to reconcile the observation that many of the low mass Kepler planets appear to have H/He envelopes with a formation scenario that involves giant impacts after dispersal of the gas disc.

317.08 — Evolution and growth of dust grains in protoplanetary disks with magnetically driven disk wind

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Magnetically driven disk winds (DWs) are one of the promising mechanism of dispersal processes of protoplanetary disks (Suzuki et al. 2010, Bai 2013). When the DWs play a key role, the gaseous component of protoplanetary disks evolves in a different manner from that of the classical viscous evolution. As a result, the subsequent planet formation is also affected by the DWs. In this work, we investigate the effects of the DWs on the radial drift of solid particles with the size of 0.1μm - 1km. We propose that the DWs is a possible solution to the "radial drift barrier" of collisionally growing dust grains, which is a severe obstacle to the planet formation (e.g., Nakagawa et al.1986). In order to study the evolution of dust grains in the disks, we calculate the advection and the collisional growth of dust particles in evolving protoplanetary disks under the 1+1 D (time + radial distance) approximation. We solve a coagulation equation of solid particles under a single-size approximation (Sato et al. 2016) for various conditions of turbulent viscosity, the mass loss by the DW, and the magnetic braking by the DW. We found that rapid grain growth occurs in the inner region of the protoplanetary disks. The DWs disperse the protoplanetary disk from inside to outside. On such the process, the region where a pressure gradient is smaller than the typical value of the protoplanetary disks appears. At the same time, the Stokes number of dust grains tend to be larger than the case without such region. The growth timescale of dust grains becomes shorter than the radial drift timescale of them in such the flat and gas dispersed region. In addition, when the disk gas is mainly lost by the DWs rather than by the accretion, an outwardly moving pressure bump is formed. The pressure bump can halt the dust radial migration (e.g., Taki et al. 2016). We confirmed that the dust grains trapped in the pressure bumps in our simulations. It is a potential advantage for the planetesimal formation.

317.09 — Inertial concentration of dust particles in accretion disks

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Turbulence in protostellar disks can cause dense concentrations of dust particles to form through a process called inertial concentration. Using Direct Numerical Simulations in the two-fluid formalism (where the particles are treated as a continuum coupled with the gas through a linear drag term), we demonstrate the existence of a scaling law relating the maximum particle concentration observed at any given time to the particle Stokes number, the particle diffusion coefficient, and the rms velocity of the turbulent fluid. This law can be explained using simple dimensional arguments. We apply our findings to dusty disks, to predict what the largest possible dust concentrations may be at any given point in the disk.

317.10 — Fragmentation favours protoplanetary discs around high mass stars

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Recent observations suggest that, when we observe wide-orbit gas giants, they are primarily found around high mass stars. A possible explanation to this may be provided by planet formation through fragmentaion. Fragmentation most likely occurs in the outer regions of protoplanetary discs where their cooling times are smallest, whilst also likely only forming massive gas giant planets and brown dwarfs rather than terrestrial planets, thus preferentially forming wide-orbit gas giants. The work done in this project aims to show that the conditions necessary for a disc to be unstable against fragmentation are more readily satisfied around higher mass stars, therefore potentially providing explaination of this observed planet population.

317.11 — Pebble-driven planet formation for TRAPPIST-1 and other compact systems

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Two years ago, a spectacular planetary system was discovered around the M-dwarf star TRAPPIST-1. Seven Earth-sized planets are circling this star with very short periods: their orbits would all fit well within Mercury's orbit in the Solar System. Three out of the seven planets are located in the habitable zone; the temperate conditions may support the presence of liquid water. Thanks to transit-timing variations, the planets' masses and therefore compositions have been constrained. Planet internal modelling suggests that the TRAPPIST-1 planets have moderate water fractions of a few to tens of mass percent, which is much more than that of the Earth. These values suggest that the TRAPPIST-1 planets formed outside the snowline and migrated inward while they were still growing. We have connected a model of the evolution of dust and pebbles and planetesimal formation with a model of the growth from planetesimals to planets. This strategy enables us to self-consistently model the assembly of the TRAPPIST-1 planets, keeping track of their composition. The model may also be applied to other compact planetary systems. One of our key predictions is that the planet water fraction shows a V-shaped trend with planet order. Future (more precise) observational measurements of planet water fractions in compact systems could therefore be used to constrain our planet formation model.

317.12 — Photodissociation-Driven Mass Loss from Young and Highly-Irradiated Exoplanets

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The most widely-studied mechanism of mass loss from irradiated exoplanets is photoevaporation via XUV ionization. However, lower-energy FUV dissociation of hydrogen molecules can also theoretically drive atmospheric evaporation on low-mass planets because the dissociation energy of hydrogen is an order of magnitude greater than the escape energy per proton from the gravity well of an Earth-sized planet. This implies that a significant fraction of a star's blackbody flux can contribute to photoevaporation, potentially to a greater degree than ionizing radiation. For temperate planets such as the early Earth, impact erosion is expected to dominate over photoevaporation in most formation models, but for highly irradiated planets such as those near the "evaporation valley" observed in *Kepler* planets, or for pebble accretion formation models, they could plausibly be sculpted primarily by photodissociation. I present results of a survey of various mass loss processes and their relative contributions to mass loss from an early Earth-like planet. In particular, we find that photodissociation could strip an atmosphere up to 0.5% of the mass of the planet even at Solar levels of irradiation. I then apply this prescription for mass loss to models of highly irradiated super-Earths and mini-Neptunes and discuss the implications of these results for rocky planet formation and the interpretation of the evaporation valley.

317.13 — Planetesimal formation at the inner edge of the dead zone: Implication for the diversity in planetary systems

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We perform simulations of the dust and gas disk evolution to investigate the planetesimal formation at the dead-zone inner edge. We show that the total mass of planetesimals is sensitive to the turbulence strength in the dead zone because of the combined effect of turbulence-induced particle fragmentation and turbulent diffusion. For a typical critical fragmentation velocity of silicate dust particles of 1 m s^{-1}, the stress to pressure ratio in the dead zone needs to be lower than $3{\times}10^{-4}$ for dust trapping to operate. if the stress to pressure ratio in the dead zone is around 10^{-3}, planetesimals with a total mass of ~ 2 Earth masses is formed at the dead-zone inner boundary, which is preferable to form the solar system terrestrial planets. If the stress to pressure ratio is lower, the total planetesimal mass is larger, which is preferable to form more massive planets such as super-Earths. The strong dependence of the total planetesimal mass on the turbulent strength might be linked with the diversity in the mass of planetary systems

317.14 — Elemental Abundances of Planetary Atmospheres and Planet Formation

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Knowing elemental abundances of a planet is key to understanding its formation. This is because the composition of a planet atmosphere is heavily influenced by the planet formation process, and subsequent evolution. Close-in giant planets are currently the best candidates to study the question of their formation from their atmospheric composition. In this work we develop a framework that uses models for protoplanetary disks and for planet formation to parameterize the inputs in simple manners and form a giant planet with its atmosphere. Ultimately we will produce model spectra of our modeled planet and compare these to observations to put limits on the inputs for the planet formation model previously constructed.

317.15 — Planetesimal formation for planetary population synthesis

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Planetesimal formation is a key process in the formation of planets and up to this day there is no direct observational data to constrain the existing theoretical models. Since the number of detected exoplanets has increased drastically in the last decades it has become possible to use the properties of this population of exoplanets to form constrains for our models in a statistical sense. The framework of population synthesis is therefore a unique and powerful tool to test models for planetesimal formation and bridge the gap of its non observability by connecting the observable initial dust density to the final observable population of planets. Latest results on the formation of planetesimals indicate a much steeper column density profile of planetesimals in protoplanetary disks than the previously assumed one, which originates from the widely used minimum mass solar nebula model. First studies using the Bern model of planet population synthesis indicate that the accretion of large planetesimals (100km) alone is a very efficient growth mechanism that can account for the large diversity in the population of exoplanets.

317.16 — The first self-consistent modeling of collisional water transport during late-stage planet formation

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The final phase of terrestrial planet formation, where planetary embryos and remaining planetesimals accrete into planets, is a dynamically stochastic process, marked by giant collisions among protoplanets and radial mixing of material over wide distances, where the origin and abundance of water is strongly tied to collisional transfer and loss processes, and of central importance for their habitability. Several approaches for treating collisions beyond (over-)simplified perfect inelastic merging have been developed in recent years, but none has been designed nor applied for modeling the collisional evolution and delivery of water to growing terrestrial planets, even though it is particularly susceptible to collisional transfer and erosion. To eventually close this gap we have successfully developed a new hybrid framework to directly combine long-term N-body integrations with Smooth Particle Hydrodynamics (SPH) simulations of individual collision events, which allows us to self-consistently model collisional water transport on a system-wide scale for the first time. This includes full treatment of frequent hit-and-run events, where not only water losses but also transfer between the colliding bodies can be crucial. In a solar-system-like setting as the first application, our simulations include varying gas giant architectures, and a bi-modal initial distribution of embryos and smaller bodies, where we find that with a realistic collision treatment final water contents are reduced by a factor of 2 or more. Our results show that water delivery is dominated by very few decisive accretionary and frequently also hit-and-run encounters, with embryo-sized or even larger impactors, and only rarely smaller bodies. Even though our model includes their collisional evolution, they seem to play only a minor (direct) role in water transport to potentially habitable planets. Beyond this first application and exciting results, we believe that this methodology offers a solid basis for including further decisive physical processes, towards a deeper understanding of water transport to terrestrial planets throughout the galaxy.

317.17 — Pebble Accretion in Massive Disks

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A better understanding of protoplanetary disks is crucial to help astronomers recreate the diversity of exoplanets that we see in our galaxy. An increasing number of studies indicate that these disks may be more massive than was previously thought, suggesting more material available for planetary formation. We apply one such observationally motivated model of protoplanetary disks to our state-of-the-art turbulent pebble accretion model, in order to probe planetary formation in this new parameter regime. Testing a wide range of turbulence strengths in the outer disk, we are able to rapidly grow injected protoplanetary cores, exploring the conditions under which these protoplanets reach the masses needed for runaway gas accretion. This model predicts cores which, upon reaching a minimum mass, grow extremely efficiently to their flow isolation masses, a natural mass at which pebble accretion halts. Depending on when and where in the disk these small protoplanets are injected, some grow to terrestrial planet masses, while others are able to reach masses required to runaway gas accretion.

317.18 — Overcoming the Meter-Size Barrier in Large Protoplanetary Disks

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The meter-size barrier is a persistent problem in current planet formation models, where particles on the order of a meter in size fail to grow because they either fragment or drift into the star. Dust grain evolution at this size can be summarized by three characteristic timescales: growth, drift, and fragmentation. Accurate models of these timescales that can resolve the meter-size barrier are important to improving our understanding of how planets form. Recent observational and theoretical studies of protoplanetary disks indicate that they are more massive than previously assumed. Using our analytic model, we find that with a more massive disk, the dust grains in the outer disk are initially dominated by the drift timescale, and as they move inward become dominated by the growth timescale. These grains are able to drift into the inner disk before collisionally fragmenting, and then grow unimpeded. We adapt the two-population dust evolution numerical model from Birnstiel et al. (2012;15) to include necessary drag regimes and verify that with larger protoplanetary disks, particles can survive the meter-size drift and fragmentation barriers, and continue to grow.

317.19 — Delivery of ammonia ice to Ceres by pebble accretion

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Ceres is the largest asteroid in the solar system, comprising almost one-third of the total mass of the asteroid belt. The spectrometer onboard the Dawn spacecraft revealed the presence of ammoniated phyllosilicates across the surface of Ceres (De Sanctis et al. 2015), suggesting that Ceres contained ammonia when it differentiated. However, ammonia alone is unstable on the surface of present-day Ceres, where the maximum temperature ($\approx$ 240 K) is well above the sublimation temperature of ammonia ice. This could imply that Ceres was born in the cold outer part of the solar nebula and subsequently migrated to the current orbit. Another possibility is that Ceres formed in situ but the solar nebula was cold enough to preserve ammonia ice even at the current orbit of Ceres. In this study, we examine the latter scenario by quantifying how much ammonia ice could have been delivered to Ceres in the solar nebula. We use a standard viscous accretion disk model to infer how the temperature of the solar nebula decreased with time. We also simulate the coagulation, radial inward drift, and sublimation of ammonia-bearing icy particles in the background gas disk to compute the radial mass flux of the particles at 3 au as a function of time. The mass flux is then converted into the accretion rate of ammonia-bearing ice by Ceres and smaller asteroids using the state-of-the-art analytic formula for pebble accretion (Visser & Ormel 2016). We find that the thickness of the ammonia-bearing ice layer forming on Ceres depends significantly on the initial mass Mdisk and dimensionless viscosity parameter α of the solar nebula. A layer thick enough to globally cover the surface of Ceres forms when $M_{disk} < 10^{-2} M_{sun}$ and $\alpha > 10^{-3}$. Our results thus provide unique constraints on the fundamental parameters of the protoplanetary disk that formed the solar system. We also find that the layer thickness is highly sensitive to the initial asteroid mass, possibly explaining why ammoniated phyllosilicates are observed in the largest asteroid Ceres.

317.20 — How scales of streaming and Kelvin-Helmholtz instabilities regulate particle overdensities in protoplanetary disks

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The formation of planetesimals in protoplanetary disks is an exciting and still unsolved problem in planet formation theory. A promising scenario to overcome dust growth barriers is the spontaneous formation of planetesimals via gravitational collapse of locally over-dense clumps. As these regions are regulated by numerous fluid-dynamical instabilities that result from the frictional coupling of dust and gas, the interplay of the scales of these mechanisms is of great interest. We employ the Pencil Code to numerically investigate the scales of Kelvin-Helmholtz instability (KHI) in the particle layer and streaming instability (SI), which was recently identified as the epicyclic resonant drag instability. While the KHI is known for setting the vertical scale of the settled dust layer and thus preventing planetesimal formation in a thin, gravitationally unstable disk, the SI was previously shown to lead to significant particle over-densities, sufficient for local gravitational instability. In addition to the global pressure gradient, which drives both KHI and SI by providing a relative dust-to-gas velocity, our study focuses on the effect of dust-to-gas ratio, which in combination with the particle Stokes number, quantifies frictional coupling essential to both instabilities. Provided SI is active, i.e.for large enough particle Stokes numbers, we find that the vertical extent of the dust layer is predominantly set by SI-induced zonal flows in lieu of the KHI scale. Moreover, for both very high and very low dust-to-gas ratios KHI-induced particle stirring is relatively weak, therefore allowing particles to settle very thin, and thus potentially leading to a gravitationally unstable disk mid-plane despite KHI turbulence. Further, we find that KHI and SI are surprisingly similar in nature. In particular, both the dust extent set by KHI and the fastest growing SI mode scale linearly in gas pressure gradient. Finally, we discuss implications for initial planetesimal sizes and how and under which circumstances these can correlate with the scales of KHI and SI.

317.21 — Warm-start planets from core accretion, and H α from accreting planets: Thermal and radiative properties of the accretion shock

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In the core-accretion formation scenario of gas giant planets, most of the gas accreting onto a planet is likely processed through an accretion shock. This shock is key in setting the forming planet's structure and thus its observable post-formation luminosity, and the radiative feedback can change the thermal and chemical structure of the circumplanetary and local circumstellar disc. Also, direct evidence for ongoing accretion has been provided very recently for PDS 70 b and c, and more forming planets are expected in the near future thanks to ongoing and new searches with e.g. SPHERE or MUSE.

We present the first dedicated radiation-hydrodynamical simulations of the planetary accretion shock, using non-equilibrium radiation transport with up-to-date opacities (Marleau et al. 2017, 2019). We derive shock properties for a large grid of parameters. We find that usually, the temperature of the shock is given by the "free-streaming" limit. At very high accretion rates, the massive Rosseland opacity of the gas raises the shock temperature dramatically, an effect which has not been discussed explicitly before. We compare these results to original semi-analytical derivations. Additionally, we compute the fraction of the total accretion energy that is brought into the planet and find it is significant compared to the internal luminosity, supporting the hot-start scenario and suggesting that young planets are luminous.

Finally, using the non-LTE radiation-hydrodynamics code of Aoyama et al. (2018), we present the first predictions of hydrogen-line emission (H α, Pa beta, Br gamma, etc.) from the accretion shock on the surface of the planet (Aoyama, Marleau et al., in prep.). We compare with PDS 70 b and c and derive joint constraints on each planet's mass and accretion rate.

317.22 — An interpretation of exoplanet masses and orbital radii with a theoretical model of gas giant formation

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About 4000 exoplanets have been detected and their statistical properties such as mass and orbital distributions become clear. However, the origin of these distributions is still uncertain. In this study, applying a recent core accretion model to data of exoplanets, we clarify whether it is possible to explain the observed distributions of masses and orbital radii, and in what protoplanetary disk they can be explain. We adopt the following theoretical model of gas giant formation in this study. We use the model of Tanigawa & Tanaka (2016) for the mass growth rate (i.e., the gas accretion rate onto a planet) and the latest model of Kanagawa et al.(2018) for the planetary migration speed. Since the growth rate and the migration speed of a planet are proportional to the disk surface density nearby, a model for global evolution of protoplanetary disk is also necessary. We also take account of disk dissipation due to the photoevaporation. From this model, we obtained evolution curves on the plane of the planet mass and orbital radius. The evolution curves are also expressed in an analytical form. Since both the growth rate and migration speed of a planet are proportional to the disk surface density nearby, the curves do not depend on the detail of the disk model. Such exoplanets do not migrate much during their formation. Even for the largest exoplanet (of which mass is 2% of the star mass), its orbital radius is reduced moderately (to 1/10). Many gas giants are located at around 2AU from their stars. This can be explained as solid cores are easily formed near snow lines of disks at ~3AU. The termination of growth of each gas giant planet is mainly determined by the initial disk mass and the disk dissipation rate due to photoevaporation. Thus for a given disk dissipation rate, we can obtain initial disk masses corresponding to each planetary masses. We find that the peak of our initial disk mass distribution agrees with the most common disk mass in observations (~0.02 solar masses, Andrews et al. 2010) if the disk dissipation rate is set to be ~3x10^{-9} solar mass per year.

317.23 — Planetesimal Population Synthesis: are Planetesimals formed in Pressure Bumps?

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Planetesimals, the smallest building blocks of planets that are gravitationally bound, are believed to be needed in order to form planets. The spacial distribution of these objects that are typically 100 km in diameter is important for the outcome of planet formation. There exist an entire zoo of different disk instabilities that can cause vortices or zonal flow within which pebbles can be trapped and form planetesimals via gravitational instability. We parameterized these traps and implemented a pebble flux-regulated planetesimal formation rate into a dust and gas evolution code. We found that the radial planetesimal distribution spans from the regions of terrestrial planet formation up to the Kuiper belt and is steeper than the initial profile of dust and gas. The latter finding indicates that the feeding zone, i.e. the region from which the material forming planetesimals originates, can be large. The final spacial planetesimal distribution strongly depends on the turbulence strength from which we can conclude that the Solar Nebula was not very turbulent ($\alpha<10^{-2}$).

317.24 — Planet Population Synthesis: the Cradle of the TRAPPIST-1 Multiplanet System

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Planet Population Synthesis is a statistical approach that serves as a bridge between theoretical planet formation and the observed population of exoplanets. It has led to testable predictions, such as the now-confirmed minimum in the planetary mass distribution between a few Earth masses and 40 Earth masses. In order to apply this technique to low-mass host stars, we have extended the Bern model of planet formation (Mordasini et al. 2009) to the different conditions in their protoplanetary disks. Changes to the original setup include a smaller inner disk radius and a down-scaled disk mass distribution.

We present a population of systems with a host star mass of 0.1 Solar masses which we compare to observables of the TRAPPIST-1 multi-planet system (Gillon et al. 2017). We find that most of its features can be robustly reproduced. Using the mean planetary mass as a metric, we find a domain in initial disk solid mass and disk extent favorable for the formation of similar systems. The fact that a well-established formation model can produce similar systems with little additional assumptions suggests that TRAPPIST-1 is not an exotic outlier but a rather typical outcome for very-low-mass systems. This raises important implications for exoplanet demographics at the limit of detectability. "

317.25 — The Formation of Jupiter's Diluted Core by a Giant Impact

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The Juno Mission is designed to measure Jupiter's gravitational field with an extraordinary precision.

Structure models of Jupiter that fit Juno gravity data suggest that Jupiter could have a diluted core and a total heavy-element mass ranging from ten to two dozens of Earth masses. In that case the heavy elements are distributed within an extended region with a size of nearly half of Jupiter's radius. Planet formation models indicate that most of the heavy elements are accreted onto a compact core, and that almost no solids are accreted during runaway gas accretion (mainly hydrogen and helium, hereafter H-He), regardless to whether the accreted solids are planetesimals or pebbles. Therefore, the inferred heavy-element mass in the planet cannot significantly exceeds the core's mass. The fact that Jupiter's core could be diluted, and yet, the estimated total heavy-element mass in the planet is relatively large challenges planet formation theory. In this work, we show that sufficiently energetic head-on collisions between additional planetary embryos and the newly emerged Jupiter can shatter its primordial compact core and mix the heavy elements with the outer envelope. This leads to an internal structure consistent with the diluted core scenario which is also found to persist over billions of years. A similar event may have also occurred for Saturn. We suggest that different mass, speed and impact angle of the intruding embryo may have contributed to the structural dichotomy between Jupiter and Saturn.

318 — Orbital Dynamics and Planet-Planet Interactions, Poster Session

318.01 — The dynamics of the planetary system of Kepler-90

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The planetary system of Kepler-90 presents some similarities to our solar system. This system has seven planets, b, c, d, e, f, g and h, in increasing distance from the star. The outer planet has an orbital distance equals to 1 AU, it is a compact system. While planets g and h are gas giants, the planets d, e and f are super-Earths and planets b and c have sizes below to 2 Earth radii. Small planets are closer to the star and the larger ones are distant from the star. Numerical simulations performed by Cabrer*a et al* (2014) have shown that some of these planets are in mean motion resonances (MMR) between them. Planets b and c are in 4:5 MMR, and planets d, e, and f are close to 2:3:4 MMR.

Through frequency analysis and long term evolution of the planets we will analyse their stability and the region surrounding them for a sample of parameters of the planets, such as their mass, semi-major axis and eccentricity. Preliminary results have shown that the system is stable for a period of 10^5 years when the eccentricities are assumed zero and the masses of the planets are derived from the paper by Granado Contreras & Boley (2018), while with the parameters derived from the work by Cabrera *et a*l (2014) one of the planets is ejected from the system.

318.02 — Dynamical evolution of extrasolar planetary systems HD 141399, HD 160691 and HD 39194

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The orbital evolution of four-planetary systems HD 141399, HD 160691 and three-planetary system HD 39194 is considered in this work. The motion equations of planetary problem are constructed analytically up to the second degree of planetary masses. The Hamiltonian of the planetary problem is written in Jacobi coordinates, and it is expanded into the Poisson series in the second system of Poincare elements. The Hamiltonian expansion is constructed up to the fourth degree of eccentric and oblique Poincare elements. The averaging process of the Hamiltonian is performed by Hori-Deprit method and the motion equations are constructed in averaged elements.

The numerical integration of motion equations is performed on time interval 1 Myr for the set of initial conditions in which unknown and known with uncertainties orbital elements vary within allowable limits. All planets in these systems are discovered by detecting of Doppler shift of their radial velocities. So, only lower limits of values of planetary masses known for studied extrasolar planetary systems. The values of orbital eccentricities and pericenters known from observations with uncertainties. Orbital inclinations and ascending nodes are not known and vary. Dynamical features of chosen extrasolar planetary systems are studied. Stability and resonant properties of these systems are defined by analysis of the integration results.

The limits of change of the orbital elements are determined depending on the initial conditions of the modeling process. The assumption about the stability of observed planetary systems allows us to eliminate the initial conditions leading to the extreme growth of orbital eccentricities and inclinations. It is shown a way to identify initial conditions in which the orbital elements remain small in the whole interval of the modeling. It becomes possible to limit the range of possible values of unknown orbital elements and determine their most probable values in terms of stability.

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318.03 — About Properties of Retrograde Co-Orbital Motion

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Most of objects in the Solar system move around the Sun in the anticlockwise manner when seen from above the north ecliptic pole. And only a small number of celestial bodies move in opposite direction (retrograde motion). The first retrograde asteroid Dioretsa was discovered only in 1999. From year to year the number of detected retrograde objects increased rapidly, but even now MPC data base contains only about a hundred of such bodies. Some of them can be classified as Centaurs, the other are either Main Belt asteroids (MBA) or Trans-Neptunian objects (TNO).

Similar to prograde motion, the retrograde motion of a celestial body can also be in resonance with one of the major planets. For example, the asteroid 2015 BZ509 is in retrograde 1:1 mean motion resonance (MMR) with Jupiter [1]. Theoretical studies demonstrated that such a resonance can prevent collision with the planet and ensure a long stay of the asteroid in this mode of motion.

Three dynamical processes can be distinguished at MMR: "fast" process corresponds to planet and asteroid motions in orbit, "semi-fast" process is variation of the resonance argument (which describes the relative position of the planet and the asteroid in their orbital motions), and, finally, "slow" process is the secular evolution of the orbit shape (characterized by the eccentricity) and orientation (it depends on the ascending node longitude, inclination and argument of pericenter).

By means of numerical averaging over the "fast" and "semi-fast" motions. we construct the evolutionary equations that desribe the long-term behavior of the asteroid's orbital elements (the "slow" process) in the case of the retrograde 1:1 MMR. These equations allow us to reveal new properties of the retrograde co-orbital motion.

[1] Wiegert, P., Connors, M., Veillet, C.: A retrograde co-orbital asteroid of Jupiter. Nature, Vol. 543, pp. 687-689, 2017.

318.04 — Tidal Formation of Binary Planets During Planet-Planet Scattering

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When more than three Jovian planets are formed in a relatively close distance, their orbits become unstable and planet-planet scatterings are caused. During the unstable stage, two planets can approach within several times of their physical radius. If enough tidal dissipation occurs between two planets, the planets become a binary and they start to orbit around the central star rotating around each other. It is known from numerical simulations assuming the dynamic tide of about 100 systems by Ochiai et al. (2015) that the binary planets are formed with a probability of about 10% regardless of the semimajor axes. However, it is still unknown why it does not depend on the semimajor axis, why it is about 10%, and how it changes when planetary size or the tidal models are changed. We found that these questions can be explained from the nature of the planet-planet scatterings. Unlike the HJ formation, once the planets are scattered strongly, it becomes almost impossible to capture the planet by tidal force. The ability of tidal capture of a planet is expressed as a function of the distance between the planets. The distance between the planets in the early stage of scattering is determined from gravitational orbital evolutions of point-mass planets, without depending on the tidal model and the planetary size. Therefore, if the relative velocity and mutual distance are recorded, probability of binary formation can be relatively well estimated even after the gravitational simulations. We performed many numerical simulations of early stage of planet-planet scatterings, and normalized the results using physical radius and hill radius. Our results make it possible to determine the probability of planet-planet collision, formation of binary planets, and scatterings following HJ formation and collision to the star as a function of tidal strength. We will report how the probability of formation of binary planet changes with respect to the initial conditions of the system such as the tides, initial eccentricity, and planetary size. We will also see that the rate of binary planets relative to the numbers of HJs.

318.05 — Stability of closely packed multiple exoplanetary systems

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There are more then 4000 exoplanets have been observed up to now and hundreds of multiple planetary systems among them. Many planet pairs are in the configuration of mean motion resonances (MMRs) or near MMRs. We investigate the stability of multiple planetary systems to find out if the MMRs configuration is more stable for planets to survive. Through numerical simulation on equal-mass multiple planetary systems, we find out that (1) If all planets undergo inward type I migration, planet pairs tend to be more stable with the increase of the relative separation between them; (2) If there are both inward and outward migration exist in the system, the separation between planet pairs will shrink to smaller Hill Radius and planet pairs can find their stable configuration if they are captured into MMRs. But the stable region is very narrow; (3) The density of the gas disk is related to the final separation between planet pairs and when they are captured into MMRs. If planet pairs migrate to small separation with larger gas density, the system are easy to be crossing. The resonances are deeper in the system with larger depletion timescale and the system are more stable (4) When the libration timescale of planet pairs larger than the migration timescale which are caused by the mass loss of planets in the system, the stable configuration can be destroyed.

318.06 — Can a flyby induce misalignment in a planet-hosting disc?

Rebecca Nealon[1]
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We now have several observational examples of strongly misaligned broken discs, where the orientation of the disc can change rapidly as a function of distance from the central star. Current models suggest that such discs are generated through the influence of a stellar or planetary companion that is orbiting in a plane misaligned to the mid-plane of the disc. Such a companion causes the disc to separate into an inner and outer disc, both of which respond differentially to the presence of the misaligned companion leading to a relative misalignment between the discs. Here we explore whether a strong misalignment between the inner and outer disc could be formed without a misaligned inner companion. Instead, we invoke an aligned planetary companion in the disc that carves a gap (essentially separating the disc into two regions) and use a flyby encounter to disturb the discs. We find strong misalignments can be generated and examine these in the context of existing observations of strongly misaligned broken discs.

318.07 — Are Closely-spaced RV Planets the Product of Smooth Migration?

Sam Hadden[1]*; Matthew J. Payne*[1]
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A number of RV-discovered planetary systems around A stars host closely-spaced (period ratios <2), Jovian-mass planet pairs. These planets are not traditionally expected to form in such close proximity and therefore are thought to have experienced post-formation migration. Capture into mean motion resonances (MMRs) is a natural dynamical outcome of convergent planetary migration and radial velocity modeling suggests that many of these planets are indeed in resonance. In the simplest smooth migration scenarios, dissipative forces should drive planets into a very specific resonant configuration, sometimes referred to as an 'apsidal corotation resonance' or ACR, that represents a fixed point of the resonant dynamics. Determining whether the dynamical states of RV planets are consistent with the outcomes of simple smooth migration is a natural starting point for better understanding the role of migration in planet formation. We assess whether closely-spaced Jovian planet pairs can be explained as the product of smooth migration using a Bayesian model comparison framework to compare a traditional two-planet model of each pairs' RV observations (that does not assume resonance) to a model that assumes the planet pair to be in an ACR, thus restricting the number of free parameters. We find that most RVs can be satisfactorily explained by ACR configurations and discuss the implications of planets' inferred dynamical states for their formation histories.

318.08 — Tidal evolution and formation for Proxima b

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Recently, Anglada et al. (2016) discovered a terrestrial planet Proxima b orbiting around Proxima Centauri in the habitable zone, with the semi-major axis of about 0.05 au and a possible eccentricity less than 0.35. Proxima Centauri is the Sun's closest neighbor at present, therefore, Proxima b will provide good opportunities to investigate Earth-like planets outside our solar system. Almost overnight, many investigations have been focused on this planetary system mainly including planet formation, the interiors and the habitable zone et al. We carry out the numerical simulations of the dynamical evolution of Proxima b based on the equilibrium tidal model. The orbital circularization during tidal decay is within 20 Myr when assumed the modified tidal dissipation parameter Q=6. The planetary orbit-spin rotation reaches synchronous in ten thousand years. Various orbital parameters are considered in studying the spin-orbit 1:1 resonance. To explain the observable eccentricity of Proxima b, we explore the dynamical evolution using a modified secular theory, assuming that there is one candidate planet around Proxima Centauri. The candidate planet excites a steady eccentricity of Proxima b before its tidal experience. Finally, the planet formation of Proxima b via type I migration in the gaseous disk is investigated, as the result shows that Proxima b reaches the inner disk with a period of 14 days, then suffers tidal decay to current orbit.

318.09 — Trojan Terrestrial Planets: stability and formation

Othon Winter[1]; Luana Mendes[1]
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Up to the present moment, no co-orbital planet has been found. Trojan terrestrial planets sharing their mean orbit with a giant planet in the habitable zone might harbor conditions of habitability. Therefore, this is a relevant subject of study. In the present work we explore the size and shape of the stability region co-orbital to a giant planet. Massless particles initially displaced in the whole co-orbital region were integrated for $7x10^5$ orbital periods of the giant planet. The initial positions of those particles that remained in the co-orbital region along the whole simulation determined the location and size of the stable region. A wide range of giant planet's mass was considered. The highest limiting mass value that allows stable horseshoe trajectories is found and the analysis of the results is divided into two blocks: tadpole and horseshoe stable regions. From the results of the tadpole regions were measured the minimum and maximum angular location, and the radial width around the triangular equilibrium points. In the case of the horseshoe regions are measured the minimum and maximum angular location, and the radial width around the equilibrium point L_3. All measurements generated empirical expressions as a function of the giant planet mass. Adopting the stable regions, simulations with massive particles whose collisions resulted in perfect merging were performed. The final outputs of such simulations generated larger co-orbital bodies that, in many cases, reached terrestrial planet masses.

318.10 — Possible 3D configurations of RV-detected extrasolar systems

Anne-Sophie Libert[1]; Mara Volpi[1]; Arnaud Roisin[1]
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Due to the limitations of the radial velocity technique, no indication on the spatial architecture of giant planetary systems can usually be given by the observations. We aim to constrain the 3D configuration of several RV-detected two-planet extrasolar systems. Through an analytical study based on a first-order secular Hamiltonian expansion and numerical explorations performed with a chaos detector, we identify ranges of values for the orbital inclinations and the mutual inclinations which ensure the long-term stability of the system. We find that long-term regular evolutions of 3D configurations exist for all the selected systems, either at low mutual inclinations, or at high mutual inclinations preferentially if the system is in the Lidov-Kozai resonance. A rapid destabilization of highly mutually inclined orbits is commonly observed, due to the significant chaos that develops around the stability islands of the Lidov-Kozai resonance. Finally, for planetary systems with close-in planets, we show how the relativistic effects influence the extent of the Lidov-Kozai resonance region.

318.11 — Cometary shape and spin-axis evolution due to long term solar driven outgassing

Yuhui Zhao[1]
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In this work we investigate the role of long term sublimation effects on reshaping the cometary nucleii using 3D shapes coupled with realistic spin-orbit evolution. We try to classify the typical morphological changes that can result from solar driven outgassing starting from various initial conditions. Our model includes different 3D shapes accounting for shadowing and self-heating, orbital elements, orientation parameters and CO sublimation driven cometary activity. These results will provide constraints on the limits pure sublimation activity can provide in terms of nucleus shape and large scale morphology changes during long term evolution of a small icy body in the Kuiper Belt. These simulations provide evidence that certain shape structures (such as observed on the 67P/CG) cannot be produced due to sublimation alone, indicating that other shape defining processes at work (e.g. Jutzi et al, 2017). Similarly, we investigate evolution of spin rates and axis orientations for different nuclei shapes.

318.12 — Transit and Radial velocity Interactive Fitting tool for Orbital analysis and N-body simulations: The Exo-Striker

Trifon Trifonov[1]
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I present a new very powerful and fast GUI tool for exoplanet orbital analysis and N-body simulations. It uses a brand new RV fitting library called "RVmod", which can model the stellar reflex motion caused by dynamically interacting planets in multi-planetary systems. The "Exo-Striker" tool offers a broad range of tools for detailed analysis of transit and Doppler data. Some of the key features of the tool are: – Period search via power spectrum analysis (GLS for RVs & TLS for transit data) – Keplerian and dynamical RV modeling of multi-planet systems – Transit, or joint Transit and RV modeling – Gaussian Processes modeling – Parameter optimization (Simplex, LM, TNC, Powell and many more) – MCMC (via emcee) and Nested sampling (via dynesty) – Long-term stability check of multi-planet systems – Fully interactive, high-quality, exportable plots ready for publication – Import/export of working sessions – Export of ready-to-use LaTeX tables with best-fit parameters, errors and statistics – Text editor, Bash-shell (Linux only) and a fully Integrated Jupyter shell – "RVmod" engine can be used as stand alone standard Python library (i.e. without the Exo-Striker GUI, simply as "import RVmod as rv") The tool is cross-platform compatible (works on MAC OS (10.6+), Linux (Suse, Mint, Ubuntu, etc.) and Windows 10), and it combines Fortran efficiency and Python flexibility. The "Exo-Striker" can be found on the "github" under https://github.com/3fon3fonov/trifon.

318.13 — Updates on the GPU N-body code GENGA and TTV calculations

Simon Lukas Grimm[1]
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We present updates on the N-body code GENGA. These include symplectic treatment of non-Newtonian forces for orbital dynamics, especially also for small bodies. We also present modifications of the hybrid symplectic integration scheme, which allows the integration of large close encounter groups. This is necessary when simulations of fully self graviting disk with 10'000 to 100'000 bodies are performed. It is also shown how GENGA is used to perform TTV analysis calculations.

318.14 — Comparison of machine learning techniques for emulating collisions in planet formation

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Collisions between planetary embryos are a fundamental agent of planet formation. However, the significant computational cost of simulating collisions, coupled with the high-dimensionality of the parameter space, has so far frustrated a comprehensive understanding of their role in planet and satellite formation. Indeed, only limited regions of the parameter space have been explored, with most studies focused on narrow problems in planetary science, such as the origin of Earth's moon (Benz et al. 1986) or Mercury's large core (Chau et al. 2018). Following the recent success of emulation techniques applied to high-dimensional problems in cosmology (Knabenhans et al. 2019) and ongoing attempts to classify and predict collision outcomes in planet formation (Cambioni et al. 2019, Valencia et al. 2019), we investigate the ability of different uncertainty quantification and machine learning techniques to accurately emulate pairwise collisions. In order to carry out this study, we have simulated an unprecedented set of 10,000 pairwise collisions. This dataset is an order-of-magnitude larger than any previous dataset used in similar studies and explores parameters largely overlooked in previous studies, such as the core mass, rotation rate, and orientation of the pre-impact bodies. In addition, we present preliminary results of N-body simulations using our emulation technique to predict collision outcomes on-the-fly.

318.15 — Comparing long-stability criteria of horseshoe coorbital planets

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Coorbital planets, should they exist, have the potential to provide new constraints on the early stages of planet formation and the subsequent dynamical evolution of systems. A number of recent numerical studies have analyzed possible transit signatures of coorbiting planets, as well as their stability. Searches have also been carried out using archival Kepler (Hippke & Angerhausen 2015; Janson et al. 2013) and radial velocity data (e.g., the TROY project, Lillo-Box et al. 2018a,b). A few candidate systems have been identified to have planets in a 1:1 MMR using follow ground-based observations, but so far there are no confirmed detections. Detecting coorbital planets, especially those in a horseshoe configuration, is challenging due to the semi-major axis exchange between the two planets, which occurs on timescales longer than the orbital period. A key factor in developing tools for coorbital searches or in confirming possible detections is the long-term stability of any given proposed coorbital. In this regard, different studies have shown using N-body simulations that coorbital configurations with zero eccentricity and planet-to-star mass ratio, i.e., $\mu=(m_1+m_2)/M_*$, between 2×10^{-6} to 2×10^{-3} can be stable for at least 10^{10} orbits. However, these simulations have only considered a constant timestep to integrate their realizations and might not be able to resolve the semi-major axis exchange of the coorbital planets. We explore the long-term stability of two-planet systems initially at conjuction, with planet-to-star mass ratios between $\mu=10^{-4}$ to 10^{-3} and initial planetary semi-major axis ratios from 1 to 1.065 using the 15th-order Integrator with Adaptive Time-Stepping (IAS15). We compare the results with those of Leleu et al. (2019), Cúk et al. (2012) and, Laughlin & Chambers (2002).

318.16 — Observable Predictions from Perturber-driven High-eccentricity Tidal Migration for Warm Jupiters

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The origin of hot Jupiters (Jupiter mass planets with periods less than 10 days) is an open question in exoplanet formation and evolution and has significant ramifications for exoplanet populations, system architecture, and early disk conditions. If we assume hot Jupiters migrated from larger semi-major axes, we can treat warm Jupiters (periods between 10 and 200 days) as intermediaries between newly formed gas giants and hot Jupiters. Warm Jupiters thus provide a test bed for assessing migration theories. Our new work investigates the validity of the perturber-modulated high-eccentricity tidal migration scenario, in which a migrating Jupiter is periodically secularly perturbed by a companion planet or star to an eccentricity large enough for its orbit to tidally shrink and circularize. We develop an observationally motivated population of warm Jupiters and assign a corresponding perturber capable of inducing precession faster than that of general relativity, a minimum requirement for this type of migration, to each planet. We then calculate the distributions of observational signals (transit timing variations, transit duration variations, radial velocities, and astrometry) these perturbers would produce and compare them to current and near future detection limits. We show that a small percentage of these perturbers are detectable within current observational limits by their transit timing variations and that many are detectable at the 1 m/s level in their radial velocities. With a longer time baseline, most of the perturbers would be detectable at the 10 m/s level. Most perturbers within 200 pc will be detectable by Gaia within the primary mission lifetime. If TESS RV followup and Gaia astrometry do not discover a significant number of massive companions in warm Jupiter systems, it may suggest this mechanism is not a common means of warm Jupiter production.

318.17 — High order regularised symplectic integrator for collisional planetary systems

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We present a new mixed variable symplectic (MVS) integrator for planetary systems, that fully resolve close encounters. The method is based on a time regularisation that allows keeping the stability properties of the symplectic integrators, while also reducing the effective step size whenever two planets encounter. We use a high order MVS scheme such that it is possible to integrate with large time steps far away from close encounters. We show that this algorithm is able to resolve almost exact collisions (i.e with a mutual separation of a fraction of the physical radius) while using the same time-step as in weakly perturbed problem such as the Solar System. We demonstrate the long term behaviour on systems of six super-Earths experiencing strong scattering for 50 kyr. We compare our algorithm to hybrid methods such as MERCURY and show that for an equivalent cost we obtain much better energy conservation.

318.18 — Can a hot Jupiter host exomoons?

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All the giant planets in the solar system host a large number of natural satellites. Moons in extrasolar systems are difficult to detect, but a Neptune-sized candidate exomoon has been recently found around a Jupiter-sized planet in the Kepler 1625 system. Of the many extrasolar Jupiters detected so far, about one-tenth lies on a short period orbit. Whether the hot Jupiter population can host (or may have hosted) exomoons is still unknown. We investigated if the presence of exoomons can allow the formation of hot Jupiters, and if the exomoon can survive the tidal migration process, by means of direct N-body simulations including tidal interactions. Here we consider the Kozai-Lidov secular interaction induced by a distant companion star as a means to trigger the high-eccentricity tidal migration process. Our results show that it is unlikely that a hot Jupiter can host exomoons, since the moon will either crash into the planet or escape from it during the migration process. In some extreme cases, perturbations from the stellar companion can trigger dynamical instabilities that lead to the ejection of the planet along with its moon. This mechanism can explain the exomoon candidate MOA-2011-BLG-262L, a candidate exomoon of a free-floating planet, and can explain the future detections of similar systems via microlensing events.

319 — Star-Planet Interactions and Tides, Poster Session

319.01 — How Stellar Flares and Storms Regulate Atmospheric Losses from the TRAPPIST-1 Planets

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Stellar flares have been observed to produce a burst of radiation over a wide range of wavelengths, among which X-rays and EUV constitute the major ionizing stellar radiation for planetary atmospheres at low and high altitudes, respectively. Stellar flares are considered an impediment to habitability, especially in the case of close-in exoplanets around M-dwarfs since these stars are highly active. At the same time, there has been a growing awareness that coronal mass ejections (CMEs) — sometimes termed as stellar storms — associated with stellar flares pose severe threats to planetary atmospheric retention. It is evident that understanding atmospheric escape is vital from the standpoint of habitability since atmospheric evolution influences the climate and the fluxes of ionizing radiation reaching the surface, among other factors.

Until now, there have been no systematic studies of the impact of stellar flares and associated storms on exoplanetary atmospheric losses despite their indubitable occurrence and pertinence. Here, we carry out sophisticated 3D MHD simulations (that includes important photochemistry) to assess how the atmospheric escape rates of the TRAPPIST-1 planets evolve during 1) a 10^{33} erg flare (based on observations) without a CME (where the CME may be suppressed or deviated from the planet) and, 2) a 10^{33} erg flare with a CME, where the CME is initialized and modeled according to the flare energy by using a stellar wind model. We found that the atmospheric escape rates are enhanced by 1-3 orders of magnitude compared to our previous study that used normal stellar wind conditions. For the outmost TRAPPIST-1h, if such flares occur at a frequency of $\sim$1 per day, a 1-bar atmosphere will be scavenged on the time scale of $\sim$ 100 million years. This time scale reduces to $\sim$ 1 million years for the innermost TRAPPIST-1b. This represents the first study where the roles of stellar flares and storms on exoplanetary atmospheric escape for the TRAPPIST-1 planets are clearly elucidated. The new results obtained herein would be of considerable interest to a wide audience and thus deserving an oral presentation.

319.03 — Magnetospheres of the TRAPPIST-1 planets

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The number of exoplanets in the habitable zone of M dwarfs has increased in the last few years thanks to ground-based observatories and space telescopes. M dwarfs are among the most active stars producing frequent and strong flares, strong stellar wind and high energy radiation. The habitability of these worlds strongly depends on their capability of retaining their atmospheres. Planetary magnetospheres play a crucial role in reducing atmospheric loss and thus providing a potentially habitable enviroment. The M dwarf star TRAPPIST-1 is of particular interest because it hosts three Earth-sized rocky planets in its habitale zone. We calculated the magnetic properties of these planets, such as the suface dipolar field strength and magnetic dipole moment, using a method based on the example of the early Earth, which assumes a process involving the exsolution of MgO as the source of the planetary dynamo. In order to follow the evolution of these properties, we applied a thermal evolution model for the TRAPPIST-1 planets. The sizes of the magnetospheres, described by the magnetoshperic standoff distance (i.e. the distance from the planet to the point where the stellar wind is balanced by the planetary magnetic field), were derived using previously modeled stellar wind parameters. Additionally, we calculated the polar cap area, which indicates the fraction of a planet's surface where magnetic field lines are open and atmosperic escape is possible. Based on our results, we will estimate the atmospheric mass loss, which can significantly limit habitability on the planets.

319.04 — It's raining hot Jupiters: 3D MHD simulations of planetary atmospheric escape

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We present 3D MHD simulations of the wind-wind interactions that occur between a solar-type star and a short period hot Jupiter exoplanet. A planetary outflow results from atmospheric escape induced by the host stars incident radiation. Circumstellar and circumplanetary material which accretes onto the stellar surface in a form of coronal rain, we characterise this interaction for a representative hot Jupiter hosting system and predict the accretion point, size and extent. The nature of this accretion is variable in both location and rate, with the final accretion point occurring at 133 degrees west and 53 degrees east of the subplanetary point. The size of the accretion spot itself has been found to vary with a period of 67 ks (approximately 1/5 of the orbital period). The results are highly dependent on the magnetic fields of both the star and the planet and on the atmospheric conditions of the hot Jupiter. We characterise this behaviour as Star-Planet-Wind Interaction (SPWI).

319.05 — Interactions of tidal flows and convection: frequency dependence and indications of anti-dissipation

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A key mechanism in the orbital and spin evolution of close proximity bodies is the dissipation caused by the interactions of tidal flows with convection. It is expected that the effective viscosity of this interaction (ν_E) would depend on the tidal frequency (ω) but to what extent is a matter of debate, particularly in the regime of fast tides (e.g. Zahn 1966; Goldreich and Nicholson 1977). It is essential to resolve this in order to correctly predict the tidal evolution of hot Jupiters. We have performed the most comprehensive investigation to date of this mechanism by way of hydrodynamical simulations and extensions to existing theory, building upon prior work by Penev et al. 2009 and Ogilvie and Lesur 2012. Our results provide a clear scaling law for the dependence of the effective viscosity on tidal frequency and also convincing evidence which suggests that this mechanism can operate as anti-dissipation (which could result in outward migration or excitation of eccentricities, contrary to prior expectations). These results can help guide the correct implementation of tidal dissipation for planet-star interactions. We will also discuss the consequences of our results for the orbital decay of hot Jupiters.

319.06 — Measurements of the Ultraviolet Spectral Characteristics of Low-mass Exoplanetary Systems (Mega-MUSCLES)

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M dwarf stars have emerged as ideal targets for exoplanet observations. Their small radii aids planetary discovery, their close-in habitable zones allow short observing campaigns, and their red spectra provide opportunities for transit spectroscopy with JWST. The potential of M dwarfs has been underlined by the discovery of remarkable systems such as the seven Earth-sized planets orbiting TRAPPIST-1 and the habitable-zone planet around the closest star to the Sun.

However, to accurately assess the conditions in these systems requires a firm understanding of how M dwarfs differ from the Sun, beyond just their smaller size and mass. Of particular importance are the time-variable, high-energy ultraviolet and x-ray regions of the M dwarf spectral energy distribution (SED), which can influence the chemistry and lifetime of exoplanet atmospheres, as well as their surface radiation environments.

The Measurements of the Ultraviolet Spectral Characteristics of Low-mass Exoplanetary Systems (Mega-MUSCLES) Treasury project, together with the precursor MUSCLES project, aims to produce full SEDs of a representative sample of M dwarfs, covering a wide range of stellar mass, age, and planetary system architecture. We have obtained x-ray and ultraviolet data for 13 stars using the Hubble, Chandra and XMM space telescopes, along with ground-based data in the optical and state-of-the-art DEM modelling to fill in the unobservable extreme ultraviolet regions. Our completed SEDs will be available as a community resource, with the aim that a close MUSCLES analogue should exist for most M dwarfs of interest.

In this presentation I will overview the Mega-MUSCLES project, describing our choice of targets, observation strategy and SED production methodology. I will also discuss notable targets such as the TRAPPIST-1 host star, comparing our observations with previous data and model predictions. Finally, I will present an exciting by-product of the Mega-MUSCLES project: time-resolved ultraviolet spectroscopy of stellar flares at multiple targets, spanning a range of stellar types, ages and flare energies.

319.07 — Eating Planets for Breakfast, Lunch, and Dinner: Signatures of Planetary Engulfment at all Phases of Stellar Evolution

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Most, if not all, TESS target stars can be expected to reside in binaries, as these stars are more massive than the Sun. Gravitational perturbations from a companion can drive a planet closer to its host star, potentially plunging the planet all the way into the star. While it is challenging to observe a planet during its plunge, we have predicted that, prior to its demise, such a planet will appear as hot as a Hot Jupiter (Stephan et al. 2018). This new class of 'Temporary Hot Jupiters' has recently been confirmed by TESS observations (e.g., HD 202772A b). As the planet is eventually eaten, it can impart distinct signatures onto the star. We follow the engulfment of planets by their host stars during different stellar life phases and calculate the changes in stellar parameters, such as stellar spin or luminosity, caused by this process. Our predictions for the observable signatures of these engulfment events will enable future and current endeavors to find post-engulfment stars, thus, advancing our understanding of planetary system architectures and dynamical evolution.

319.08 — Impact of Stellar Magnetism on Star-planet Tidal Interactions

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Over the last two decades, about 4000 exoplanets have been discovered around low-mass stars. For the shortest period exoplanets, star-planet tidal interactions are likely to have played a major role in the ultimate orbital evolution and on the spin axis evolution of the host stars. Although low-mass stars are magnetically active objects, the question of how the star's magnetic field impacts the excitation, propagation and dissipation of tidal waves remains open.

In this work, we have derived the magnetic contribution to the tidal force and estimated its amplitude all along the structural and rotational evolutions of low-mass stars (from M to F-type). For this purpose, we have used detailed grids of rotating stellar models computed with the stellar evolution code STAREVOL. The amplitude of dynamo-generated magnetic fields is estimated via physical scaling laws at the base and the top of the convective envelope. We find that the star's magnetic field has little influence on the excitation of tidal waves in near circular and coplanar Hot-Jupiter systems, but that it has a major impact on the waves dissipation. Our results therefore indicate that a full MHD treatment of the propagation and dissipation of tidal waves is needed to assess the impact of star-planet tidal interactions for all low-mass stars along their evolution.

319.09 — Magnetic fields of hot Jupiters calculated from star-planet interactions

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Planetary magnetic fields have a critical impact on atmospheric physics, damping winds on hot, short-period planets and potentially creating the necessary conditions for habitability on temperate terrestrial worlds by deflecting stellar wind particles. Despite their importance, exoplanet magnetic field detections remain elusive. For the first time, we report the derivation of the magnetic fields of a sample of hot Jupiters using flux-calibrated signals of magnetic star-planet interactions (SPI). We find that the surface magnetic field values for the hot Jupiters in our sample range from 20 G to 120 G, 10 - 50 times larger than the values predicted by pure dynamo theories for planets with rotation periods of 2 to 4 days. Such large field strengths should have severe consequences for velocity flows in the planets' atmospheres and exhibit peak frequencies of electron-cyclotron emission in the range of facilities such as LOFAR.

319.10 — Exploring the Stellar CME-flare Relation: from Historic Events' Analysis to Stellar Activity Modeling

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A crucial aspect of habitability is the space environment of the planet, which can be extreme and violent for short-orbit planets or planets orbiting active M-dwarfs. CMEs, flares and energetic particles are the most dramatic stellar activity events. How the stored magnetic energy gets distributed between these different energetic coronal phenomena remains a vital field of research. In the Sun, more energetic solar X-ray flares are associated with faster and more massive CMEs (e.g. Drake et al 2013). While highly energetic flares are continuously observed in active stars, such as M-dwarfs, no stellar CME has been definitively observed yet (e.g. Crosley & Osten 2018). In this presentation we discuss our most recent unpublished results (paper accepted by ApJ) on the stellar CME-flare relation by examining the most probable historic CME candidates, all of which were observed on magnetically active stars. We use the CME cone model to infer masses and kinetic energies from observed quantities, and convert the associated emission to the GOES 1–8 Å band. When the inferred CME masses, found in the range $\sim 10^{15}$ to 10^{22} g, are presented as a function of associated flare energy they lie on the solar extrapolated trend. The kinetic energies, found in the 10^{31} to 10^{37} erg, however, lie below the extrapolated relation used on solar events. This is an indication that in the stellar regime there is an energy partition between flare X-ray and CME kinetic energies, contrary to the solar case where X-ray flares have 100 times less energy than their associated CMEs. A possible mechanism responsible for constraining the CME speeds more than their masses is the effect of strong large-scale overlying magnetic fields. Stellar CME with lower kinetic energies present an optimistic scenario for the impact of mass ejecta on close in exoplanets relative to their stellar hosts.

319.11 — Precise characterisation of the 55 Cnc and HD219134 transiting exoplanetary systems

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The harvest of exoplanets detection has led to the quest of their characterisation. In particular, the determination of exoplanet masses, radii and densities is mandatory to derive their bulk composition, itself related to their formation and potential habitability. However, these parameters totally rely on their host star parameters. Indeed, the transit method (resp. radial velocity measurements) provide the ratio of planetary to stellar radius (resp. mass). When both methods can be applied to a system, then the planetary density can be obtained. Unfortunately, most of transiting exoplanets hosts are too faint for their mass and radius to be accurately determined, leading to approximate or imprecise parameters. We will present two systems that host transiting exoplanets, 55 Cnc and HD219134. Since the stars are bright, we performed interferometric observations to measure their angular diameter, leading to accurate radii R. Using the transit light curves, we also directly derive their density. We thus obtain an independent measurement of their mass M. More precisely, we computed the joint probability density function of these parameters, and the correlation between R and M. This allows to derive the planetary parameters, independently from any stellar evolution model. Using the R-M correlation, the planetary density can be refined, and subsequently the internal composition of the transiting exoplanets. Contrary to what previous studies claim, the transiting exoplanet 55 Cnc e may only have a thin atmosphere and its interior structure might not be dominated by carbon. The system of HD219134 hosts two transiting exoplanets of similar properties, but HD210134 b shows a higher density while smaller radius and mass than HD219134 c. This could be explained by a molten interior possibly induced by tidal heating caused by a high eccentricity during its formation. Those systems are benchmarks to investigate both exoplanet and stellar properties in detail thanks to our method that provides the best characterisation of these systems so far. It will be generalised with the coming bright TESS and PLATO targets.

319.12 — Evryscope & K2 Constraints on TRAPPIST-1 Superflare Occurrence and Planetary Habitability

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TRAPPIST-1 is an ultracool dwarf (UCD) of spectral type M8V with seven terrestrial planets, three of which have equilibrium temperatures that may sustain surface liquid water. The TRAPPIST-1 system is a compelling target for habitability studies. However, like many UCDs, TRAPPIST-1 frequently erupts in flares. High-energy flares can deplete or even destroy the ozone column of exoplanetary atmospheres, allowing ultraviolet radiation and high-energy particles to bombard the planet's surface. Thus, detailed knowledge of TRAPPIST-1's flare rate is important for studies of the system's habitability. The Evryscope at CTIO observes the entire southern sky at two-minute cadence, and is thus especially well suited to characterize the occurrence rate of superflares—flares of energy $\geq 10^{33}$ erg—for ultracool dwarves such as TRAPPIST-1. We combine Evryscope observations with *Kepler* observations to constrain the high-energy flare rate of TRAPPIST-1. The Evryscope complements short-cadence K2 data by providing data on TRAPPIST-1's long-term average activity. Although no flares were confirmed in Evryscope data, we calculate the minimum detectable flare energy for TRAPPIST-1 with Evryscope, and thereby recompute the flare frequency distribution (FFD) of TRAPPIST-1 using flares observed by K2 and non-detections of high-energy flares from Evryscope. We place new constraints on the high-energy flare rate for TRAPPIST-1, finding that the annual superflare rate is expected to be $13.4^{+3.3}{}_{-0.3}$ per year. Converting bolometric flare energy to energy emitted in the biologically relevant UV-B bandpass and comparing to early-Earth UV-B insolation, we find the top-of-atmosphere UV-B flux at each TRAPPIST-1 planet due to high-energy flares is insufficient to rule out life, assuming intact atmospheres. We further analyze the impact of TRAPPIST-1's flare rate on pre-biotic chemistry and ozone depletion. Our preliminary results do not rule

out habitability for TRAPPIST-1's planets.

319.13 — Star-planet tidal interactions in the WASP-12 system

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To date, the exoplanet WASP-12 b is the only hot Jupiter for which the shortening of its orbital period was detected. A mechanism that drives this orbital decay remains a puzzle. Equilibrium stellar tides were found to be too weak to explain the observed rate of inspiral and dynamical stellar tides or planetary obliquity tides have been considered. Using the new radial velocity (RV) measurements, we show that the orbital eccentricity of WASP-12 b is non-zero at a 5-σ level, and the longitude of pericentre of this apparently eccentric orbit is close to -90 degrees. This orbital configuration is compatible with a solution containing a circular orbit and an RV signal induced by the tidal fluid flow in the star. The amplitude of the RV tides was found to be consistent with a value calculated using the equilibrium tide approximation. We expect that further precise RV measurements will allow us to refine the phase lag of the stellar tides.

319.14 — Chaotic Dynamical Tides in Eccentric Gas Giants and Hot Jupiter Formation

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High-eccentricity (high-*e*) migration is an important channel for the formation of hot Jupiters (HJs). In this scenario, a giant planet is excited onto a very eccentric orbit that decays and circularizes on Gyr timescales due to tidal effects. Previous studies of high-*e* migration have used parameterized treatments of weak tidal friction and overlooked critical contributions from dynamical tides. These earlier works have suggested that high-*e* migration can reproduce multiple features of the observed HJ population (e.g. a pile-up at a few Roche-radii and the lack of planetary companions), but that it struggles to explain the frequency of observed HJs without assuming that young gas giants are many times as dissipative as Jupiter. We demonstrate that the inclusion of chaotic dynamical tides can help resolve this issue. In particular, we focus on high-*e* migration due to Lidov–Kozai (LK) oscillations of orbital eccentricity/inclination induced by a distant planetary or stellar companion. When the planet's orbit is in a high-eccentricity phase, the tidal force from the star excites oscillatory f-modes and i-modes in the planet. For sufficiently large eccentricity and small pericenter distance, the modes can grow chaotically over multiple pericenter passages and eventually dissipate non-linearly, drawing energy from the orbit and rapidly shrinking the semimajor axis. We study the effect of such chaotic tides on the planet's orbital evolution. We find that this pathway produces very eccentric ($e > 0.9$) warm Jupiters (WJs) on short time-scales (a few to 100 Myr). These WJs efficiently circularize to become HJs due to their persistently small pericenter distances. Chaotic tides can also save some planets from tidal disruption by truncating LK eccentricity oscillations, significantly increasing the HJ formation fraction for a range of planet masses and radii. Chaotic tides endow LK migration and other flavors of high-*e* migration with several favorable features to explain observations of HJs.

319.15 — 3D hydrodynamic simulations of the planetary system GJ436: constraining the planetary wind parameters through spectroscopic observations.

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GJ436b was the first detection of atmospheric escape from a warm-Neptune around an M-dwarf. The extreme absorption observed in the Ly-α line during transit indicates the existence of a very long tail of planetary neutral material trailing the planet, not being completely swept by the interaction with the stellar wind. Previous work based on particle simulations (Bourrier et al. 2016, 2015; Ehrenreich et al. 2015) have shown that the Ly-α absorption profile can be reproduce with a high planetary wind velocity (50-70 km/s) and a very low stellar wind velocity and temperature (80 km/s and $2{\times}10^3$ K). As GJ436b lies in the edge of the sub-Jovian desert, the characterisation of the stellar and planetary wind parameters will help to understand the process involved in the erosion of the planetary atmosphere, and will give us a hint on the possibles scenarios that lead to the formation of such desert. In this talk we will present the unpublished results of the first 3D hydrodynamics simulations of GJ436 planetary system. These simulations take into account the stellar and planetary wind interaction and include the process of charge-exchange, radiation pressure and photoionization. With the output of the simulations we can compute synthetic Ly-α transit profiles that we compare with the observations. We will show that observed absorption profiles in Ly-α can be reproduced in a hydrodynamic scenario where the interaction of both winds forms a shock ahead of the planet. We will also show the constrained parameters obtained for the planetary wind and the influence that charge-exchange and radiation pressure have on the escaping planetary material. The new derived values are not in agreement with the ones presented in the work of Bourrier et al. (2016), showing that the observations in Ly-α alone can not be used to constrain the planetary wind parameters. In this sense, we also explore synthetic observations of the H-α line during transit.

320 — Disk-Planet Interactions and Migration Theory

320.01 — The 4:7 resonant population and a dilemma of the inclination distribution in the Kuiper belt

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The 4:7 mean motion resonance (MMR) locates at the heart of the classical Kuiper belt, it can provide unprecedented clues about the history of planet migration. By making use of a semi-analytical model based on the simplified disturbing function, we would supply new insights into the dynamics of the 4:7 MMR. For this high-order resonance, there are two different modes: (1) The first one is the eccentricity-type resonance, inside which the peculiar eccentricity and inclination distribution of the resonators could be perfectly constrained by a theoretical limiting curve. Accordingly, a survey strategy of the highly inclined components is proposed; (2) The second one is only associated to the high-inclination resonators, while the number ratio of simulated to observed samples raises a dilemma of the inclination distribution of the primordial Kuiper belt objects.

320.02 — Early-phase simulations of circumplanetary disk formation

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Regular moons such as Galileans are thought to form in gaseous disks around gas giant planets. Studying the gas flow into the vicinity of planets is important not only to learn the formation of planetary atmospheres but also to discuss satellite formation. Gas around a sufficiently massive planet is thought to form a circumplanetary disk instead of falling directly onto the planet. Recent studies, however, have shown that the circumplanetary gas forms an expanded envelope rather than a thin, rotationally supported Keplerian disk in cases where the gas temperature is very high. Thus, calculating the temperature of the accretion flow properly is important to determine the disk structure. We performed three-dimensional radiation hydrodynamic simulations of the formation of circumplanetary disks with an equation of states that considers effects such as hydrogen dissociation and helium and hydrogen ionization. The region within the deep potential of the planet reached very high temperature, yet, we observe a disk to form in our simulations.

320.03 — Debris Disks in Multi-Planet Systems: Are Our Inferences Compromised by Unseen Planets?

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Resolved debris disk structures (e.g., warps, offsets, edges and gaps, azimuthal asymmetries, thickened rings, scale heights) contain valuable information about the underlying planetary systems, such as the posited planet's mass, semi-major axis, and other orbital parameters. Most existing models assume a single planet is sculpting the disk feature, but recent observations of mature planetary systems (e.g., by radial velocity surveys or *Kepler*) have revealed that many planets reside in multi-planet systems. Here we investigate if/how planet properties inferred from single-planet models are compromised when multiple planets reside in the system. For each disk feature, we build a two-planet model that includes a planet b with fixed parameters and a planet c with a full range of possible parameters. We investigate these two-planet systems and summarize the configurations for which assuming a single planet (i.e., planet b) leads to significantly flawed inferences of that planet's properties. We find that although disk features are usually primarily dominated by a single planet, when using single-planet models we are at risk of misinterpreting planet properties by orders of magnitude in extreme cases. Specifically, we are at high risk of misinterpreting planet properties for the warp feature; at moderate risk for the edge and gap feature, the thickened ring feature, and the scale height feature; and at low risk for the offset feature and the azimuthal asymmetry feature.

320.04 — It can be hard to become a Gas Giant: 3D Radiation Hydro Simulations of Circumplanetary Envelopes

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Why do find so many 10 M_{earth} planets in the universe close to their host star? What prevented them from going into runaway gas accretion? Here we present long-term monitoring simulations of planetary cores interacting with the nebula gas. We measure the mass, entropy, heat and radiation flux across the Hill Sphere and across sub-shells of the Hill Sphere to high precision. We investigate cores of 5, 10 and 30 Earth masses. We find the Hill Sphere to be highly turbulent. This seems to be a result of the interaction with the Keplerian Sheer into which the core is embedded. The dissipation of kinetic energy leads to a luminosity from the Hill Sphere that can prevent any net accretion of gas from the solar nebula for a wide range of planet masses and locations. This finding helps to understand the survival of super-Earth planets close to their host star.

320.05 — How flat can a planetary system get? The case of TRAPPIST-1.

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The seven planets orbiting the M dwarf TRAPPIST-1 in a compact near-resonant chain offer a unique case to study in planet formation theory. Of particular interest is the remarkable flatness of the system, exceeding that of any other known planetary system. We use 3D hydrodynamic simulations to study interactions between the planets and the gaseous disk in which they formed. We demonstrate with these simulations that the system's flatness is an important constraint on the formation of the system, and can be used to place an upper bound on the mass of the disk. This result favors models for the formation of the TRAPPIST-1 system that do not require very massive disks, such as that proposed by Ormel et al. (2017), and disfavors models that require more massive disks, such as in situ formation and certain models of long-range migration.

320.06 — A young planetary system modified by a near-coplanar stellar flyby

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Close stellar encounters have the potential to significantly alter the architecture of planetary systems. Stars passing close to our solar system have been invoked to explain the formation of the Oort cloud, comet showers, the disruption of the Kuiper Belt, and the distant detached orbits of dwarf planets such as 90377 Sedna, as well as the hypothetical Planet Nine. Such stellar flybys have also been invoked to explain the orbital properties of extrasolar planets. However, direct empirical evidence for these hypothetical encounters is lacking.

Here we show that the 15 Myr-old planet-hosting binary star HD 106906 underwent a close stellar encounter that can explain the system's current architecture. Using the exquisite precision of ESA's Gaia satellite for measuring stellar motions we have discovered a pair of external stellar perturbers that approached within 1 pc of the HD 106906 system in a flyby geometry that is coplanar with the observed, highly asymmetric circumbinary disk. This flyby is consistent with the scenario that the massive planet HD 106906 b formed in a disk near the binary star, was ejected from the inner system through interactions with the eccentric binary, and was subsequently stabilized onto its current wide orbit (~740 au) by the perturbations of the passing stars.

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321 — Interior Structure Modeling, Poster Session

321.01 — Modeling the evolution of ice-rich planets

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Ice-rich bodies in the Solar System and beyond are of great interest to the pursuit of extraterrestrial life and present a challenge to our understanding of the formation and evolution of planetary systems. If formed at the outskirts of the planetary disk, they must have grown slowly, by accretion of planetesimals, without extended atmospheres. Among the hundred and more rocky exoplanets recently discovered in planetary systems, a fraction must be of similar ice-rich composition and structure. By means of a numerical code, we follow continuously the long-term growth of a planet by accretion of ice-rich material, as well as its subsequent evolution up to present time. The assumed composition includes silicate rock and ice in a compressed or porous structure, depending on local pressure. We use a second-order Birch-Murnaghan equation of state, with an adaptive coefficient, depending on the total mass of the planet, and include radiogenic heating, latent heat and gravitational potential energy in the energy balance equation. We allow for flow of water through the pores.

Two cases are discussed, for two different accretion rates. The typical structure that develops during the long-term evolution is an ice-depleted core, a liquid-filled middle layer (where saturation is almost unity and temperatures are in the liquid water range), and a top ice-rich cold layer. The outer layer is porous, with porosity increasing from close to zero at the lower boundary, to almost 0.6 near the surface. During the accretion phase, the surface temperature rises well above the local equilibrium temperature, allowing the planet to cool, but also allowing sublimation of some of the accreted ice. Hence, in the final model, the ice/rock ratio varies widely throughout the planet, and is different from the ratio assumed for the accreted material. In conclusion, we show that the emerging structure of such a planet, grown from a small embryo, should be differentiated at the end of a 1-2 Gyr accretion phase, with an ice-depleted rocky core, an intermediate region filled with liquid water and an outer ice-rich layer.

321.02 — Hot and Steamy, Cold and Icy, or Temperate and Habitable: Modeling the Early Evolution of Water World Exoplanets

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Waterworlds are water-rich (>1% water by mass) exoplanets that never attained masses sufficient to accrete or retain large amounts of H/He nebular gas. Waterworlds are especially timely given the discovery and characterization of the TRAPPIST-1 planetary system, which hosts several planets that may contain several percents to several tens of percent of water by mass.

To date, studies of the interior structure of waterworld exoplanets have either assumed that the planets are cold and icy (with interiors structures similar to scaled-up versions of Jupiter's moon Ganymede) or that the planets are hot and steamy (with most of their water in extended envelopes of supercritical steam). Models have not yet demonstrated the evolution of waterworlds from an initial post-accretion hot and steamy state to habitable and temperate conditions (with surface or subsurface water oceans).

We have performed the most detailed calculations to date of the post-accretional thermal evolution of waterworlds with pure water envelopes. We account for the condensation of liquid water and high-pressure ices as the planets cool, along with the temperature dependence of water opacities in the infrared and visible. In this presentation, we will delineate the regions of the parameter space (orbital separation, planet mass, radius, and water envelope mass) wherein waterworlds are likely to be hot and steamy, cold and icy, and temperate and (potentially) habitable.

Our results have important implications for both the habitability of waterworlds and its observable characteristics — i.e. the apparent transit radius, mean planet density, and atmospheric spectra.

321.03 — How magmatic degassing of C, O, and H affects Earth's early atmosphere

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The build-up of the Earth's early atmosphere is a key point to investigate the planet's evolution and potential habitability. In this research we investigate the volcanic outgassing of C, O, and H and the related development of the atmosphere using the equilibrium and mass balance method for volatile speciation. We estimate the outgassing process soon after the magma ocean crystallization, simulating both magma production and lithostatic pressure effect on volatile solubility. Considering the volume of melt produced, we calculate the composition and pressure variation in the accumulated outgassed atmosphere during the early Earth's evolution. Our results indicate that the outgassed chemical composition is mainly affected by the oxidation state of the mantle and by the pressure dependence on the volatile solubility. The early Earth history was characterized by core-mantle segregation. During this process, the oxidation state of the mantle evolved from an initially reduced state to the more oxidizing present-day value. The different melt redox states would have affected the evolution and chemical composition of the early Earth atmosphere. The volatile species vary from H_2 and CO in reducing state to H_2O and CO_2 in oxidizing conditions similar to present days. We find that both chemical and pressure variations of the atmosphere are directly linked to the evolution of the mantle. The abundances of the outgassed species are also affected by the different solubility of the volatiles. Considering the pressure increase of magmatic reservoirs due to formation of the overlying crust, the outgassed volatile species change according to their different solubility, influencing the degassing process and thus atmosphere composition. Furthermore, planetary mass and radius may affect melt production and atmospheric thickness. The coupling of the volatile speciation to the melt production suggests that this technique is useful to describe the early Earth evolution but it has also the potential to investigate the habitability of planets other than the Earth including rocky exoplanets.

321.04 — The Limits on Interior Pressures and Temperatures of Likely Super Earths

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The interior composition of structure, composition, and dynamics of exoplanetary Super Earths are not observable. Recently described observational trends suggest that rocky exoplanets, that is, planets without significant volatile envelopes, are likely limited to ≤1.5 Earth radii. This likely upper limit in the radii of purely-rocky Super-Earth exoplanets, the maximum expected core-mantle boundary pressure and adiabatic temperature is relatively moderate, 630 GPa and 5000 K, while the maximum central core pressure varies between 1.5 and 2.5 TPa. We further find that for planets with radii less than 1.5 Earth radii, core-mantle boundary pressure and adiabatic temperature are mostly a function of planet radius and insensitive to planet structure. The pressures and temperatures of rocky exoplanet interiors, then, are less than those explored in recent shock-compression experiments, ab-initio calculations, and planetary dynamical studies. We further show that the extrapolation of relevant equations of state does not introduce significant uncertainties in the structural models of these planets. Mass-radius models are more sensitive to bulk composition than any uncertainty in the equation of state, even when extrapolated to TPa pressures.

321.05 — On the Concept of Multi-Stable Tectonic States: The Un/Inevitability of Plate Tectonics

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With the plethora of recently discovered exoplanets, it is a natural question to consider how many of these bodies could operate within a plate tectonic regime, and host life, as we observe for the Earth. However, our understanding of Earth's evolution is far from complete. Geologic evidence suggests that plate tectonics may not have operated on the early Earth, with both the timing of onset and the length of activity far from certain. Uncertainty about the initiation of plate tectonics, and the initial tectonic state for Earth has been extended to extra-solar planets. It is an open question of whether terrestrial planets larger and more massive than Earth are more or less likely to have plate tectonics, with groups arguing that a single plate regime should be favoured, while others argue that plate tectonics should dominate. Recently, tectonic bi-stability (multiple stable, energetically allowed solutions) has been shown to be dynamically viable, both from analytical analysis and through numeric experiments in two and three dimensions. From scaling analysis, high-temperature planets with a large contribution from internal heating (radiogenics or tidal sources) will operate in different velocity-stress scaling regimes compared to cooler-temperature planets that may have a larger relative contribution from core heating. Thus, differences in predictions for plate tectonics on exoplanets may in part result from different model assumptions being more appropriate to different times in the evolution of a terrestrial-type planet. This indicates that multiple tectonic modes may operate on a single planetary body at different times within its temporal evolution. It can then be shown that identical planets at similar stages of their evolution may exhibit different tectonic regimes due to random fluctuations. We will discuss a new framework of planetary evolution that is based on general physical principals, as opposed to particular rheologies, that further incorporates the potential of tectonic regime transitions and multiple tectonic-state viability at equivalent physical and chemical conditions.

321.06 — New Giant Planet Physics from Statistical Population Models

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The dramatic rise in the number of well-characterized giant exoplanets has enabled a powerful approach to understanding their physics: combining detailed physical models with statistical population models to infer their physical properties. Here I will present two new results from this approach. The first is that hot Jupiters quickly reinflate in response to their parent stars brightening on the main sequence. This reinflation can only occur this rapidly if the inflationary mechanism is depositing heat below the radiative-convective boundary (RCB) of the planet's atmosphere. Thus delayed cooling mechanisms are ruled out, as is our present understanding of Ohmic dissipation, which relies heavily on the insulating effects of shallowly deposited heat. The second key result is that in order to explain their radii, the interior entropies of hot Jupiters must be so high that the RCB will be pushed up to much lower pressures than previously appreciated. A typical hot Jupiter will have its RCB at around ten bars, rather than the hundreds of bars to 1 kbar usually considered. This has important implications for atmosphere modelling, including 3D general circulation models, 1D models used for analyzing spectroscopic data, and cloud models that rely heavily on an understanding of cold traps and vertical mixing.

322 — Planets around Young Stars, Poster Session

322.01 — Search for Hα from accreting protoplanets with Subaru/SCExAO+VAMPIRES

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The Visible Aperture Masking Polarimetric Interferometer for Resolving Exoplanetary Signatures (VAMPIRES) has newly started operation with Subaru/SCExAO. This instrument enables variety of imaging modes of polarization differential imaging (PDI), aperture masking, and spectral differential imaging with a Hα filter (SDI). The main purpose of the instrument is high-resolution imaging of circumstellar disks but the Hα SDI mode can provide another aspect of high-contrast imaging; accretion signatures. As reported accreting protoplanet candidates around LkCa 15 or PDS 70 hydrogen emissions from protoplanets will directly benefit discussion of planet formation mechanisms. We introduce Hα high-contrast imaging observation and reduction schematics in the presentation.

322.02 — Formation and atmospheric constraints of the youngest hot Jupiter.

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The last three years have ushered in the era of young exoplanets. Despite young stars exhibiting extreme levels of variability, a handful of newly formed exoplanets have been detected through transits and radial velocity. We will present the latest results from our young planet survey. For the first time, using high-resolution infrared spectra, we have a direct detection of CO in the atmosphere of the youngest exoplanet CI Tau b, confirming the planet, and providing evidence for a hot start mechanism. Our discovery shows that hot Jupiters either form incredibly close to their parent star, or, that migration occurs within the first 2 Myr.

322.03 — The nature of a low-mass companion in an edge-on protoplanetary disk system

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We report on the properties of the low-mass companion to the Ophiuchus young stellar object SSTc2dJ162221.0-230402. The companion is projected at 130 AU separation along the plane of the primary star's edge-on protoplanetary disk seen in Hubble Space Telescope images. Optical and near-IR photometry from HST and Keck show that the companion spectral energy distribution is very similar to the young brown dwarf GQ Lup B but with 10× less luminosity. Narrowband HST images show that the companion has strong Hα emission. The companion is also detected as an unresolved source by ALMA in 1.3 mm dust continuum, consistent with only ∼0.01 M_{jup} of surrounding material if the emission is optically thin. While this set of results is consistent with an accreting planetary mass companion, recent analysis of our HST grism and Keck OSIRIS K-band spectra indicate a mid- to late- M spectral type. The latter implies a strongly underluminous object just below the hydrogen burning limit, perhaps seen indirectly via scattered light from its own edge-on disk. Ways to confirm this scenario and its implications for the system properties will be discussed.

322.05 — Spectroscopic search for circumplanetary material during the Beta Pictoris b Hill Sphere transit

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During 2017-2018, the Hill sphere of the directly imaged planet Beta Pictoris b transited its stellar host. This provided a unique opportunity to probe the gas and dust in the circumplanetary environment of a young, recently formed gas-giant planet. We present the results from a high-resolution monitoring campaign with the UVES spectrograph (R∼100,000) at the VLT. Over the course of 160 epochs distributed across one year we obtained observations of both the Hill sphere transit and an out-of-transit baseline. This cadence is more than sufficient to detect ring crossings as well as monitor any variations in gas absorption along the line of sight, in particular in the Ca H & K lines, where there are also signs of the circumstellar gas and exocomets. In addition, this unique dataset provides strong constraints on the presence of transiting giant planets on short (<200 day) orbital periods.

322.06 — Results from the Beta Pictoris b Hill Sphere Transit Campaign

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Beta Pictoris b is the only extrasolar gas giant planet that has been directly imaged and has an edge-on orbit that causes the planet's Hill sphere to transit approximately every 22 years. Based on multi-epoch direct imaging observations from the Gemini Planet Imager, the Hill sphere began transiting in April 2017, with closest approach to within 20% of the 1.2au Hill sphere radius in August 2017.

We present the results from the combined space and ground based photometric campaigns that cover the entirety of the Hill sphere transit during 2017 and the first half of 2018, to search for signs of circumplanetary dust and rings. These include a dedicated monitoring instrument in South Africa and Australia (the bRing project), the BRITE-Constellation nanosatellites, two telescopes in Antarctica (ASTEP and AST3) and HST/COS data.

322.07 — Mass Limits and Helium Variability for Young Transiting Planets in the Hyades with the Habitable-Zone Planet Finder

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While the demography of old planetary systems can inform models of their formation and evolutionary pathways, the characterization of young planets and their host stars is needed to directly trace the evolution of planetary atmospheres and orbits. Recently, the K2 mission has discovered many young planetary systems in star clusters, where it is easiest to characterize the host star's age, distance, and metallicity. While transits yield radius measurements, spectroscopic observations of these stars are needed to determine planetary masses and atmospheric compositions. The high activity level of young stars, however, introduces large stellar jitter to their radial velocities, making it harder to extract a planetary signal. To mitigate this issue, it is necessary to observe young stars at high cadence in the infrared, where RV noise due to stellar activity is smaller than in the optical. The Habitable-zone Planet Finder on the HET is a new, high precision NIR spectrograph uniquely suited to sift through stellar noise and detect planetary signals around young stars. The HPF bandpass also includes the He 10830 triplet, which can be used to detect evaporating exospheres around transiting planets without the need for expensive and challenging space-based UV observations. We will present observations of planet hosting Hyades members K2-25 and K2-136, with radial velocity time series and measurements of the variability of the He triplet. Our results demonstrate HPF's unprecedented near-infrared RV precision, and from these data we will present mass limits for the transiting planets in these two systems. We show that the helium profile is stable to roughly 2% in the young K-dwarf K2-136, meaning it is possible to detect young helium exospheres if the signal is comparable to previous detections (3-8%). Lastly, we present the current status of our large program to observe other young planetary systems, and discuss limits on non-transiting long period planets in those systems.

322.08 — Planetary Magnetic Response to Young Star Stellar Wind Environment

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Young stars are known to exhibit strong magnetic activity in the form of both steady and eruptive outflow. This, combined with the majority of known Earth-like planets orbiting their stars closer than Mercury orbits the Sun, results in an extreme stellar wind environment at the planet. We employ a 3D coupled MHD model to simulate the planetary response to this environment with an emphasis on the exchange of plasma between the planetary magnetosphere, ionosphere and stellar wind. We will present the results of two cases: the case of extreme, steady stellar wind and the case of successive Sun-like Coronal Mass Ejection (CME) impacts over short timescales. These results demonstrate how exoplanetary environments differ from Earth's and provide insight into how early stage star-planet interactions may impact future evolution of the planetary environment.

322.09 — Searching for Wide Companions and Identifying Circum(sub)stellar Disks through PSF-Fitting of *Spitzer*/IRAC Archival Data

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The last decade has seen the discovery of a growing population of planetary-mass companions (~<20 M_{Jup}; PMCs) to young stars which are often still in the star-forming regions where they formed. These objects have been found at wide separations (>100 AU) from their host stars, challenging existing models of both star and planet formation. Demographic trends with mass and separation should distinguish between these formation models.

The extensive *Spitzer*/IRAC data set of major star-forming regions and associations within 300 pc has great potential to be mined for wide companions to stars. I will present new results from my automated pipeline to find wide companions of stars via point spread function (PSF) subtraction in IRAC images. A Markov Chain Monte Carlo algorithm is the backbone of this PSF subtraction routine that efficiently creates and subtracts χ^2-minimizing instrumental PSFs, measuring IR photometry of the systems across the four IRAC channels (3.6 μm, 4.5 μm, 5.8 μm, and 8 μm). I will present a re-analysis of archival IRAC images of 11 low-mass (44 M_{Jup}–0.88 $M_\odot$; K3.5–M7.5) stars in 3 nearby star-forming regions (Chameleon, Taurus, and Upper Scorpius; $d \sim$ 150 pc; $\tau \sim$ 1–10 Myr) known to host faint companions over a range of projected separations (1.7″–7.3″). I will discuss the characteristics and disk-hosting potential of the systems found to have low-mass companions with non-zero [3.6] – [8] colors, including the confirmation of a $\rho = 4.66''$ (540 AU), $M = 20\ M_{Jup}$ companion to [SCH06] J0359+2009, a young brown dwarf in Taurus.

My survey is sensitive to companions with masses near that of Jupiter at orbital radii of a few hundred AU, discovering wide PMCs in their birth environments and revealing their circum(sub)stellar disks. I will present my newest results in measuring the mid-IR photometry of directly-imaged substellar companions and an automated companion search of all known young stars with existing *Spitzer*/IRAC data, concluding with my ongoing follow-up of candidate wide PMC systems with ground-based telescopes and the outlook for future observations with space-based telescopes.

322.10 — Deep Asymmetric Eclipse of V928 Tau

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V928 Tau is a previously known astrometric weak-lined T Tauri binary, with an orbital period inferred to be greater than 58 years (Schaefer et al. 2014). In addition to confirming for the first time that V928 Tau A+B are physically associated on the basis of nearly identical spectra, obtained from adaptive-optics resolved spectroscopy, we report the detection of a single, deep, asymmetric eclipse from K2 data. We suggest this is due to a previously unknown companion at intermediate separation (orbital period > 80 days). From modeling of the eclipse shape we find evidence that the transiting or eclipsing companion is surrounded by a circumsecondary disk or a vast ring system on an eccentric orbit around a single component of the binary. This modeling is done by new software developed specifically for the fitting of inclined and tilted circumsecondary disks or ring systems to light curves. Photometry from ground-based time-domain surveys reveal additional eclipses of the young star system, which provide period constraints, which in turn provide mass and eccentricity constraints of the orbit of the secondary. We find several possible periods and report the corresponding predictions of the next transits, which will be monitored to fully determine the orbital period of the companion. Once this has been done an observing campaign can be organised to fully characterise the physical and chemical properties of the circumsecondary disk allowing us to better understand gas giant formation.

323 — Protoplanetary Disks — Observations, Poster Session

323.01 — The Early Chemical Evolution of Planet Forming Material

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There is growing observational evidence that evolution in protoplanetary disks begins early. Gaps in the dust disk, an indication of grain growth, now appear to be ubiquitous. Many disks have low CO-to-dust ratios, suggesting evolution of the gas phase disk as well. Kinematic evidence even points to the presence of fully formed giant planets within these gas rich disks. It is looking more and more likely that most planet formation has already occurred by the Class II phase of disk evolution. Within this context I will discuss new observations of N_2H^+ and HCO^+ in the envelopes of four Class I protostars which have previously been shown to have low CO abundances. Combined with a new physical-chemical model of envelope+disk systems, I will use these observations to constrain the earliest chemical evolution of the volatile gas available to forming planets.

323.02 — A young cousin of our solar system: New results from HD169142

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The disk around the closest Herbig Ae star, HD169142, has been studied extensively at multiple wavelengths. At an almost face-on inclination, it reveals three major components: a yet unresolved ring/halo at only ~0.1 au from the star, a bright ring around ~20 au, and an outer disk stretching from ~55-122 au. The gaps are emptied from dust and gas, which is a strong indicator for the presence of planets. In our series of observations (2012-2018) we report for the first time the presence of brightness variations inside the major ring at 20 au (Bertrang+2018, Bertrang in prep.). Assuming Keplerian velocity, we determine that the brightness dip is consistent with a shadow cast by a Jupiter-mass planet or brown dwarf surrounded by dust at a radial distance of only 12au, an orbit comparable to Jupiter's. For this talk I will reveal new multi-wavelength observations together with radiative transfer models and hydrodynamical simulations which support the picture that HD169142 might be a young version of a multi-planet system such as HR8799 or our own solar system.

323.03 — New constraints on the dust and gas distribution in the LkCa 15 disk

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We search a large parameter space of the LkCa 15's disk density profile to fit the observed radial intensity of 12CO obtained from ALMA. The best-fit model within the parameter space has a disk mass of 0.1 M (using an abundance ratio of 12 CO/H2 = 1.4 ×10−4 in mass), an inner cavity of 45 AU in radius, an outer edge at ∼ 600 AU, and the disk surface density profile follows a power-law that $\propto r^{-4}$. We found that for the disk density profiles that can lead to a small reduced χ^2, there is a clear linear correlation between their disk masses and the power-law index γ in their disk density profiles. This means the 12CO disk of LkCa 15 is optically thick and we can fit its 12CO radial intensity profile using either a lower disk mass with a smaller γ or a higher disk mass with a bigger γ. However, such a degeneracy in disk mass and γ can be broken using the morphology of the 12CO channel maps, and we find that only models have a disk mass of ∼ 0.1 M can reproduce the observed morphology of the 12CO channel maps. The dust continuum map of the LkCa 15 disk shows that although the mm-size dust disk has a similar inner cavity of the gas disk, its out edge is at ∼ 200 AU, much smaller than the fitted gas disk. Such a discrepancy between the outer edges of the gas and dust disks is what would be expected from dust drifting models.

323.04 — You are what you eat: the elemental composition of disks and planets

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The carbon-to-oxygen ratio, C/O, is often touted as a tracer of the formation location of a giant planet. To determine if this hypothesis is true, and interpret or predict the elemental composition of any planet reliably, we require an understanding of the composition of planet-forming gas and solids. In parallel with the high-profile efforts to measure the C/O ratio and overall composition of exoplanet atmospheres, a matching effort in disks is thus needed. I will present a brief review of what we know of the elemental composition of disks so far, the techniques we are employing to learn more, and present new results on the abundances and time-evolution of carbon, oxygen, and other elements in several protoplanetary disks. To conclude, I will outline a class of planetary systems where many pieces of the composition puzzle are beginning to come together.

324 — Protoplanetary Disks — Theory, Poster Session

324.01 — Disk Population Synthesis

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Recently, a sub-arcsecond resolution survey of the dust continuum emission from nearby protoplanetary disks, conducted with the Submillimeter Array showed a strong correlation between the sizes and luminosities of the disks. Performing models of gas and dust disk evolution, we recreate this relation using a large grid of models that varies the initial conditions. We calculate the disk continuum emission and the effective radius for all models as a function of time. We simulate two different cases: a smooth disk surface density profile, and one that includes pressure bumps. By selecting only the disks that lie on the observed size-luminosity relation we constrain the parameter range and search for trends between the initial conditions and the survival frequency of every disk. By applying neural networks, we determine the influence of every parameter on the final outcome, showing significant results for the initial disk mass, the turbulence-parameter α, and the stellar mass.

324.02 — The thickness of dusty protoplanetary disks depend on metallicity

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The sharpness of dust rings commonly observed in protoplanetary disks can be explained by having solids settle to a thin layer at the disk midplane. Indeed, dust settling is widely considered as a precursor to planet formation. On the other hand, theoretical considerations suggest that protoplanetary disks should develop hydrodynamic turbulence that would stir up dust particles. How can dust sediment in spite of turbulence? I perform numerical simulations of dusty protoplanetary disks to settle this conundrum. I focus on large radii in protoplanetary disks, accessible by ALMA, where turbulence is characterized by large-scale vertical motions, which tends to loft particles. I show that enhancing the total solid abudance above a few times the solar value can weaken turbulence and allow dust to settle. Thus, in addition to particle size and turbulence strength, dust settling in realistic protoplanetary disks is also affected by the disk metallicity. Conversely, observations of thin dust layers may provide an indirect constraint on the local solid abundance. As a corollary, I predict dust rings should be thinner than dust gaps. This can be tested by measuring the dust layer thickness as a function of radius. I also show that the interaction between newly born protoplanets and its surrounding dust-rich disk differ significantly from pure gas disks. This may have implications for shaping the final architecture of planetary systems. Finally, I present the latest 3D simulations aimed at testing whether or not the settled dust rings seen in protoplanetary disks are compatible with sculpting by planets.

324.03 — Evolution of the Water Snow Line in Magnetised Protoplanetary Disks

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Understanding the location of the water snow line provides the formation region and time of rocky planets, which probably formed inside the snow line. In this talk, we present the migration of the snow line in magnetised protoplanetary disks, based on nonideal magnetohydrodynamic (MHD) simulations (Mori et al., 2019) which produce laminar disks due to nonideal MHD effects. The simulation showed that magnetic accretion heating is significantly less efficient than conventional viscous heating. We build a new temperature model that reproduces our simulation results well, and then revisit the time evolution of the snow line location. The result shows that for instance, the snow line passes 1 AU at 0.4 Myr after the star formation, whereas the time for the conventional turbulent disk is 3 Myr. For Earth-like planets to form with sustaining low water content, the protoplanet should have formed in a young solar nebula with gas inflow from a surrounding envelope.

324.04 — Orbital Reshuffle of the Asteroids due to the *IN SITU* Emergence of Jupiter and Clearing of the Main Belt During the Depletion of the Solar Nebula

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The distinctive compositional differences between C-type and S-type asteroids suggest that they were originated from two well-separated regions in the primordial solar nebula, howerve, their overlapping spatial distributions implies a substantial radial mixing of S and C-type asteroids after their birth. We adopt the hypothesis that S-type asteroids are native in the main belt, whereas C-types originate from a broad, more distant (∼ 3.3–9 AU) region outside the ice line. We also assume that they formed before the emergence of gas giants and consider the possibility that the orbits of the C-types' planetesimal progenitors were destabilized by the rapid mass increase of Jupiter and Saturn during the advanced stages of their in situ formation. We perform a series of N-body simulations and confirm that it is possible for a significant fraction of C-type asteroids' progenitor planetesimals to be scattered from the proximity of Jupiter's birth site into the extended main belt region. We also show that this effect alone cannot lead to the substantial removal of most native planetesimals. But, during the subsequent depletion of the solar nebula, Jupiter and Saturn's secular resonances sweep through a wide region and excite the planetesimals' eccentricity along its path. The diminishing gas also circularizes the orbits of these planetesimals and causes their semi major axis to decay. This scenario resolves the issues of mass deficit in the main belt. Due to the size-dependence of the drag force, the clearing process leads to a knee in the size distribution among those planetesimals retained in the main belt. This effect can account for the observed size-distribution of both C and S-type asteroids. This in situ dynamical shake-up scenario provides a solution for both the collocation of compositionally distinctive C and S-type asteroids and the mass distribution in the inner solar system without invoking the "grand-tack" scenario that Jupiter has meandered extensively through the solar nebula.

324.05 — Dust back-reaction stops the gas accretion at the snowline

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In protoplanetary disks, the water snowline can act as a traffic jam for drifting dust particles, leading to high dust-to-gas ratios in the inner regions. Using numerical simulations that include dust growth, evaporation and condensation of water, and the dust back-reaction onto the gas, we find that the dust concentration around the snowline can stop the accretion of light gases (such as hydrogen and helium), and further enhance the accumulation of solid material in the inner disk. The back-reaction effects stop once the reservoir of dust particles from the outer disk is exausted (in approximately 1 Myr), and never take place if the disk turbulence is high, or if the primordial dust content is low.

324.06 — Can a dust gas mixture be modelled as a single fluid?

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In the formation of planets, overcoming the meter barrier requires a mechanism to speed up planetesimal growth and slow down migration. This is especially true in the formation of super earths and other massive planets, where a large amount of solids are present. For all these cases, migration timescales can be extremely short making it exceptionally difficult to form massive planets. Vortices are a promising catalyst for planet formation, collecting and retaining dust, allowing for planetesimals to grow without quickly migrating towards the star. The stability of such dust-laden vortices has been shown, by some analytical and computational work, to become compromised as dust collects inside the vortex; potentially making vortices short lived in protoplanetary discs. Despite making up only 1-2% of protoplanetary discs by mass, dust is very important to the dynamics and evolution of the disc. For a complete understanding of this phenomenon, a model of the dusty gas is required. The terminal velocity approximation is one of these models, it is a way to simplify the complex and computationally costly equations involved in modelling dust and gas as two fluids coupled by drag terms. By treating the dust as being at terminal velocity in the gas, only the evolution of a single fluid has to be solved instead. This

approximation makes the equations simpler to approach numerically and more tractable using analytic methods, as it only requires advancing a single additional equation for the evolution of the dust to gas ratio. We have studied the behaviour of the locally isothermal terminal velocity approximation, a special case of the terminal velocity approximation where the dust evolution equations becomes a modified equation of state. Through our analytical study we show that the model can trivially be extended to α viscous discs, and that this model breaks down around shocks. We also have produced an implementation of this model within FARGO3D using an unconditionally stable integrator to advance the nonlinear dust cooling term. With this we set the groundwork for our study of the dynamics of dusty vortices in protoplanetary discs.

324.07 — Multiple Gaps and Rings Produced by Planets in Protoplanetary Disks: The Role of Thermodynamics

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Multiple concentric gaps and rings have been revealed in a number of protoplanetary disks by submm observations using ALMA. An exciting possibility is that these features are produced by planets. In particular, it has been recently suggested that a single planet in a disk may produce multiple gaps and rings, as a result of the complex propagation and dissipation of the multiple spiral density waves it excites in the disk. Numerical efforts to verify this idea and infer the properties of the putative planets have largely utilized the so-called locally isothermal approximation, using a prescribed disk temperature profile. However, in protoplanetary disks this approximation does not provide an accurate description of the density wave dynamics on scales of tens of AU where rings and gaps are observed. Instead, a more realistic treatment of the disk thermodynamics, including explicit cooling, is necessary. I will discuss how these considerations modify the details of planet-disk interaction, using both linear perturbation theory and numerical simulations. Locally isothermal simulations tend to overestimate the contrast of ring and gap features, as well as misrepresent their shapes and positions, when compared to simulations which explicitly solve the energy equation and include cooling. This can be traced to the different behavior of the wave angular momentum flux, a key quantity characterizing the strength of planet-excited waves, under different thermodynamic assumptions. Caution should be exercised in using locally isothermal simulations to explore planet-disk interaction, and more generally in other studies of wave-like phenomena in astrophysical disks. I suggest an improved numerical setup for planet-disk interactions, which could be used to more accurately determine the plausibility of the observed features being produced by planets.

324.08 — Constraints on the stickiness of icy aggregates in the protoplanetary disk around TW Hya

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Understanding how dust grows in protoplanetary disks is crucial for understanding how planet formation begins. Theoretically, how far dust growth can proceed is highly uncertain because the stickiness of dust aggregates is largely unconstrained. Previous models assumed that water ice is sticky and facilitates dust growth in the outer part of protoplanetary disks. However, it is now under debate whether water ice grains are really sticky at low temperatures (Gundlach et al. 2018; Musiolik & Wurm 2019). It is also possible that some nonsticky materials like CO_2 ice cover the grains and prevent their collisional growth (Musiolik et al. 2016). Elucidating whether dust grains in the outer regions of disks are sticky or not is particularly important for understanding how icy planets and small solid bodies like comets form. In this study, we derive constraints on the stickiness of icy aggregates from observations of the protoplanetary disk around TW Hya, which has a massive protoplanetary disk. Recently, high-resolution observations with the ALMA telescope revealed that the dusty disk has circular gaps at 25 au and 41 au (Andrews et al. 2016; Tsukagoshi et al. 2016). Based on the scenario that the gaps are created by two sub-Neptune-sized planets, we simulate how dust aggregates grow and radially drift in the gapped disk assuming that the aggregates fragment upon collisions at velocities above a given threshold. We find that the fragmentation threshold of as low as $0.5\ \mathrm{m\ s^{-1}}$ gives the best match to the ALMA observations. Higher fragmentation thresholds lead to significant dust accumulation at the outer edges of the planetary gaps and to dust depletion interior to the 25 au gap, both inconsistent with the observational appearance of the TW Hya disk. The derived fragmentation threshold is considerably lower than previously anticipated for aggregates made of 0.1 μm-

sized water ice grains (≈ 80 m s^{-1}; Wada et al., 2013). Possible explanations for this include (1) water ice grains are indeed not as sticky as previously thought, (2) the icy grains are larger than 10 μm, and (3) the grains are covered by nonsticky CO_2 ice.

324.09 — Creating Extreme Solar Systems through stellar flybys

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It is now well established that stellar flybys occur within stellar cradles. Therefore, the process of planet formation around young stellar objects does not occur in isolation. More specifically, this kind of encounters dramatically affect the protoplanetary discs where planets born. Here we show in detail the dynamical and observational signatures of flybys: warps, spirals, shadows & misalignments. These results allow us to interpret several very recent (unpublished) ALMA and VLT observations of discs exhibiting mysterious asymmetries (e.g. FU Ori, AS 205, UX Tau, SR 24). We have strong reasons to believe that we are currently witnessing interacting discs. This very fact raises others fundamental questions: What is the effect of the environment on planet formation? How frequent are these encounters? Did the Solar System experience such a flyby? To conclude, we discuss the importance of flybys in producing Extreme Solar Systems.

324.10 — The interplay between MRI and GI: vigorous dynamo and Neptune-mass fragmentation.

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The gravitational instability (GI) and magneto-rotational instability (MRI) are two major instabilities in driving accretion of astrophysical disks. We performed ultrahigh resolution global three-dimensional magnetohydrodynamic (MHD) simulations of self-gravitating disks with outflow boundary condition to study the interplay between GI and MRI. For comparison, we also reproduced global MRI turbulence using the same meshless finite mass (MFM) scheme (Deng et al. 2019) similar to previous finite volume method simulations. In magnetized self-gravitating disks, the GI spirals become fuzzy when MHD turbulence fully develops, and superthermal fields puff up the GI disk driving strong outflow. On the other hand, the vertical circulation besides the spirals drags the mean toroidal fields to form poloidal fields which regenerate amplified toroidal fields due to the background shear as also shown in local simulations of Riols & Latter (2017). This large scale dynamo is fundamentally different from MRI dynamo and leads to fast accretion. It is resilient to magnetic diffusivity that kills the MRI completely. We identify tentative resonance and dynamo cycles that may be related to the accretion bursts seen in young stellar disks.

The critical cooling rate for GI disk fragmentation is not affected by the MHD turbulence. However, light fragments of a few percent Jupiter mass can form from overdense spirals. Upon the onset of the fragmentation, the magnetic fields grow quickly around the clump and truncate the mass feeding along the spiral arms. The low mass fragments in self-gravitating MHD disk provide potential channels for ice giant formation which pose challenges for core accretion models.

324.11 — Migrating Binaries: Friends or Foes to Circumbinary Planet Formation?

Diego Jose Munoz[1]

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Circumbinary accretion disks are a natural byproduct of binary star formation via disk fragmentation. They are key actors in the process of binary coalescence/migration, and are the birthplaces of circumbinary planets. Circumbinary disks are thought to (1) modulate accretion onto the central objects, (2) modify the orbital elements of the binary and (3) be eccentric, thus altering the usual picture of planet growth and migration. Some of these processes are confirmed observationally, while others are in tension with what is known from observations. In particular, whether the disk decreases or increases the angular momentum of the binary is not a settled issue. This debate has broad and important implications for the origin of close binaries, some of which host planets. In this talk, I will discuss how circumbinary hydrodynamics are relevant to star and planet formation as well as to protoplanetary disk evolution, and will show how moving-mesh numerical methods can improve our ability to directly simulate such complex hydrodynamic interactions. I will present simulation results produced with the AREPO code, showing that the long-term (steady-state) behavior is consistent with binaries gaining angular momentum from the gas. As a result, accreting binaries soften rather than harden, contradicting the generally accepted picture of disk-induced binary migration. In addition, I will discuss the phenomena of pulsed accretion, alternating accretion, and disk eccentricity excitation, all of which are relevant to current observations of binary T-Tauri stars (e.g., DQ Tau, UZ Tau E, TWA 3A). In particular, understanding disk eccentricity excitation is essential for addressing the planet-forming potential of young binary systems, and for establishing parallels to main sequence binaries (like Kepler-16 and Kepler-38) that are known to host planets.

324.12 — Modelling Infrared Line Spectra of Complex Organic Molecules in Protoplanetary Disks

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Protoplanetary disks are the natal place of planets. Understanding chemical components of gas, dust and ice in the disks is essential to investigate the origins of materials in our Solar system and other planetary systems. We investigate the synthesis of complex organic molecules (COMs) in protoplanetary disks using a large gas-grain chemical network including COMs together with a 2D steady-state physical model of a disk irradiated by UV and X-rays from the central star. COMs are efficiently formed on cold and warm grains in the disk midplane via hydrogen adding as well as radical-radical reactions on grain surface. Radiation processing on ice forms reactive radicals and helps build further complexity. Part of the icy molecules are photodesorbed into gas and their transition lines become observable. Actually, ALMA observations have detected CH3CN and CH3OH from protoplanetary disks. The line emitting region of these molecules are the outer relatively cold disk, which suggests that the molecules are non-thermally desorbed from grains following the formation on dust grains. Based on our model calculations, we perform ray-tracing calculations to predict line spectra of complex organic molecules observable with SPICA, which shows that detectable lines trace warm inner region of the disk where radical-radical reactions and thermal desorption take place. Also, we discuss possible connection of COMs in protoplanetary disks to those in the Solar system objects, such as comets.

324.13 — Irradiated Disks Naturally Form Rings and Gaps

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Images of protoplanetary disks (e.g., by ALMA) have shown that typical disks are not the smooth power-laws beloved by theorists. Rather, bright rings and dark gaps are ubiquitous. Much work on explaining these surprising features has blamed unseen planets. Here we show that the features can be accounted for by a different possibility: that irradiated disks naturally form rings and gaps when the self-consistent migration of dust is properly accounted for. Planet formation likely proceeds differently in such a structured disk.

325 — Debris Disk Observations and Modeling, Poster Session

325.01 — Dust Spreading in Debris Discs: Do Small Grains Cling on to Their Birth Environment?

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Debris discs are dusty belts of planetesimals around main-sequence stars, similar to the asteroid and Kuiper belts in our solar system. The planetesimals cannot be observed directly, yet they produce detectable dust in mutual collisions. Observing the

dust, we can try to infer properties of invisible planetesimals. Here we address the question of what is the best way to measure the location of outer planetesimal belts that encompass extrasolar planetary systems. A standard method is using resolved images at mm-wavelengths, which reveal dust grains with sizes comparable to the observational wavelength. Smaller grains seen in the infrared (IR) are subject to several non-gravitational forces that drag them away from their birth rings, and so may not closely trace the parent bodies. In this study, we examine whether imaging of debris discs at shorter wavelengths might enable determining the spatial location of the exo-Kuiper belts with sufficient accuracy. We find that around M-type stars the dust best visible in the mid-IR is efficiently displaced inward from their birth location by stellar winds, causing the discs to look more compact in mid-IR images than they actually are. However, around earlier-type stars where the majority of debris discs is found, discs are still the brightest at the birth ring location in the mid-IR regime. Thus, sensitive IR facilities with good angular resolution, such as MIRI on JWST, will enable tracing exo-Kuiper belts in nearby debris disc systems.

325.02 — Testing the Paradigm of Asteroidal Dust around White Dwarfs with the Prototype

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At least one quarter of all white dwarfs are actively accreting debris from planetesimals or planetary fragments. The prototype system G29-38 was discovered at the IRTF in 1987. Yet despite the intervening decades and a complete paradigm shift in the explanation from interstellar material to exoplanetary debris, there remain fundamental questions. The common assumption now is that the dust debris is in a circumstellar disk, yet if so the geometry and vertical optical depth are observationally degenerate. Optically thin and thick cases vary in disk mass — and hence parent body mass — by orders of magnitude. The parent body masses have far-reaching implications for planetary system architecture and long-term dynamics. We report on our work to break this degeneracy and even to test whether the dust is in a disk at all or some other geometrical distribution based on the fact that the prototype system contains a well-studied, pulsating star. Using MORIS and SpeX at the NASA 3-meter Infrared Telescope Facility, we simultaneously monitored the optical stellar pulsations and the ensuing infrared dust response. These observations can distinguish among a range of dust configurations, based on the observed infrared response to the known geometry of the optical pulsations.

325.04 — A survey for resolved debris disks in the Sco-Cen association with the Gemini Planet Imager

Jenny Patience[1]; Justin Hom[1]; Thomas M. Esposito[2]; Paul Kalas[3]; Marshall D. Perrin[7]; Elisabeth Matthews[4]; Pauline Arriaga[6]; Christine Chen[7]; Johan Mazoyer[8]; Maxwell A. Millar-Blanchaer[8]; Stanimir Metchev[5]; Brenda Matthews[9]; Michael P. Fitzgerald[6]; Schuyler Wolff[10]; Gaspard Duchene[2]

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With the Gemini Planet Imager (GPI), we are conducting a survey of debris disk systems in the Scorpious-Centaurus OB association. Each target was observed in the polarimetry mode of GPI which is specifically designed for spatially-resolved, high-contrast observations of debris disks. A subset of the targets was also observed in the spectroscopic mode of GPI, covering the same H-band as the polarimetry mode data. The target sample consists of a complete set of 28 early-type A and F stars located within the Upper Centaurus Lupus and Lower Centaurus Crux regions of Sco-Cen that are bright enough for GPI observations and exhibit the highest Spitzer-detected infrared excesses, with values of L_{IR}/L_{star} above 2.5×10^{-4}. Overall goals of the ongoing survey include exploring the range of debris disk properties around stars of similar age and formation environment, placing constraints on disk geometric properties and the potential dynamical signatures of planets. Of the systems observed thus far, 80 percent have been spatially resolved. Among the newly-resolved systems, the majority have close to an edge-on geometry, one system shows a ring structure and another disk exhibits significant asymmetry, possibly indicating the presence of a substellar companion gravitationally interacting with the debris disk.

326 — Planetary Atmospheres — Hot Jupiters

326.01 — Exploring the Internal Structures of hot Jupiters using the GCM DYNAMICO: Deep, Hot, Adiabats as a Possible Solution to the Radius Inflation Problem

Felix Sainsbury-Martinez[1]; Pascal Wang[2,1]; Sebastian Fromang[3]; Pascal Tremblin[1]; Thomas Dubos[4]; Yann Meurdesoif[5]; Jermey Leconte[6]; Aymeric Spiga[4]; Isabelle Baraffe[7]; Nathan Mayne[7]; Florian Debras[2]; Gilles Chabrier[2,7]; Ben Drummond[7]

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The anomalously large radii of highly irradiated exoplanets have long remained a mystery to the Exoplanetary community, with many different solutions suggested and tested. These solutions have included tidal heating of the atmosphere, or ohmic heating from a strong magnetic field. Another solution was also suggested by Tremblin et Al. (2017): The inflated radii of highly irradiated exoplanets can be explained by the advection of potential temperature, via mass and longitudinal momentum conservation, leads to the deep atmosphere attaching to a hotter adiabat than would be suggested by 1D models, thus implying an inflated radius. In that paper this mechanism was tested using 2D steady-state models, and successfully reproduced an inflated HD209458b scenario. Here we extend this work to both the time-dependent and 3D regimes using the GCM Dynamico (Itself developed as a new dynamical core for LMD-Z, and verified against Hot Jupiter benchmarks as part of this work), exploring the evolution of the deep P-T profile, and the stability of a deep adiabat as the steady state solution. As a result of these calculations we confirm that a deep, hot, adiabat is both the target of long term evolution of the deep atmosphere, and is stable against typical forcing expected at deep pressures — we also note that this deep adiabat takes a very significant time to form from an isothermal initial condition (hence why it has not previously been seen in GCM simulations beyond a kink in the deep profile), and suggest that future GCM models should use an adiabatic profile to initialise the deep atmosphere. Taken as a whole, our results confirm the theory of Tremblin et Al. (2017): the inflated radii of highly irradiated exoplanets can be explained by connecting the atmosphere with a deep, hot, internal adiabat.

326.02 — Admissible types of magnetospheres of hot Jupiters

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The orbits of exoplanets of the hot Jupiters type, i.e., exoplanets with masses comparable to the mass of Jupiter and orbital semi-major axes less than 0.1 AU, as a rule, are located close to the Alfven point of the stellar wind of the parent star. At this, many hot Jupiters can be located in the sub-Alfven zone in which the magnetic pressure of the stellar wind exceeds its dynamic pressure. Therefore, magnetic field of the wind must play an extremely important role for the flow of the stellar wind around the atmospheres of the hot Jupiters. This factor must be considered both in theoretical models and in the interpretation of observational data. The analysis shows that many typical hot Jupiters should have shockless intrinsic magnetospheres, which, apparently, do not have counterparts in the Solar System. We confirmed this inference by the three-dimensional numerical simulation of the flow of the parent star stellar wind around the hot Jupiter HD 209458b in which we took into account both proper magnetic field of the planet and magnetic field of the wind.

326.03 — Dynamical effects of hydrogen dissociation on atmospheric circulation of ultra-hot Jupiters

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Recent secondary eclipse spectral and phase curve observations of ultra-hot Jupiters with dayside temperatures in excess of 2500 K have found evidence for new physical processes at play in their atmospheres.

Here, we investigate the dynamical effects of the dissociation of molecular hydrogen and recombination of atomic hydrogen on the atmospheric circulation of ultra-hot Jupiters. To do so, we incorporate these effects into a general circulation model (GCM) for hot Jupiter atmospheres, and run a large suite of models varying the incident stellar flux and strength of frictional drag. We find that including hydrogen dissociation and recombination reduces the day-to-night temperature contrast of ultra-hot Jupiter atmospheres and causes the speed of the equatorial jet to decrease. This is because the large energy input required for hydrogen dissociation cools the dayside of the planet, and the energy released due to hydrogen recombination warms the nightside. The associated large heating/cooling rate and the mean molecular weight change modify the wave-mean-flow interactions, which likely results in the weaker equatorial jet. The results from our GCM experiments qualitatively agree with previous theory that the day-night temperature contrast of ultra-hot Jupiters should decrease due to hydrogen dissociation and recombination. Lastly we compute full-phase light curves from our suite of GCMs, finding that the reduced day-to-night temperature contrast in ultra-hot Jupiter atmospheres causes a smaller phase curve amplitude. The reduction in phase curve amplitude due to hydrogen dissociation and recombination could explain the relatively small phase curve amplitudes of observed ultra-hot Jupiters WASP-33b, WASP-103b and KELT-9b. Our work would first provide valuable understanding on the basic dynamical processes of ultra-hot Jupiters, helping to interpret future observations of their atmospheres. Secondly our work would stimulate further theoretical investigations, revealing complex interplays between different physical processes in atmospheres of ultra-hot Jupiters.

326.04 — Time Variability in Hot Jupiter Atmospheres

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Hot Jupiter atmospheres are expected to be dynamic environments with time-variable large scale circulation patterns. However, to date there has been no detection of variability of hot Jupiter atmospheres in the infrared, while the visible light phase curve of HAT-P-7b has been observed to show a periodic oscillation in its phase offset. In this work, we perform the first study of the expected infrared time-variability of a broad range of hot Jupiter atmospheres in preparation for JWST. To do so, we perform a large suite of atmospheric circulation models, varying the incident stellar flux and atmospheric drag strength. We place lower limits on the atmospheric variability, as we do not include the effects of Lorentz forces, large-scale shear instabilities, and clouds. In general, we find that the amplitude of variability is largest in the equatorial regions and increases with increasing incident stellar flux and frictional drag strength, both in terms of temperature and emergent flux. We show that JWST will be able to detect variability due to atmospheric circulation in the secondary eclipse depth and may be able to detect variability in the phase curve amplitude and offset. The periodicity and amplitude of detected variability will provide a first-order understanding of the interaction of large-scale standing waves in hot Jupiter atmospheres. Additionally, if variability significantly larger than expected from our simulations is found, that may provide evidence for additional physical processes (e.g., magnetic effects, clouds) affecting the emergent flux of hot Jupiters.

326.05 — Leaking Exoplanets: Understanding how Stars Affect Atmospheric Escape in Exoplanets

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The atmospheres of highly irradiated exoplanets are observed to undergo hydrodynamic escape, resulting in planetary mass loss. However, stellar winds can shape and even prevent atmospheric escape, affecting observable signatures of escape such as Lyman-α and H-α line profiles. In this work, we simulate atmospheric escape of close-in exoplanets and investigate whether they are affected by stellar winds. We show that, although younger hot-Jupiters experience higher levels of atmospheric escape, owing to a favourable combination of higher irradiation levels and weaker planetary gravity, stellar winds are also stronger at this young age, which act to reduce/inhibit escape rates of young exoplanets.

326.06 — Revisiting the NUV Transmission Spectrum of HD 209458b: Signs of Ionized Iron Beyond the Roche Lobe

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Ultraviolet transit observations probe the upper atmosphere of exoplanets, where mass loss occurs. Our analysis of the archival HST/STIS NUV transmission observations of HD 209458b shows evidence for ionized iron, but no evidence for neutral iron, neutral magnesium, nor ionized magnesium. While our non-detection of neutral magnesium resolves the tension with theoretical models from previous results, our results are at still odds with lower-atmosphere models resulting from optical and infrared observations. These upper-atmosphere observations indicate that hydrodynamic escape is strong enough to carry heavy atoms like iron beyond the planetary Roche lobe; however, lower-atmosphere observations suggest the presence of cloud condensates. With iron-bearing aerosols condensating more strongly than magnesium-bearing aerosols, if magnesium is trapped in the lower atmosphere, iron should be as well. The intricate relationship between lower- and upper-atmosphere properties makes the combination UV and optical/infrared observations more valuable than the sum of its individual parts. The unique properties of the HD 209458 system place its transiting hot Jupiter in a pivotal role in our understanding of planetary atmospheres, few other planets will ever enable such precise measurements of both their upper- and lower-atmosphere properties. Here, I will present the analysis and theoretical interpretation of the HD 209458b NUV observations. Then I will discuss the prospects of future observations to elucidate the puzzling nature of this planet's atmosphere as a whole, which is of particular value before the the imminent launch of the James Webb Space Telescope.

326.07 — Supervised machine learning for interpreting ground-based, high-resolution transmission spectra of exoplanets

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We present a novel, unpublished approach to performing atmospheric retrieval on high-resolution ground-based data for exoplanets using supervised machine learning. We have developed a technique that combines the well-established method of cross-correlation with our random forest retrieval algorithm.

High-resolution spectroscopy using meter-class, ground-based telescopes has revolutionized our ability to identify atoms and molecules in the atmospheres of exoplanets. However, the high levels of noise and large number of spectral points provide a challenge for traditional methods of retrieval. Currently, detections of molecules are made using the technique of cross-correlation, which matches line positions of atomic and molecular species with the high-resolution absorption spectra. But used on its own, cross-correlation does not yield the posterior distribution of the abundance of an atom or molecule, or the properties of the atmosphere being observed.

We introduce a hybrid retrieval method that combines the cross-correlation method with a supervised machine learning method using the random forest. It leverages the statistical content of the spectrum to overcome the high level of noise and uses feature engineering to reduce the size of the training set. We use the hybrid method to interpret the HARPS-N transmission spectrum of KELT-9b, deriving posterior distributions for the metallicity and temperature and demonstrating that it is able to diagnose missing physics in the retrieval. The hybrid method will be decisive for performing retrieval on suites of high-resolution spectra with broad wavelength coverage as the next generation of ground-based spectrographs come online.

326.08 — Modeling disequilibrium chemistry of exoplanet atmospheres using a sequence of post-processed forward models

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In anticipation of the next era of space telescopes for exoplanet characterization (James Webb, ARIEL) it is essential that sophisticated modeling tools for the atmospheres of transiting planets are developed. However, the associated effects of strong stellar irradiation and tidal locking make these objects inherently three-dimensional (3D) in nature, and multidimensional forward models are thus required to accurately simulate the multitude of processes that comprise an atmospheric system. This is especially the case for the out-of-equilibrium chemical composition, which is tightly coupled to the planetary climate through dynamical quenching and can show large longitudinal variations due to day-night temperature differences and photochemical reactions. Despite fast developments in the field, coupling 3D general circulation models (GCM) with radiative transfer and chemistry, computation times are a major bottleneck of these models and thus they are only applied to a small number of planets.

In an effort to remedy this limitation, we employ a range of post-processed forward models in sequence: a 3D GCM (MITgcm, Adcroft+2004) with simplified, Newtonian radiative transfer (based on petitCODE, Mollière+ 2015), a post-processed pseudo-2D chemical network solver (Agundez+ 2014) and a ray-tracing code (petitRADTRANS, Mollière+ 2019), to compute an extensive grid of planetary atmospheres and synthetic transmission spectra. This allows us to study the mechanisms of disequilibrium chemistry and their effect on the observables in a systematic way for a large range of planets. More specifically, we report on the change in synthetic transmission spectra due to longitudinally-varying vertical mixing and photochemistry. This enables us to derive general parametrizations for these processes for implementation in 1D retrieval codes, a necessary step in preparing for the interpretation of high-quality data coming from the James Webb Space Telescope and ARIEL.

326.09 — Exoplanet atmosphere characterization with SPIRou: first results for HD 189733b

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SPIRou is the new high-resolution, near-infrared spectro-polarimeter at the Canada-France-Hawaii Telescope. Primarily built to detect earth-like exoplanets around M-dwarfs through precise radial velocity measurements, it is also, thanks to its large spectral range (Y to K band) and its high R$\sim$70,000 resolving power, an excellent instrument for exoplanet atmospheric characterization via transit and emission spectroscopy. SPIRou observed its first exoplanet transit — of the planet HD 189733b — in September 2018. I will present preliminary results of this first observation, and of other transits that have been observed since then as part of the SPIRou Legacy Survey. Thus far, we can re-confirm the detections of water and metastable helium signals in the transmission spectrum of HD 189733b.

326.10 — Atmospheric Characterization of HD209548 and HD189733 with High Resolution Cross Correlation Spectroscopy

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High Resolution Cross Correlation Spectroscopy (HRCCS) has become a powerful tool to constrain both the physical characteristics and abundances of atomic/molecular constituents in exoplanetary atmospheres. Brogi & Line (2019) recently introduced a novel Bayesian atmospheric retrieval methodology that can combine observations from both longer wavelength (2-4 micron), ground-based, HRCCS and shorter wavelength (1-2 micron) space-based observatories such as the Hubble Space Telescope (HST). Here we present results from the first application of this technique to both new and previously published observations of HD209458b and HD189733b from VLT/CRIRES, HST, and Spitzer. The more complete wavelength coverage provides a more comprehensive assessment of the atmosphere by way of stronger constraints on the thermal profiles, atmospheric metallicity, and carbon/oxygen inventory for these two benchmark planets. We also investigate the impact of possible model-induced biases including assumptions regarding molecular cross-sections, cloud model prescriptions, and thermal profile parameterizations. Finally, we present what constraints may be possible in the future by performing retrievals of synthetic observations from the next generation of high-resolution spectrographs like CRIRES+. This work has laid a foundational dataset that combines both space and ground-based observations to comprehensively characterize exoplanetary atmospheres and will be a useful benchmark in comparison to future efforts for both transiting and non-transiting atmospheric characterization.

326.11 — Three-Dimensonal Mixing of Photochemical Hazes in the Atmospheres of Hot Jupiters

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The transmission spectra of many hot Jupiters show signatures of high-altitude aerosols. The nature and composition of these aerosols is unknown—one possible explanation is that they are produced through photochemical processes. Previous studies of photochemical hazes on tidally locked exoplanets used one-dimensional models. These 1D models have to make strongly simplifying assumptions about the strength of vertical mixing. Furthermore, they ignore that the strong day-night contrast on hot Jupiters, the spatially varying production rate of photochemical species acting as haze precursors and the interaction with the atmospheric circulation can lead to inhomogeneous aerosol distributions. General circulation models (GCMs) are needed to better understand how photochemical hazes are mixed by the atmospheric circulation, what the resulting 3D aerosol distributions are, and how 1D modelers can make more informed choices to represent 3D processes as accurately as possible in a 1D framework. As photochemical hazes are produced at much higher altitudes than condensate clouds and are expected to have small particle sizes, they may interact differently with the atmospheric circulation than condensate clouds.

We present results from GCM simulations of hot Jupiter HD 189733b to explore the mixing of photochemical hazes. With an equilibrium temperature near 1,200 K, this well-studied planet is cool enough that photochemical hazes and condensate clouds with a variety of compositions are both expected to exist. We use passive tracers representing photochemical hazes to study how hazes are transported by the atmospheric circulation. We also include tracers representing condensate clouds for comparison. We present the resulting 3D distributions of each species for different constant particle sizes. Furthermore, we analyze the efficiency of vertical mixing and derive effective eddy diffusion coefficients that describe resulting global-mean particle distribution, to be used in 1D models. Our study also addresses sensitivity to initial conditions of the tracer abundance and the long-term behavior of the simulations.

326.12 — Transit Timing Variations and Transmission Spectroscopic Studies of Seven Exoplanets with Thai Telescopes

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Since 2012, National Astronomical Research Institute of Thailand (NARIT) has operated the 2.4 metre Thai National Telescope and seven 0.5-0.7 metre class telescopes of the Thai Robotic Telescopes network, located in Thailand, Chile, China, USA and Australia. As a part of collaborations with the Spectroscopy and Photometry of Exoplanetary Atmospheres Research Network (SPEARNET), seven transitting exoplanets: HAT-P-26b, HAT-P-36b, HAT-P-43b, KELT-3b, WASP-11b/HAT-P-10b, WASP-43b and WASP-127b, were monitored with Thai telescopes from 2015 to 2019. Transit Timing Variations (TTV) and transmission spectroscopic analyses are performed on multi-wavelength optical photometric observational data, yielding results which indicate interesting properties of monitered exoplanets. TTV analysis of WASP-43b shows that the case of orbital decay can be ruled out, while in WASP-127b a significant Rayleigh scattering effect is confirmed through transmission spectroscopic analysis of u'-band light curves. Moreover, TTV analyses of two planets with large TTVs: HAT-P-26b and HAT-P-43b, have been performed in order to verify results published in the previous works. The first optical transmission spectroscopic analyses of two hot-Jupiters HAT-P-36b and WASP-11b/HAT-P-10b are also carried out.

326.13 — Helium in extended exoplanet atmospheres observed at high spectral resolution

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Since the early age of exoplanetology, the near infrared helium triplet was seen as one of the most promising tracers of exoplanet atmospheres. However, it is only very recently, with the help of high-resolution spectrographs, that it could be detected and its full potential exploited.

I will show that high-resolution spectrographs can retrieve a fully resolved helium signature. I will present two helium detections obtained on the warm Neptune HAT-P-11b and the warm Saturn WASP-107b, and I will show how the helium triplet can probe the atmospheric expansion and dynamics. Using the CARMENES spectrograph, the helium features have been spectrally and temporally resolved, at an overall significance of more than 20 σ. The helium profile of HAT-P-11b is clearly symmetric but slightly blueshifted, while the helium profile of WASP-107b is asymmetric with a clear excess absorption in its blue wing. We model these profiles with a 3D code allowing us to characterize the structure and dynamics of their extended atmospheres (thermosphere and exosphere). The HAT-P-11b modeling shows that helium is present in its thermosphere, is negligible in its exosphere and reveals the presence of zonal wind from the day to the night side. On the contrary, the modeling of WASP-107b shows that helium fills the thermosphere but the majority of it is present in the exosphere in the form of a cometary-like tail.

In general, the near infrared helium triplet offers strong synergies with space-based UV observations. It will help us understand the formation and evolution of the hot Neptune evaporation desert by studying planets from Jupiters to super-Earths in different conditions of irradiation and stellar environments.

326.14 — Remote sensing of exoplanetary atmospheres with ground-based high resolution near-infrared spectroscopy

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Thanks to the advances in modern instrumentation we learned about many exoplanets that spawn a wide range of masses and composition. Studying their atmospheres provides insight into planetary diversity, origin, evolution, dynamics, and habitability. Present and future observing facilities will address these important topics in very detail by using more precise observations, high-resolution spectroscopy, improved analysis methods, etc. In this contribution we investigate the feasibility to retrieve the vertical temperature distribution and molecular abundances from expected exoplanet spectra at very high spectral resolution from ground based observations. We focus our research on Cryogenic high-resolution IR Echelle Spectrometer (CRIRES+) on the Very Large Telescope scheduled by the end of 2019 for the European Southern Observatory (ESO). The instrument will operate between 0.9-5.3 micron with a highest achievable resolving power of R=100k. We studied several cases of simulated observations at different spectral bands, their combinations, spectral resolving powers, and signal-to-noise ratios (S/N). Our simulations show that we can retrieve accurate temperatures in very wide range of atmospheric pressures between 1 bar and 10^{-6} bar depending on the chosen spectral region. Retrieving molecular mixing ratios is very challenging, but a simultaneous observations in two separate infrared bands will help to obtain accurate estimates. For that, the exoplanetary spectra must be of relatively high S/N>10. We also present determinations of optimal observational strategies to increase accuracy in the retrievals and list potential targets. We show that high resolution near infrared spectroscopy is a powerful tool to study exoplanet atmospheres because profiles of numerous lines of different molecules could be analysed simultaneously. Instruments similar to CRIRES+ will provide data for detailed retrievals and bring new important constraints for the atmospheric chemistry and physics.

326.15 — Theoretical Spectra of Young Giant Planets at Optical Wavelengths

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Optical characterization of young planets is a natural intermediate step as the community strives to develop the technology necessary to characterize mature exoplanets. While young planets are dimmer in the optical than in the infrared, they are generally still much brighter in the optical than a mature planet of similar mass. An instrument just barely able to characterize a mature planet, should easily attain high precision photometric imaging and spectroscopy of young self-luminous planets. In this work we present spectra for a selection of known and hypothetical self-luminous substellar companions extending into optical wavelengths. For the hypothetical objects we compute spectra at several points along their evolution for a grid of masses and planet-star separations. For each mass and planet-star separation we determine the age at which both the reflected-light and the self-luminous portion of the planet spectrum are contributing significantly to the optical spectrum, because this regime presents exciting possibilities for breaking the degeneracy between a planet's phase function and radius. The spectra computed for known systems are selected to be possible observing targets for WFIRST-CGI.

326.16 — Uniformly hot nightside temperatures on short-period gas giants

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I will present results of a meta analysis of the full-orbit phase curves of twelve hot Jupiters, ranging from HD 189733b to the ultra-hot Jupiter WASP-33b. Using published phase curves at multiple wavelengths for each planet, we inferred the wavelength dependent day side and night side brightness temperatures, and used Gaussian process regression to estimate effective temperatures for the day and night sides of each planet. We found that even though dayside temperatures on these planets increase linearly with increasing amounts of stellar irradiation, their nightside effective temperatures are all clustered around 1100K, with a slight upward trend. Neither atmospheric model we attempted to fit could explain the nightside trend — our favoured explanation is that these planets all have very similar cloud species on their nightsides, which condense slightly above ∼1100K, and radiate at a similar temperature.

326.17 — Irradiation of exoplanetary atmosphere

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Nearly 75% of the stellar population in our galaxy is made up of low mass/ red stars, making them the most common stars in our neighborhood, in turn, the most frequent planet hosts. Due to intrinsically low luminosities of red stars, the habitable zone lies close to the host stars making the orbiting world extremely vulnerable. The high-energy radiation from the host stars strongly determine the amount of gas lost from the atmospheres of close-in exoplanets. In this talk, I will address the consequence of high energy radiation absorbed by the upper planetary atmosphere. I will present my ongoing work on a systematic and detailed characterization of irradiation-induced exoplanetary mass-loss.

326.18 — Multi-color transit observations of the warm Jupiter WASP-80b with MuSCAT/MuSCAT2

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Transit depths of a true planet have a weak wavelength dependence caused by the nature of the planetary atmosphere. To measure the weak wavelength dependence in transit depths is useful to study the composition of a planetary atmosphere. WASP-80b is a warm Jupiter in a 3-day orbit around a late-K/early-M dwarf. The number of giant planets around a late-K/early-M dwarf which have been discovered so far is small. As the planet has an equilibrium temperature of ∼800 K or less, the existence of haze is theoretically suggested. The transmission spectrum observed by Kirk et al. (2018) indicates a weak negative slope, suggesting the possible existence of haze in the atmosphere. On the other hand, Parviainen et al. (2017) reported a flat spectrum, indicating a negative result on the haze existence. However, in observations made so far, the planet-to-star radius ratio in g-band has not yet been constrained enough. If haze exists, the possibility that the spectrum in the g band becomes larger than other bands due to the effect of Rayleigh scattering. Therefore, we conducted multi-color transit observations including the g band using the Okayama 188 cm telescope / MuSCAT and the Canary Islands 1.5 m telescope / MuSCAT 2. In this study, we use two approaches to remove systematics, linear model and Gaussian Process (GP). As a result, we found that GP could remove systematics better than linear model. As a final result, neither the flat model nor the Rayleigh slope model could be rejected with the result of both MuSCAT and MuSCAT2, but the result of the only MuSCAT2 supported the flat model. In the future, we plan to investigate the characteristics of warm planets' atmosphere by observing similar planets.

326.19 — Wind of Change: Revealing thermospheres of exoplanets from high-resolution spectroscopy

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The sodium doublet in the optical is one of the most powerful probes of exoplanet atmospheric properties, when observed in transmission spectroscopy during transits. Recent high-spectral resolution observations of the sodium doublet in hot gas giants allowed us to resolve the line shape, opening the way for extracting thermospheric properties using line-profile fitting. I will present the latest results from the HEARTS survey for hot exoplanetary atmospheres at high-spectral resolution with HARPS and HARPS-N (Seidel et al. 2019a, A&A) which found a strongly broadened sodium doublet in the ultra-hot Jupiter WASP-76b. I interpret the findings via a retrieval method exploiting the resolution of the line profile to determine the temperature-pressure profile and the velocity of high-altitude winds in the thermosphere of WASP-76b and HD189733b. The method could be applied to the whole sample of planets from the on-going HEARTS & SPADES survey for hot exoplanetary atmospheres at high-spectral resolution with HARPS and HARPS-N, and to the observations with next generation spectrographs like ESPRESSO. With the thus determined temperature-pressure profile and velocity of high-altitude winds I will create a clearer picture of the impact of winds and stellar irradiation on planetary upper atmospheres (Seidel et al. 2019b, in prep.).

326.20 — Probing Transiting Exoplanet Atmospheres With Multi-Object Spectrophotometry

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Observations of exoplanets during transit and eclipse have revealed the atmospheric compositions and thermal properties of some of these objects. In this context, ground-based facilities provide the opportunity to study close in transiting exoplanets through spectral characterization studies. We show visible-light and near-infrared spectra of hot Jupiters obtained with ground-based multi-object spectrographs (MOS). We compare the spectra to atmospheric emission and transmission models and interpret the results in terms of atmospheric properties, constraining the physics of our targets in the broader context of comparative exoplanetology. We present our findings in the context of the upcoming ELT and JWST observatories.

326.21 — Metals in the emission spectrum of Kelt-9b

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Ultra-hot Jupiters are planets hotter than 2,200 K, that thus offer the opportunity to study the physics and chemistry of planetary atmospheres in a regime that is not accessible in the solar system or in other exoplanets. At such temperatures, molecules begin to dissociate and atoms become ionized, which gives rise to opacity sources such as H- or metal lines. Indeed, recent transmission spectroscopy observations at high resolution (R>100,000) revealed for the first time lines from metals in the atmosphere of the hottest planet of this category: KELT-9b (4,000 K). These observations probe the terminator of the planet, at the transition between its permanent dayside and its permanent nightside. While they offer the first glimpse in the refractory component of the composition of a planet, these observations are difficult to interprete due to the uncertainty in the thermal conditions at the day-night transition region. In this talk, we present a set of complementary observations of Kelt-9b that target the light directly emitted from its dayside. We report a detection of metal lines in emission, and discuss the techniques used and our interpretation of the observations. In combination with the existing transmission spectroscopy data, our observations provide the chance to map the 3D structure of the planet.

326.22 — ACCESS: the Arizona-CfA-Catolica-Carnegie Exoplanet Spectroscopy Survey

Chima McGruder[1]; Mercedes Lopez-Morales[2]; Dániel Apai[4]; Andrés Jordán[6]; David Osip[5]; Alex Bixel[4]; Néstor Espinoza[3]; Jonathan Fortney[7]; James Kirk[2]; Nikole Lewis[8]; Benjamin Rackham[4]; Florian Rodler[9]; Ian Weaver[1]

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Transmission spectroscopy provides a powerful tool to study the atmospheric properties of exoplanets. Optical transmission spectra are particularly important, since they provide the spectral baselines for clear, cloudy, and hazy atmospheres needed to correctly interpret infrared transmission spectra observed with HST and the upcoming JWST. For 6 years the Arizona-CfA-Católica-Carnegie Exoplanet Spectroscopy Survey (ACCESS) has been observing and analyzing the atmospheres of over a dozen planets, ranging from hot Jupiters to super-Earths. These observations have been collected with IMACS mounted on the 6.5-m Magellan telescope with a homogeneous setup designed for measurements from 0.4-0.9 microns. The homogeneity of ACCESS's data is extremely important because it allows for minimization of systematic differences between instruments and better optimization of data analysis techniques. This dataset has allowed us to study 1) how stellar heterogeneities can masquerade as atmospheric features and some methods to correct for such effects, 2) optimal detrending algorithms that produce the highest accuracy and precision, 3) observing techniques with ACCESS's telescopes that produce the greatest scientific yield, and more. We give an overview of the status of the survey and summarize the main findings from our published studies. We also describe the expansion of ACCESS to the northern hemisphere with the new BINOSPEC spectrograph on the 6.5-m MMT and our plans to start characterizing the atmospheres of transiting planets discovered by TESS.

326.23 — Comparing low- and high-resolution transmission spectra of hot Jupiters: What do we really know?

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The analysis and interpretation of exoplanet spectra from time-series observations remains a significant challenge to our current understanding of exoplanet atmospheres, due to the complexities in understanding instrumental systematics. Observations with ground- and space-based telescopes often result in conflicting data. The relatively recent development of high-resolution time-series spectroscopy offers a new avenue to confirm or refute atmospheric signals detected at low-resolution. Here we present low- and high-resolution transit observations of the hot Jupiters WASP-31b and WASP-121b with UVES and FORS2 on the VLT and GMOS on Gemini-South. Both planets have been extensively observed from ground and space, and have large atomic and molecular signals detected at optical wavelengths, making them excellent targets for high-resolution followup to enable comparison of signals across instruments and methods, and to verify observational techniques. Our results demonstrate significant limitations to our understanding of instrumental systematics even with our most stable space-based instrumentation, but also the power of combining low- and high-resolution techniques to gain a complete picture of exoplanet atmospheres.

326.25 — Atmospheric Characterization of Extremely Inflated Exoplanets: The Curious Case of KELT-11b

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In recent years, a population of extremely inflated sub-Saturn-mass exoplanets orbiting bright stars has emerged from the thousands of exoplanets known. These exoplanets are phenomenal targets for atmospheric characterization due to their bright host stars and large atmospheric scale heights. Subsequently, they are being studied intensively to measure the abundances of water and other metals in their atmospheres in order to place constraints on the location of their origin within a disk. Such inflated sub-Saturn-mass planets bridge the divide between super-Earths and Jupiters, so constraints on their atmospheric composition and metallicities are particularly important for informing planet formation models.

We present new results for the atmospheric characterization of the hottest planet in this population: KELT-11b. We have an ultra-precise near-infrared transmission spectrum collected with the Hubble Space Telescope as well as infrared transit and eclipse measurements from the Spitzer Space Telescope. The Transiting Exoplanet Survey Satellite also recently provided an extremely precise measurement of the optical transit. We combined these data to probe the atmospheric constituents and metallicity of the hot, inflated planet KELT-11b for the first time. The data surprisingly reveal that KELT-11b likely has an unusually metal-poor atmosphere, yet it orbits a metal-rich star. This combined with the fact that KELT-11b's host star is also slightly evolved enables us to perform a unique comparison between KELT-11b and the other planets in the inflated sub-Saturn-mass population that all orbit main-sequence stars. We present what the various observations of KELT-11b and the other planets in this population have revealed about their origins so far.

326.26 — Search for clouds on the planetary daysides by ground-based wavelength-resolved albedos

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One decade of transmission spectroscopy of extrasolar planets has shown the general presence of clouds at the exoplanet terminator region. At the day side of the same planets, however, we are still ignorant of the presence of clouds. The planets and moons in the solar system, which are massive enough to hold a significant atmosphere, all show a substantial reflectivity, i.e. a high geometric albedo, which is caused by clouds high in their atmospheres. Also for extrasolar planets, clouds of condensates are predicted to cause geometric albedos of 0.4 at short optical wavelengths. The measurement of the reflectivity of an exoplanet, i.e. its geometric albedo, has so far been the realm of space-based telescopes. Their data, however, rarely delivered wavelength-resolved albedo information, although theory showed it to be a very useful tool to investigate the chemical composition of the atmospheres on the day side of the exoplanet. In this presentation, I will describe my observational effort to measure the wavelength-resolved albedo for a sample of selected exoplanets. One approach includes the use of the well-proven spectrophotometric capabilities of low-resolution spectrographs at 8m-class telescopes. The other method employed to obtain multi-color albedos is the co-addition of broadband secondary eclipse light curves of small telescopes taken in different filters. I will present first results from 400 to 900 nm showing dark worlds without significant cloud reflection, and I will outline the near future for the measurements of ground-based exoplanet albedo spectra.

326.28 — The role of mid-sized telescopes for the characterisation of exoplanets

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The TESS space mission and, later, PLATO, will find several thousand of exoplanetary candidates around bright host stars, which will be suitable targets for follow-up with 2m-class telescopes. We will be able to characterise and study atmospheres of a few hundred gas giants via transmission spectroscopy. Here we discuss the synergy of mid-sized telescopes with TESS and PLATO space missions. Also, we present some new exoplanetary results from the Perek 2-m telescope located at the Ondrejov observatory and operated by the Czech Academy of Sciences.

326.29 — The convective blueshift center-to-limb and line depth variations using Solar eclipse observation

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High spectral resolution transmission spectroscopy has been proven to be the most powerful technique to study transiting planet atmospheres. The transmission spectra retrieval relys on an accurate knowledge of the host star spectra and its variation during the planetary transit, which are mostly based on the theoretical models of stellar atmosphere. Therefore, high resolution spectroscopic observations of the disk integrated Sun (Sun-as-a-star) during an eclipse can help us to obtain better understanding of those variation and also define observational strategies to mitigate its impact in transmission spectra retrieval. We will present a new analysis of spectroscopic observation which were taken during partial solar eclipse with our Fourier Transform Spectrograph at the Institute for Astrophysics Göttingen with using I2 as its wavelength reference. We used a two dimensional cross-correlation function (CCF) using I2 and G2 star mask for estimating RV of Sun during the eclipse. In order to re-investigate the convective blueshift and its dependence on line strength and also limb angles, we also estimated the RV as a function of line depths during the solar eclipse. Our result show a steady decrease in the convective blueshift from shallow to deep lines and also from center to limb of the Sun. Our results can be implemented for more realistic and robust stellar contamination correction for studying transmission spectra of planets transiting a solar-like stars with ongoing and upcoming missions such as ESPRESSO, ARIEL and JWST.

326.30 — New Empirical Trends From Two Large Spitzer Phase Curve Surveys

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A long-standing mystery about close-in exoplanets is what parameters control the transport of energy in their atmospheres. Thermal phase curve measurements hold the key to resolving this mystery, but previous work on this topic has been limited by the available sample size. We have recently obtained phase curves of 15 previously-unobserved hot Jupiters with a range of physical parameters as part of observing programs totaling ∼1,300 hours with the Spitzer Space Telescope. This sample doubles the number of planets with phase curve data, thus enabling unprecedented statistical analyses and comparative studies. We present results from this survey, including a definitive test of the fundamental prediction that the irradiation level is the primary factor controlling heat transport for close-in planets. Furthermore, we identify empirical trends in the data that help to inform us on the roles that planet gravity and rotation rate play in atmospheric dynamics and cloud formation. Finally, we highlight results from compelling individual systems, including the inference of nightside clouds in the WASP-43b-twin Qatar-2b and the detection of molecular dissociation/recombination energy transport in the extreme planet KELT-9b.

326.31 — A Complete Optical to Infrared Transmission Spectrum of HAT-P-32Ab: Interpreting Atmospheric Properties in the Presence of Clouds

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We present a 0.29-1.7 micron transmission spectrum of the hot Jupiter HAT-P-32Ab observed with the Space Telescope Imaging Spectrograph (STIS) and

Wide Field Camera 3 (WFC3) instruments mounted on the Hubble Space Telescope. The spectrum is composed of 49 spectrophotometric bins measured to a median precision of 48 ppm, and is characterized by a steep slope in the optical and a weak water feature at 1.4 microns. Comparing the observed transmission spectrum to a grid of 1D radiative-convective forward models indicates the presence of clouds/hazes, consistent with previous ground-based observations. To provide more robust constraints on the planet's atmospheric properties, we perform the first full optical to infrared retrieval analysis for this planet and verify our results using two independent retrieval frameworks. This result is part of the HST Panchromatic Comparative Exoplanetary Treasury (PanCET) Program (GO 14767).

326.32 — Testing Assumptions in Atmospheric Retrievals of Spectroscopic Phase Curves

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From Jupiter's banded structure and iconic Great Red Spot, to Earth's constantly changing cloud patterns, planetary atmospheres are complex 3D structures. Can a 1D atmospheric model capture this complexity? With the upcoming JWST, we will obtain data from exoplanet atmospheres of higher precision than ever before. Given this opportunity, we must understand the accuracy of our data interpretation. Our model-driven interpretation of an atmosphere's spectrum fuels our understanding of the day-night heat redistribution and establishes chemical abundance estimates, which impact theories on planet formation.

Without the ability to spatially resolve exoplanet atmospheres, we often approximate them as 1D and uniform to model hemispherically-averaged spectra. Retrieval models have traditionally followed this assumption. Could our inferences be biased as a result? In 2016, I pioneered an investigation for hot Jupiters, which have large day-night temperature contrasts due to close-in, tidally-locked orbits. I showed that one can fundamentally mischaracterize planetary abundances when relying on a 1D model for atmospheres made up of half-hot and half-cool regions.

In my poster, I will discuss my latest work in preparation for the era of high-precision spectra. How does the 1D assumption bias our estimates of planetary composition as a function of orbital phase? HST has obtained "spectroscopic phase curves" for a small number of planets, but JWST will study more targets with higher quality observations. What reliable inferences can be made across the orbit? I consider synthetic data taken both with HST and future data expected from JWST. I also demonstrate the effect on actual Hubble phase curve data of a hot Jupiter WASP-43b. With JWST-quality data, our simplifying 1D assumptions always lead to incorrect estimates of all molecules, compared to a more realistic 2D temperature structure. The need for more accurate models is clear. The framework I will present is also ideal for incorporating patchy clouds, hot spots, and chemical gradients. This invites input from the community as we develop the appropriate model given a data set.

326.33 — Unveiling hazes and energy balance in the exoplanets atmospheres with STIS

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The discovery of thousands of transiting exoplanets in the last decade and the upcoming planets to be discovered with TESS makes the characterization of exoplanets atmospheres one of the most promising fields. By analyzing the atmosphere of the planets, we can infer their composition and obtain information about their formation and evolution. In particular, by observing in the visible wavelengths one can probe the presence and size of atmospheric aerosols (haze and clouds), and therefore differentiate between haze (a sloped spectrum) and clouds (a flat spectrum). In this work, we analyse the visible spectra of various targets observed by the STIS/HST instrument (0.3—1.0 μm) using our Bayesian data-reduction pipeline to obtain the transmission spectra. Our analysis also incorporates spectral retrievals of all targets providing the best set of atmospheric parameters using a MCMC sampling.

326.34 — Gemini/GMOS Transmission Spectroscopic Survey of Gas Giant Exoplanets

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Estimating the nature and abundances of chemical species and clouds in exoplanetary atmospheres forms the backbone of comparative exoplanetology. We present a long-term ground-based survey of a dozen transiting hot Jupiters observed in the visible bandpass using the Gemini Multi-Object Spectrograph (GMOS). By observing transits of an ensemble of hot Jupiters spanning a range of masses, radii, and host star types, and using a consistent methodology for extracting their optical transmission spectra across the sample, we derive common properties for their atmospheres. We present the results of this survey, the challenges faced by such an experiment, and the main lessons learned for future MOS observations and instrument designs. Ultimately, our survey improves our understanding of the diversity of physical processes at play in exoplanetary atmospheres. We also introduce novel techniques to analyze the data that lead to improved precision and expand the capabilities of the MOS technique towards the observations of exoplanets transiting bright stars, which is relevant for compelling targets discovered by TESS.

326.35 — Atmospheric Rossiter-McLaughlin effect of KELT-9b

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We observed the planet-hosting star KELT-9 (A-type star, vsini ~110 km/s) in the framework of the GAPS project (Global Architecture of Planetary Systems). GAPS is a long-term italian program using the HARPS-N and GIANO-B spectrographs at the TNG telescope in order to detect and characterize planetary systems, with a strong focus on the study of the exoplanets' atmospheres. We extracted from the high-resolution optical HARPS-N spectra of KELT-9 the mean stellar line profiles with a custom analysis based on the Least Square Deconvolution technique. Then, we computed the stellar radial velocities with a method developed for fast rotators, by fitting the mean stellar line profile with a purely rotational profile instead of using a Gaussian function. The new spectra and analysis led us to update the orbital and physical parameters of the system. The former depends on the improvement on the Kstar value, that we measured with an 8-σ significance, a remarkable result for such a fast rotating star. We discovered an anomalous in-transit radial velocity deviation from the theoretical Rossiter-McLaughlin effect solution, previously calculated from the known spin-orbit angle obtained from the line profile tomography. We

prove that this deviation is caused by the planetary atmosphere of KELT-9b, thus we name this effect Atmospheric Rossiter-McLaughlin effect. By analysing the magnitude of the radial velocity anomaly, we obtained information on the extension of the planetary atmosphere as weighted by the model used to retrieve the stellar mean line profiles. The Atmospheric Rossiter-McLaughlin effect will be observable for other exoplanets whose atmosphere has non-negligible correlation with the stellar mask used to retrieve the radial velocities, in particular ultra-hot Jupiters with iron in their atmospheres. The duration and amplitude of the effect will depend not only on the extension of the atmosphere, but also on the in-transit planetary radial velocities and on the projected rotational velocity of the parent star, and this could led to strange in-transit RV variations.

326.36 — Characterizing Exoplanet Atmospheres using the all new SPIRou High-Resolution Spectrograph

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Over the last decade, high-resolution near-infrared spectroscopy has led to a multitude of unambiguous molecular detections in transiting and non-transiting exoplanet atmospheres by identifying the distinct signature of their unique spectral features. One shortcoming of many of the previous observations is, however, that they only cover a very narrow wavelength range thus greatly hindering the inference of precise molecular abundance ratios. This major limitation can be overcome using the brand-new ultra-stable SPIRou spectrograph recently installed at CFHT. Its unique combination of wavelength stability, high spectral resolution (R~75000), and wide wavelength coverage (0.98-2.5um) enables us to detect multiple molecules simultaneously and constrain their relative abundances. Here we present how SPIRou observations of hot Jupiters can be combined with state-of-the-art modelling frameworks to constrain molecular abundances in exoplanet atmospheres and provide robust carbon to oxygen ratio measurements that would greatly help shed light onto long-withstanding questions about planetary formation.

326.37 — The strange chemistry of the Dr. Dayside and Mr. Nightside

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We discuss phase-curve spectroscopy of three hot Jupiters with ultra-short periods (P<1 day): WASP43b, WASP18b and WASP103b. To date, these are the only exoplanets with spectroscopic phase-curve observations. Multiple phase-curves have been observed with HST/WFC3 at 1.1-1.7 μm and with Spitzer/IRAC at 3.6 and 4.5 μm. Because of their short orbital periods, these exoplanets are tidally-locked, therefore exhibiting a hotter dayside and a cooler nightside. Phase-curve spectroscopy enables unique access to horizontal distribution and dynamics of the exoplanet atmospheres. However, state-of-the-art atmospheric modelling tools fail to provide a consistent model for the observations at all wavelengths, ofter invoking peculiar chemistry to explain the excess of infrared emission from their daysides. We present here revised data analyses and comparisons with a grid of atmospheric models for the aforementioned exoplanets. We select those models from the grid that give the most consistent results at all wavelengths and discuss their likelihoods. Finally, we comment about the possible causes for the remaining (but reduced) discrepancies, and whether such causes could be astrophysical or instrumental in nature.

326.38 — New models and thermal emission spectra for hot Jupiters, and a look at population-level trends

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Hot Jupiters are compelling targets for thermal emission observations because their high signal-to-noise allows precise atmospheric characterization. Theory predicts a continuum of thermal structures and resulting emission spectra for these objects: Planets below ~1800 K are expected to have uninverted atmospheres and display absorption features in their emergent spectra, while those warmer than ~2100 K should have inverted atmospheres and emission features. Ultra-hot planets with temperatures above ~2500 K are predicted to display blackbody-like spectra because of a combination of high-temperature effects including water dissociation and H^- opacity. We present new high signal-to-noise spectra for three hot Jupiters observed with the Hubble Space Telescope Wide Field Camera 3 (HST/WFC3) from 1.1 to 1.8 microns. We also present an update to the Fortney et al. (2008) grid of self-consistent 1D hot Jupiter model thermal structures and emission spectra for comparison to these data. This new grid extends to higher temperatures and includes all the physics and chemistry for ultra-hot planets that has been discussed recently in the literature. We combine our newly measured hot Jupiter emission spectra with 9 previously published HST/WFC3 observations to perform a population study of the 12 planets with the highest signal-to-noise WFC3 spectra. We compute the degree of absorption or emission observed in their emergent spectra by quantifying their deviation from a blackbody in a new color-magnitude-type plot. While cooler planets do show absorption features as expected, the ensemble of planets at temperatures above ~2100 K do not show the emission features predicted by our models. When analyzed together as a statistical sample, these planets instead show spectra consistent with blackbodies to temperatures much lower than expected from current theory. This suggests that existing models may still be missing important physical effects that could act to mute emission features at lower temperatures. We present some possible explanations for the discrepancy and observations that could be done to test these hypotheses.

326.39 — A comparison of retrieved water abundances using the clear-atmosphere, hot-Saturn WASP-39b as a test case

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WASP-39b provides a benchmark test case for comparing different retrieval approaches and assumptions. It has a deep and precisely measured water feature, however, the water abundances retrieved in the literature differ by over four orders of magnitude. We will present a new analysis of all available transmission spectra of this planet in addition to a new WHT/ACAM transmission spectrum obtained through the LRG-BEASTS survey. We have run retrievals on various combinations of literature data sets and a combined transmission spectrum covering a wavelength range of 0.29 to 5.06 microns. We will highlight how different assumptions made during retrieval analyses can lead to order of magnitude differences in the retrieved water abundances, which in turn lead to different conclusions about the planet's formation. WASP-39b is one of the very best targets for transmission spectroscopy, with a transit depth per atmospheric scale height of 450 ppm. We must understand and be aware of the impact of our assumptions before we can begin to understand the transmission spectra of targets with smaller signals.

326.40 — Investigating Trends in Atmospheric Composition of Gas Giant Planets Using Spitzer Secondary Eclipses

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It is well-established that the magnitude of the incident stellar flux is the single most important factor in determining the day-night temperature gradients and atmospheric chemistries of short-period gas giant planets. However it is likely that other factors, such as planet-to-planet variations in atmospheric metallicity, C/O ratio, and cloud properties, also contribute to the observed diversity of infrared spectra for this population of planets. In this study we present new 3.6 and 4.5 micron secondary eclipse measurements for five cool ($T < \sim 1000K$) transiting gas giant planets: HAT-P-15b, HAT-P-17b, HAT-P-18b, HAT-P-26b, and WASP-69b, as well as five hotter transiting gas giant planets: HAT-P-5b, HAT-P-38b, WASP-7b, WASP-72b, and WASP-127b. For the cooler planets, we expect that the ratio of methane to CO and CO_2 should vary as a function of atmospheric metallicity and C/O ratio. We use our measured eclipse depths for these planets to search for trends in $CH_4/(CO+CO_2)$ ratio as a function of planet mass, temperature, bulk metallicity, and host star metallicity. We see no evidence for a solar system-like correlation between planet mass and atmospheric metallicity, but instead identify a potential (1.9 σ) correlation between the inferred $CH_4/(CO+CO_2)$ ratio and stellar metallicity. Building on the work of Garhart et al. (2019), we place these new planets into a broader context by comparing them with the sample of all planets with measured Spitzer secondary eclipses (over 80 planets). This allows us to search for empirical trends in the spectral slopes of these planets that cannot be explained purely by changes in incident flux.

326.41 — Detecting analogues of the L-T transition in eccentric warm Jupiters.

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One of the main goals of current exoplanet research is in studying the atmospheric composition and dynamics of exoplanet atmospheres. Recent success has been made in identifying the spectral features of carbon monoxide and titanium oxide in the atmospheres of highly irradiated planets as well as identification of broad metallic ionization lines. However, these studies have generally been performed for tidally locked planets in circular orbits, and are likely in a steady state. In this talk, I will discuss the optical phase curve of KOI 614.01, a warm-Jupiter in an eccentric orbit around a Sun-like star. KOI 614.01 exhibits smooth brightness variations in its phase curve, but resides at an orbital distance where the amplitudes of doppler beaming, tidal distortion, and reflection effects are greatly diminished. When combined with extant radial velocity data, these brightness changes are correlated with the planet's distance from the host star. The system's total brightness increases by 30 ppm when the planet resides at a distance with an equilibrium temperature of 1000 Kelvin, and takes approximately 12 hours to change states. In this talk I will discuss the possible origin of this effect and its similarities to the L-T transition in brown dwarfs as well as future prospects for studying the effects of time-variant irradiation on exoplanet atmospheres.

326.42 — Hubble spectroscopic phase curve observations for the ultrahot Jupiter WASP-121b

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WASP-121b is an extreme system, even by exoplanet standards. With a radius 1.8× that of Jupiter, it is one of the most inflated planets known, and orbits a bright F6 star only ∼15% beyond its Roche limit, where it is subjected to intense tidal forces and the atmosphere is heated to ∼2700K. Radiation from the dayside hemisphere has been measured using Hubble and Spitzer, revealing spectral features due to H- ions, H2O, and CO. Notably, these features are observed in emission rather than absorption, providing the first definitive evidence for a thermal inversion in an exoplanet atmosphere. This dayside thermal inversion is likely caused by strong absorption of incident stellar radiation at optical wavelengths, a picture supported by the Hubble transmission spectrum, which probes the atmospheric opacity at the day-night boundary. It shows evidence for significant absorption across the optical, possibly due to VO gas, as well as a dramatic near-UV absorption signal, not seen before for any other planet. We will present new observations of WASP-121b, in the form of a full-orbit spectroscopic phase curve acquired with Hubble at near-infrared wavelengths. Phase curves provide information about the circulation and 3D properties of the atmosphere, unobtainable through primary transits and secondary eclipses alone. In particular, phase curves allow the day-night brightness contrast to be determined and can reveal evidence for advective heat transport in the form of the dayside hot spot being offset from the substellar point, both constraining atmospheric dynamics. The new phase curve data will also track how the H2O band within the Hubble bandpass transitions from being in emission on the dayside to absorption on the cooler nightside, producing a longitudinally-resolved map of WASP-121b's vertical thermal structure. Through detailed comparison with 3D circulation models, these measurements will provide valuable new insights into the efficiency with which optical absorbers such as TiO and VO are removed from the upper atmosphere via condensation cold-trapping.

326.43 — The atmospheric dynamics of WASP-49b

Tom Louden[1]; Peter Wheatley[1]
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I will present an analysis of the spectrum of WASP-49b using Terminator, a code developed to spatially resolve the atmospheres of exoplanets. Simulations of hot Jupiters with GCM's predict the presence of a strong equatorial jet, as well as a day-to-night flow. Without spatial resolution, it is only possible to measure an average velocity of the planet, and hence it is not possible to disentangle these contributions. Transit Limb Scanning makes it possible to spatially resolve the atmosphere of an exoplanet during transit. This technique was first used in Louden & Wheatley 2015 to spatially resolve the atmosphere of the hot Jupiter HD 189733b. I build upon this technique and show that it is also possible to separate out contributions from polar and equatorial regions of the planet. I will present an analysis of WASP-49b showing 3 distinct velocity regions in the atmosphere; eastern and western equatorial regions with velocities of -3 +- 1 and 1+-1 km/s, and a polar region with an average velocity of -1 +- 1 km/s. This is only the second time that an equatorial jet has been directly measured on exoplanet, and is the first evidence of a distinct polar region.

326.44 — Consistent Cloud Models in Retrieval

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To date, there have been two theoretical approaches used to model clouds and understand cloud formation: (1) the phase-non-equilibrium concept of microphysical dust formation, Helling et al., and (2) the phase-equilibrium concept of thermal stability, Marley et al. While the first approach describes the end state of the cloud formation, assuming that the gas is well mixed, transported above the cloud base and grains fall under the influence of gravity; the second approach explores the kinetic processes of cloud formation, where the dust particles form, fall down and grow, until they evaporate below the cloud base. Understanding the nature of clouds in exoplanetary atmospheres is crucial for interpreting transit observations, particularly those made with James Web Space Telescope (JWST), as aerosols are extremely common in planetary atmospheres and dramatically change the appearance of spectral features. Within the retrieval community, until very recently, only simple cloud parametrizations (gray or opaque cloud decks) were considered when analyzing current observations, as the data are not of sufficient quality to respond to the complexity of more advanced cloud models. With the imminent approach of the JWST era, a need for more consistent cloud models in retrieval have become a necessity. Here, we present the first implementation of the microphysical kinetic cloud model in 1D retrieval that explores the aggregate cloud formation in a self-consistent way; and a parametrized thermal stability cloud model, based on the phase-equilibrium concept, that utilizes a parametrized cloud shape and effective particle size, and wraps the atmospheric mixing and settling inside the cloud extent and number density of the particles as free parameters.

326.45 — ACCESS: A Flat Visual Spectrum of the Hot Jupiter WASP-43b without evidence for Na or K

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We present a new ground-based visual transmission spectrum of the hot Jupiter WASP-43b, obtained as part of the ACCESS Survey. The spectrum was derived by combining four transits observed between 2015 and 2018, with combined wavelength coverage between 5,300 Å - 9,000 Å and an average photometric precision of 708 ppm in 230 Å bins. We perform a full atmospheric retrieval of our transmission spectrum combined with literature HST/WFC3 observations to search for the presence of clouds/hazes as well as Na, K, Hα, and water planetary absorption and stellar spot contamination over a combined spectral range of 5,317.90 Å - 16,420 Å. We do not detect a statistically significant presence of Na I or K I alkali lines in the atmosphere of WASP-43b. We do find, however, that the transmission spectrum is best explained, although only marginally, by including the effect of heterogeneities on the photosphere of the host star, yielding a log-evidence of 3.875 ± 0.20 higher than a flat (featureless) spectrum. In particular, the models favor the presence of large, low-contrast stellar heterogeneity over the four transit epochs with an average covering fraction f_{het} = 0.47 ± (0.30, 0.23), temperature contrast ΔT = 113 K ± 65 K. Within the planet's atmosphere, we recover a total log water volume mixing ratio of -5.61 ± (2.47,-2.58) from the combined visual/NIR data.

326.46 — Optical Transmission Spectra for the Two Hot Jupiters WASP-79b and WASP-101b

Alexander Rathcke[1]
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Several advancements in the characterization of exoplanetary atmospheres, such as the improvement and refinement of analysis techniques with the implementation of more flexible noise-modelling frameworks, has led to progress at a rapidly increasing pace. This progress implies that the near future will allow us to go from atmospheric characterization on an individual basis to a statistical significant sample of characterized atmospheres, which will help explain the observed planetary diversity as a result of system architectures, planetary compositions and planetary environments. In this talk, I present optical transmission spectra of two hot Jupiters, WASP-79b and WASP-101b, where in particular the determining factor(s) between a cloudy and a clear atmosphere is still not understood. These observations were obtained with HST/STIS as part of the Panchromatic Comparative Exoplanetary Treasury program (PanCET), which aims at providing the community with the first large-scale simultaneous UVOIR comparative study of atmospheres. Using a Gaussian process approach to model systematics, we produce a high precision, low resolution spectrum of these two planets between 2900 & 10200 Å. The resulting transmission spectrum of WASP-101b shows a flat, featureless spectrum, indicating a high-altitude cloud cover muting spectral features. In contrast, the transmission spectrum for WASP-79b is varying with wavelengths, which hints at an atmospheric opacity that is wavelength dependent. I will discuss possible explanations for this and relate it to what JWST might find when it probes the planet in transmission as part of the Transiting Exoplanet Community Early Release Science Program in cycle 1.

326.47 — Storms or systematics? The search for atmospheric variability in hot Jupiters

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The observation of exoplanets during their primary transits and secondary eclipses is a powerful tool to characterise their atmospheres. These observations provide important information about their temperature structures and circulation efficiencies, as well as the ability to detect the presence of clouds, hazes and specific molecular features. However, repeat observations of hot Jupiters routinely yield significantly different results. Without understanding the source of each of these disagreements, which could arise due to systematic errors or genuine atmospheric variability in the exoplanets themselves, it is difficult to reliably constrain the atmospheric properties of these exoplanets. I will present a summary of these discrepancies—including my own secondary eclipse observations of WASP-12b—along with a discussion of their various causes. I will also describe future ground-based and space-based observational strategies to discriminate between explanations involving storms and systematics.

326.48 — Search for alkali metals in the atmospheres of low-density exoplanets

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Exoplanets with relatively clear atmospheres are prime targets for detailed studies of chemical compositions and abundances. Alkali metals have long been suggested to exhibit broad wings due to pressure broadening, but most of the alkali detections only show very narrow absorption cores, which probably hints the presence of clouds. We have been conducting an optical transmission spectroscopy survey using the low-resolution OSIRIS spectrograph at the 10.4 m GTC. Our survey has revealed very diverse alien worlds, from cloudy or hazy atmospheres to partly cloudy atmospheres, and to clear skies. We will present a comparative study of low-density exoplanets with similar equilibrium

temperatures but different masses. We detected alkali metals in these planets, which show distinct absorption profiles. In particular, we detected Li in one of them, which, if confirmed, could play a critical role in understanding the planet formation histories. When pressure-broadening is resolved, we performed spectral retrieval to constrain the chemical abundances and cloud properties. The absorption profiles of alkali metals, when acquired at low- and high-resolution, can probe a wide range of atmospheric layers. This poses a bright future for us to comprehensively understand the atmospheric structures, from troposphere to thermosphere, as well as the underlying physics, chemistry and dynamics.

327 — Planetary Atmospheres — Terrestrial Planets and Mini-Neptunes, Poster Session

327.01 — Accretion of Nebula-originated Proto-atmospheres on Planets with Eccentric Orbits

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Protoplanets are believed to form before gas dissipates in the protoplanetary disk and are likely to capture proto-atmospheres from the nebula gas. Such hydrogen-rich atmospheres have been detected and characterized in exoplanetary systems (e.g. low-density super Earths and mini Neptunes). The accretion process and the structure of the proto-atmosphere is subject to the disk environment such as the evaporation of nebula gas, the eccentricity of the planet's orbit and the planet mass, etc. In this study, we used the hydrodynamic code PLUTO and the radiation transport module MAKEMAKE to model the accretion event of H_2-dominated atmospheres. We established a 2-D radiative accretion model with sophisticated opacity treatment to simulate low-mass protoplanets on eccentric orbits capturing proto-atmospheres. We revealed astonishing recycling behaviors of gas flow around the planet, forming an asymmetric but stable atmosphere inside the bow shock structure. We also quantitatively explored how such primordial atmospheres are sensitive to the relative velocity of the planet and disk gas, the planet mass, disk gas density/pressure and the overall orbital evolution. A supersonic environment turns out to be favorable for planets to keep an early stable atmosphere, rather than harmful. In general, the bigger the planet and the smaller the Mach number (still supersonic), the thicker the atmosphere can be retained. The orbital evolution of the planet can also insert a forced oscillation on the atmosphere properties. Our study provides important insights in understanding how planet migration and orbital eccentricity affect the formation and evolution of proto-atmospheres for Earth-size planets. The problem of proto-atmosphere accretion is fundamental to science topics including the nebula origin of terrestrial water and other volatiles, the supply of noble gases, etc. Understanding how the proto-atmospheres could influence or even create the current terrestrial planetary environments has general significance to the study of exoplanet geochemistry and habitability.

327.02 — Thermo-compositional diabatic convection in the atmospheres of brown dwarfs, exoplanets, and in Earth's atmosphere and oceans

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By generalizing the theory of convection to any type of thermal and compositional source terms (diabatic processes), we show that thermohaline convection in Earth's oceans, fingering convection in stellar atmospheres, and moist convection in Earth's atmosphere are derived from the same general diabatic convective instability. We also show that "radiative convection" triggered by the CO/CH4 transition with radiative transfer in the atmospheres of brown dwarfs is analogous to moist and thermohaline convection. We derive a generalization of the mixing-length theory to include the effect of source terms in 1D codes. We show that CO/CH4 "radiative" convection could significantly reduce the temperature gradient in the atmospheres of brown dwarfs similarly to moist convection in Earth's atmosphere, thus possibly explaining the reddening in brown dwarf spectra. By using idealized 2D hydrodynamic simulations in the Ledoux unstable regime, we show that compositional source terms can indeed provoke a reduction of the temperature gradient. The L/T transition could be explained by a bifurcation between the adiabatic and diabatic convective transports and seen as a giant cooling crisis: an analog of the boiling crisis in liquid/steam-water convective flows.

The study of the impact of different parameters (effective temperature, compositional changes) on

CO/CH_4 radiative convection and the analogy with Earth moist and thermohaline convection is opening the possibility of using brown dwarfs to better understand some aspects of the physics at play in the climate of our own planet.

This mechanism, with other chemical transitions, could be present in many giant and Earth-like exoplanets. We present first results towards the simulation of this process for the CO/CO_2 transition in secondary atmospheres of hot rocky exoplanets (young or irradiated) which could be applied to the primitive stages of the atmospheres of Earth, Mars or Venus.

327.03 — Near-Infrared Transit Spectroscopy of 55 Cancri e

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Thousands of transiting exoplanets have been discovered, but the extreme brightness contrast between these planets and their host stars makes characterizing their atmospheres particularly challenging. Recent work has focused on transmission spectroscopy during transits, when the light from the host star passes through the planet's atmosphere and allows for the detection of any atomic or molecular species present. While this method has been used to make atmospheric detections around several hot Jupiters, the atmospheres of cooler, lower-mass planets remain elusive, requiring extremely high-resolution observations that are only now becoming available with the latest generation of spectrographs. In this poster, I will present our recent analysis of high-resolution ground-based observations of the hot super-Earth 55 Cancri e, using near-infrared data from the CARMENES instrument at the Calar Alto Observatory and the newly-operational SPIRou instrument at the Canada-France-Hawaii Telescope. Through use of the Doppler cross-correlation technique pioneered by Snellen et al. (2010), which takes advantage of the extreme changes in radial velocity during close-in exoplanets' transits, we investigate and place constraints on the presence of CO, CO_2, H_2O, and HCN in the atmosphere of 55 Cancri e. Our high-resolution observations allow for an unprecedented look at this super-Earth's atmosphere in the infrared regime, not only allowing us to investigate the potential HCN detection by Tsiaras et al. (2016), but also resulting in some of the most stringent constraints to date on the atmospheric composition of this enigmatic exoplanet.

327.04 — Do Habitable Worlds Require Magnetic Fields?

David Brain[1]; Yaxue Dong[1]; Robin Ramstad[1]; Hilary Egan[1]; Tristan Weber[1]; Rebecca Jolitz[1]; Kanako Seki[2]; Janet Luhmann[3]; Jim McFadden[3]; David Mitchell[3]; Laila Andersson[1]; Jared Espley[4]; Jasper Halekas[5]; Bruce Jakosky[1]

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In recent years the idea that a planet's magnetic field shields its atmosphere from being removed to space through interaction with a stellar wind has been increasingly questioned, based largely on observations of atmospheric escape from Venus, Earth, and Mars. This has motivated new thinking about the role that a magnetic field plays in determining atmospheric escape rates — whether it shields the atmosphere by deflecting incident charged particles from the planet's host star, or whether it collects more energy from the stellar wind to drive escape by increasing the cross-sectional area of the planet. Since an atmosphere is required to keep water stable in liquid form at a planet's surface, this question is relevant to our understanding of the habitability of planets.

Various approaches are currently being used to make progress on this question. Basic theoretical arguments have been advanced, but require observations to confirm them. Computer simulations of atmospheric escape are being pursued with promising results, but are difficult to validate. Observations offer opportunity for ground truth, but comparisons between planets in our own solar system are complicated by the fact that planets differ in many ways, so that isolating the influence of a global magnetic field is non-trivial.

Mars may offer an opportunity for a planetary-scale control experiment on the influence of magnetic fields on atmospheric escape. This is because Mars possesses regions of strongly magnetized crust, as well as regions of non-magnetized crust. Thus it is possible to study atmospheric escape from different regions of Mars while controlling for many of the other variables that could influence escape. The MAVEN spacecraft currently orbiting Mars is making measurements that allow us to address this question.

In this presentation we will summarize the current understanding about the role of magnetic fields in atmospheric retention, and present an analysis of MAVEN measurements of charged particle escape from the atmosphere from magnetized and unmagnetized regions. The analysis consists of both global statistics of the spacecraft observations and detailed case studies above individual regions.

327.05 — Exploring the Climate of Exoplanets with OASIS

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In the last two decades, the astrophysical community discovered a multitude of planets orbiting other stars. The variety of planetary environments that these exoplanets may harbour is still unknown. Most importantly it propels the fundamental scientific and philosophical quest of searching for the first detection of life beyond our own planet. As more observational data become available, models of exoplanetary atmospheres are essential, at a first level to interpret the data and more importantly to reproduce and explain the physical and chemical processes that generate the climate of planets.

My poster presents the new planet simulator, *OASIS,* that I have developed from scratch to study planet's habitability and search for life in exoplanets. Our new planetary virtual lab includes a new state-of-the-art 3D atmospheric model (*THOR*) coupled self-consistently with other modules that represent the main physical and chemical processes that shape planetary climates and their evolution. We have recently submitted a manuscript presenting our first results using *OASIS*. Using our new platform, we successfully performed challenging simulations of Venus-like environments and compared the model's results to Venus observations. We will present our new results and describe the main advantages of using *OASIS* compared with other models. The new results show that *OASIS* is a robust and efficient tool to simulate a large diversity of planet's environments.

327.06 — Clouds of fluffy mineral aggregates in warm mini-Neptunes

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Recent observational efforts have revealed that mini-Neptunes are often covered by clouds that exist at extremely high altitudes. Although a number of theoretical studies have examined cloud formation in exoplanetary atmospheres, it is still highly uncertain what processes lead to the formation of clouds at extremely high altitude. One of the promising mechanisms of the high-altitude cloud formation is the evolution of particle porosity. Solid mineral condensates, likely formed in warm exoplanetary atmospheres, can grow into fluffy aggregates that are easily lofted to upper atmospheres; however, there has not been a study on microphysical modeling of such fluffy-aggregate clouds to date. Here, we investigate how the porosity of cloud particles evolves in exoplanetary atmospheres and influences observations of transmission spectra. We first construct a porosity evolution model that takes into account the fractal aggregation and compression of aggregates caused by the gas drag and high-energy collision. Our cloud microphysical model coupled with the porosity evolution model demonstrates that the cloud particle aggregates can be highly porous without significant compression. As a result, fluffy-aggregate clouds ascend to altitude much higher than classically assumed compact-sphere clouds. We also calculate synthetic transmission spectra and find that the fluffy-aggregate clouds largely obscure the molecular signatures, while it produces spectral slopes originated by the scattering properties of aggregates. Comparing the synthetic spectra with the observations of GJ1214b, a mini-Neptune suggested to be covered by the high-altitude clouds, we find that its flat spectrum could be explained by the fluffy-aggregate clouds if the atmosphere is highly metal-rich ($\geq$100$\times$solar). The high-metallicity atmosphere potentially encapsulates the information of past gas accretion processes onto GJ1214b.

327.07 — An extensive search for metallic ions in the upper atmosphere of the warm Neptune GJ 436 b

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The M2.5 star GJ 436 hosts a warm Neptune that displays an extended atmosphere that dwarfs its own host star. Predictions of atmospheric escape in such planets state that H atoms escape from the upper atmosphere in a collisional regime and that the flow can drag heavier atoms to the upper atmosphere. We leveraged the extensive coverage of HST/COS observations of GJ 436 from the Hubble PanCET program to search for signals of metallic ions in the upper atmosphere of GJ 436 b, as well as to study the activity-induced variability of the star at short wavelengths. Despite being a relatively quiet M dwarf, we found that the FUV an unexpectedly high flare rate of GJ 436 is ∼10 events per day. Furthermore, the host star seems to possess either a long-lived active region or an active longitude that modulates the FUV fluxes coherently for several years. We reproduced the Lyman-α transit of GJ 436 b with COS, despite the strong geocoronal contamination, indicating that the large atmospheric loss rate is stable over the timescale of a few years. Several metallic lines of ions in the transition region of GJ 436 are present in our datasets, but the in-transit light curves for each species do not reveal any evidence for the presence of such ions to be escaping from the planet. The previously claimed in-transit absorption in the Si III line is likely an artifact resulting from the stellar magnetic cycle. Given its featureless optical transmission spectrum, it is still not completely clear if it has a high metallicity or a cloudy atmosphere. The non-detection of metallic species in its exosphere, in particular Si, suggests that, if GJ 436 b possesses a cloudy atmosphere, then mixing is not efficient in dragging the Si-rich clouds high enough for sublimation and allow for a significant escape rate of metallic ions.

327.08 — The Transit Spectrum of the Super-Earth 55 Cnc e at Low and High Resolution

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The ultra-hot (∼2000 K) exoplanet 55 Cnc e is the most favorable super Earth for atmospheric characterization, as well as the only super Earth for which there have been convincing claims of atmospheric detections. Notably, Tsiaras et al 2016 report an upward sloping spectral slope in the HST/WFC3 1.1–1.7 μm bandpass, which they attribute to HCN in a hydrogen dominated atmosphere. We jointly analyze the low resolution transit spectrum of 55 Cnc e taken with multiple instruments at multiple wavelengths, namely HST/WFC3 at 1.1–1.7 μm, Spitzer at 3.6 μm, and Spitzer at 4.5 μm. In addition, we search for the molecular signatures of HCN, CH4, and H2O using high-resolution L band (2.8–3.7 μm) transit spectra collected with the upgraded NIRSPEC on Keck. Our 14-transit dataset is the largest and most diverse yet assembled for this planet. We confirm the upward sloping spectral shape reported by Tsiaras et al 2016 in the WFC3 bandpass. Using a Bayesian retrieval analysis, we also confirm that it can be explained by HCN in a hydrogen dominated atmosphere under conditions of super-solar metallicity and high carbon-to-oxygen ratio. However, we do not see evidence of the excess absorption due to HCN expected in the Spitzer 3.6 μm bandpass, nor of the forest of absorption lines expected at high resolution in L band. We discuss possible instrumental and physical reasons for the discrepancy.

327.09 — Characterizing exoplanetary atmospheres in the TESS era

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The characterization of exoplanet atmospheres will be a major scientific endeavor in the coming decades, in particular the search for biosignatures in the atmospheres of temperate, rocky exoplanets. It is a primary science driver for upcoming space-based (e.g., JWST) and ground-based (e.g., GMT) facilities. There are currently several different research directions in exoplanet atmosphere characterization that probe fundamental questions in exoplanet formation and evolution, as well as provide stepping stones to developing the facilities and techniques to ultimately detect biosignatures in the atmospheres of small planets. Observations of extended atmospheres provide an opportunity to not only measure the current conditions in the planetary atmosphere, but also put constraints on formation history and interior structure (Owen et al. 1999), interactions with host star (Cauley et al. 2017), and atmospheric and planetary evolution (Oberg et al. 2011). One such research direction is the characterization of extended exoplanetary atmospheres with different spectral absorption lines, namely Lyman-α, H-α, or HeI at different wavelengths. Here, we present an analysis aimed to estimate the planetary mass-loss rate and the signal of these lines starting from the properties of the TESS candidates sample. This allows to select the more promising targets for a follow-up with radial velocities and possibly atmospheric characterization. We also present a summary of our follow-up observations to characterize the planets in the system GJ9827, the nearest planetary system that Kepler or K2 has ever found, with three super-Earth planets in 1:3:5 commensurability. GJ9827b has a relatively hot atmosphere, which makes it an ideal target for measuring atmospheric escape, particularly given the high activity of its host star.

327.10 — On the observational assessment of M-Dwarf Rocky Planet Atmospheres

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Preface: This abstract is about three new studies, forming a collaborative effort about rocky exoplanet atmospheres. In agreement with the email instructions of the SOC these studies are not yet published and thus “new”, and also “exciting” because they treat the question of observability and characteristics of rocky exoplanet atmospheres, a class of exoplanets that will undoubtedly be in the focus of future observations.

Abstract: Maybe the most promising candidates for near-future characterization attempts with JWST are super-Earths orbiting small M-dwarfs, as they provide a unique insight into smaller, rocky exoplanets while offering a comparatively high signal contrast. In order to understand these objects better, we simulate model atmospheres in radiative-convective equilibrium including the effects of a solid planetary surface of the three super-Earths, TRAPPIST-1b, GJ 1132b, and LHS 3844b. Our self-consistent modeling shows that the atmospheric radiative transfer is significantly influenced by the cool M-star irradiation. Specifically, we find temperature inversions in the upper atmosphere and a mitigation of convection in the lower atmosphere due near-infrared non-gray gas opacity. Since the strength of spectral features directly depends on the temperature gradients in the visible atmosphere, we stress that parametrized atmospheric models, often used in observability studies, are not sufficient to accurately predict spectral emission of exoplanets. The question remains whether these planets retain atmospheres at all, given the high-energy flux of their host star. In this context, we explore the opportunities of secondary eclipse photometry with JWST as a test for the presence of atmospheres. We find that secondary eclipse measurements are well suited to distinguish between rocky planets that do and do not possess atmospheres. The underlying idea is that measuring a relatively cool dayside or high Bond albedo is indicative of an atmospheric day-night heat transport or the presence of reflective clouds. Our findings allow us to optimize the scientific return of future JWST observations and are thus interesting to the broad exoplanet community.

327.11 — Living on the Edge: The Effects of a Surface on Atmospheric Circulation and Emission Features for 1.5 R_{Earth} Planets

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It is well known that planets between the radius of Earth and Neptune have been the most commonly detected to-date. Without a direct comparison in our Solar System, we are left without an immediate understanding of what the compositions of these types of planets are. To classify them, we have traditionally turned to mass-radius relations and composition curves in order to determine the likelihood of such a planet being rocky or gaseous. While previous work has determined that at a radius of approximately 1.5 times that of Earth a planet is equally likely to be either terrestrial or gaseous, we cannot expect that any transition between these two compositions will be a sharp cut-off due to the wide range of possible composition curves that can agree with a given density measurement for a planet of this size. Therefore, we must turn to alternative methods to classify these planets when they fall in this regime and when aerosols limit our ability to break this degeneracy by measuring atmospheric composition directly through transmission and emission spectroscopy. In this talk we present one such new method using 3D general circulation models of 1.5 Earth radii planets. With this method, we study the effects of a surface on observable quantities such as equator-to-pole differences in emitted and reflected light with an eye on detecting the presence of a surface through secondary eclipse mapping with future instrumentation. In this talk we will present our updated GCM, verified on the circulations of Earth and Neptune, before discussing our modeling choices and results for our transition planets. Finally, we discuss the comparison of models with surfaces at various pressures and without surfaces while exploring the prospects of detecting a surface through secondary eclipse observations in the near future.

327.14 — Atmospheric Models and Transit Spectra for Hot Rocky Planets

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We are building a set of atmospheric models to calculate the structure, composition, and both transit and eclipse spectra for hot rocky exoplanets in short period orbits. These hot worlds offer the best opportunity to characterize and understand the formation and evolution rocky exoplanets with current and future instruments. We are using a fully non-grey radiative-convective atmospheric structure code with cloud formation combined with a self-consistent treatment of gas chemistry above the magma ocean. Being in equilibrium with the surface, the vaporized rock material can be a good tracer of the bulk composition of the planet. We are investigating both volatile-poor and volatile-rich compositions, with the volatile poor ranging from completely depleted, to water-free (Venus-like), to containing only sulfur and halogens (Io-like). To properly account for these exotic compositions and thermodynamic regimes, including vertical mixing, condensation, and photochemistry. We present our models for the atmospheric structure of hot rocky planets, as well as new predicted transit and eclipse spectra with the identification of specific spectral signatures in the optical through mid-IR. Our models will inform the design and interpretations of follow-up observations with JWST and ground-based instruments, and provide a better understanding of volatile behavior in these atmospheres.

327.15 — Limits on the atmosphere of a habitable-zone terrestrial planet from ground-based spectroscopy

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LHS 1140b is a terrestrial exoplanet orbiting in the habitable zone of an M4.5 star (Dittmann et al. 2017b; Ment et al. 2019). From radial velocity measurements of its mass and transit measurements of its radius, we know that LHS 1140b has a rocky composition, though its radius of 1.7 Earth radii puts it at the upper limit of the population of rocky worlds (Fulton et al. 2017). It is an open question whether or not temperate terrestrial planets orbiting low-mass stars can retain atmospheres. The exploratory investigation we present here aims to put upper limits on what we can achieve with ground-based observatories to answer this question. This investigation faced challenges: the 25-day orbital period and 2-hour transit duration of LHS 1140b means that there are few observable transits per year from any single observing location. Over the course of 2017 and 2018 we observed two transits of LHS1140b, each time using both 6.5 m Magellan Telescopes at Las Campanas Observatory simultaneously. We used the multi-object spectrographs LDSS3C and IMACS to produce a transmission spectrum from 610-1030 nm. The residuals in our data are within 1.5× the photon-noise limit. This data set is not sufficient for us to test realistic models of the atmosphere of LHS 1140b, owing to its cool equilibrium temperature (235 K), high surface gravity (23.7 m/s2), and likely high mean molecular weight composition. Alternatively, if we can identify a system similar to LHS 1140 (i.e., having a terrestrial planet orbiting in the habitable zone of a mid-M star) but at a distance of 5 pc and with the Earth's surface gravity, an atmospheric detection could be achieved in as few as 8 transits, depending on the atmospheric composition. In the era of extremely large telescopes (ELTs), we may be able to access the atmospheres of hard-to-reach planets like LHS 1140b.

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327.16 — The evaporating atmosphere of the young exoplanet K2-25b

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Host stars create environments that shape the atmospheric structure and composition of their exoplanets, the effects of which we observe today. The stellar wind and high energy radiation present within astrospheres can erode planetary atmospheres, leading to the detections of atmospheric evaporation for short-period planets Gl 436b and GJ 3470b. We have obtained 2 transit observations of the Neptune-sized exoplanet K2-25b in Lyman α with *HST*/STIS. The young age of the K2-25 system and K2-25b's size and similarities with Gl 436b suggest the possibility of a large amount of atmospheric escape. Studying this planet will further our understanding of the evolution of small planets by probing how planetary properties, like size and youth, impact atmospheric escape. By characterizing the total intrinsic Lyman α and X-ray flux from K2-25, we will present constraints on the EUV environment the exoplanet resides in and the mass loss it is experiencing.

327.17 — Iceland, Iceline, IcePlanets

Li Zeng[1]
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Exoplanet radii show a bimodal distribution, with two peaks corresponding to smaller planets (likely rocky) and larger intermediate-size planets, respectively. We apply interior structure model, growth model, as well as atmospheric escape model, and conduct Monte Carlo simulations, to demonstrate that many intermediate-size planets are water worlds. This result has profound implications on planet formation theory and origins of life. (https://arxiv.org/abs/1906.04253)

327.18 — The transition from primary to secondary atmospheres

Edwin S. Kite[1]
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I will address two questions: (1) Do TESS/*Kepler* super-Earths have atmospheres? (2) For sub-Neptunes, how does magma-atmosphere exchange set the composition of the atmosphere? Both involve coupling between magma oceans and H_2-rich atmospheres.

(1) After stellar XUV flux declines, Super-Earth volcanism continues for Gyr. Late volcanism might rejuvenate atmospheres, but only if the solid mantle has enough volatiles. Volatiles that have high-molecular-mass (high-μ) are delivered in the first $\sim 10^8$ yr. On this timescale, for short-period exoplanets, early-accreted nebular atmospheres are ablated. Thus, rocky exoplanet volatiles might be entrained by escaping H_2. The extent of high-μ loss depends on magma ocean crystallization timescales. If this is slow, then because the atmosphere and magma are equilibrated, all of the high-μ volatiles can escape. However, early crystallization favors later existence of an atmosphere. The (small) fraction of volatiles which are trapped within the crystals are shielded during the era of high XUV. Crystallization timescale depends on stellar luminosity, so this model suggests a period threshold for atmosphere absence on Super-Earths.

(2) Sub-Neptunes are mostly magma by mass, and are mostly atmosphere by volume. I explore the effect of the magma on the atmosphere. For the Fe-Mg-Si-O-H system, the fate of H (and the sub-Neptune atmosphere's composition) is set by magma oxidation state. In turn this oxidation state is set by the details of planet assembly. Depending on magma redox state, a nebular-derived atmosphere can masquerade as an outgassed atmosphere and vice versa. Fortunately, planet radius and atmosphere scale height can be used to tell these scenarios apart. H_2O dissolved in the magma is a major H sink for sub-Neptunes: the total volatile budget can be mostly dissolved H_2O even when $\mu_{atm} \sim 2$. Because of these sinks, the amount of H_2 needed to explain the radius of sub-Neptunes is much greater than usually assumed.

These results point the way to future modeling work, combining magma-ocean chemistry with fractionating escape during the transition from primary to secondary atmospheres.

327.19 — Testing Atmospheric Retrieval Assumptions

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Transmission spectroscopy is a powerful probe of the physical properties of exoplanet atmospheres and, with the upcoming launch of the James Webb Space Telescope (JWST), will soon be used to study the Earth-sized planets orbiting TRAPPIST-1. However, the method by which we interpret transmission spectra, known as atmospheric retrievals, often employs simplified physics to make as a means to improve statistical rigor. Here, we attempt to validate numerous physical assumptions, common in atmospheric retrievals, by inferring the atmospheric composition from synthetic transmission spectra generated with a line-by-line full physics radiative transfer code.

Specifically, we investigate non-uniform vertical atmospheric thermal structures and molecular mixing ratios, aerosol parameterizations, and ray tracing with refraction versus geometric optics. These tests help to validate the information that may be retrieved from observed terrestrial exoplanet transmission spectra, but also expose potential biases that emerge from using simplified physical models. Our results will elucidate a more complete picture of the feasibility of JWST to accurately retrieve information on the atmospheres, habitability, and biosignatures of small rocky planets.

328 — Planetary Atmospheres — Directly Imaged Planets and Brown Dwarfs, Poster Session

328.01 — First Light of the Keck Planet Imager and Characterizer

Jason Wang[1]; Dimitri Mawet[1]; Nemanja Jovanovic[1]; Jacques Robert Delorme[1]; Charlotte Bond[2]; Jacklyn Pezzato[1]; Sylvain Cetre[3]; Daniel Echeverri[1]; J. Kent Wallace[4]; Randall Bartos[4]; Scott Lilley[3]; Sam Ragland[3]; Garreth Ruane[4]; Peter Wizinowich[3]; Mark Chun[2]; Ji Wang[5]; Michael P. Fitzgerald[7]; Andy Skemer[6]; Emily Martin[6]; Ed Wetherell[3]; Eric Wang[7]; Shane Jacobson[2]; Eric Warmbier[2]; Charles Lockhart[2]; Donald Hall[2]

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High-resolution spectroscopy has enabled detailed characterization of the composition and dynamics of exoplanets through measurements of individual spectral lines. The Keck Planet Imager and Characterizer (KPIC) consists of upgrades to the Keck II adaptive optics (AO) system and instrument suite. This presentation will focus on the first light science results from the novel fiber injection unit (FIU) of KPIC that isolates and injects planet light from the AO system into the NIRSPEC spectrograph via a single mode fiber. By combining high-contrast imaging and high-resolution spectroscopy, the KPIC FIU is the first instrument to implement high dispersion coronagraphy to study faint imaged exoplanets close to their host stars at high spectral resolution. We are obtaining K-band R~35,000 exoplanet spectra sensitive to spectral lines of water, methane, and carbon monoxide in their atmospheres, as well as planetary radial velocities and spin rates. These measurements provide insights into the composition, formation, and accretion history of these young gas giants. I will present early science results from data we have obtained this year. I will conclude with upcoming upgrades to KPIC that will enhance its science capabilities such as detecting radial velocity exoplanets and discuss the science case for high dispersion coronagraphy on the Thirty Meter Telescope based on the performance of KPIC.

328.02 — Spectral and atmospheric characterisation of a new benchmark brown dwarf

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Evolutionary models of brown dwarfs are plagued by a lack of observational constraints. The complex molecular chemistry of their atmospheres leaves a relatively wide parameter space for models to span. Placing accurate mass and luminosity data to observationally populate the mass-luminosity relationship provides a major contribution to an understanding of the interplay between gravitational contraction and nuclear burning.

To date, individual dynamical masses are known for only a handful of brown dwarfs, therefore any new detections contributes greatly to brown dwarf models as they provide important analogues for the characterisation of exoplanets.

Radial velocity measurements provide only a lower limit on the measured masses due to the unknown orbital inclination. Therefore directly imaging these candidates is needed to break that degeneracy and provide constraints on the dynamical mass of the companion. With over 20 years worth of radial velocity measurements from the CORALIE survey for extrasolar planets, we have identified several promising candidates that we have directly observed.

In this talk we will announce the detection of a new benchmark ~30 M_{Jup} brown dwarf with radial velocity and direct detections allowing us to constrain its dynamical mass, luminosity, spectral type and we obtain a low resolution spectrum of the companion.

The discovery of benchmark sources provides a powerful and critical tool of advanced evolutionary models. As we move toward imaging smaller and smaller objects it is important to use these objects as a laboratory to test theoretical atmospheric models.

328.03 — Detection of New Strongly Variable Brown Dwarfs in the L/T Transition

Simon Christoffer Eriksson[1]*; Markus Janson*[1]*; Per Calissendorff*[1]

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Brown dwarfs in the spectral range L9 – T3.5, within the so called L/T transition, have been shown to be photometrically variable at higher amplitudes and with greater frequency than other field dwarfs. This strong variability allows for the probing of their atmospheric structure in 3D through multi-wavelength observations for studying the underlying physical mechanisms responsible for the variability. The few known strongly variable dwarfs in this range have been extensively studied. Now, more such variables need to be discovered and studied to better constrain atmospheric models, also critical for the understanding of giant exoplanets, and to shed light on a number of possible correlations between brown dwarf characteristics and variability. The largest ground survey to date (Radigan et al. 2014) suggest an occurrence rate for strong variability (peak-to-peak amplitudes > 2 %) of up to ∼39 % among brown dwarfs within the L/T transition.

Here we present the results from a survey with the 2.5 m Nordic Optical Telescope, where we have observed 10 L9.5 - T3.5 brown dwarfs, alongside the known strongly variable 2MASS J01365662+0933473, in the J-band during 2017/2018 and find 4/10 to be strongly variable at a high level of significance, yielding a variability occurrence rate of $40^{+32}{}_{-19}$ %. We detect variablity amplitudes up to 10.7 % for the T1 dwarf 2MASS J22153705+2110554, for which we also detect significant light curve evolution between the 2017 and 2018 epochs, possibly similar to the evolution seen in other brown dwarfs, e.g. T2 2MASS J13243553+6358281 (Apai et al. 2017). We further confirm the continued strong variability of J0136 and find marginally significant but strong variability in another target.

This survey almost doubles the number of known strong variables in the L/T transition, providing much needed targets for the continued multi-wavelength study of brown dwarf atmospheres using the SST or HST. Combining our findings with those in the literature, we've also created an extensive multi-epoch catalogue over all known strongly variable brown dwarfs and discuss possible correlations that can be identified from this overview.

328.04 — Spectral characterization of newly detected young substellar binaries with SINFONI

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Multiplicity studies of stars and brown dwarfs have shown a decrease in multiplicity frequency as a function of primary mass and spectral type, with fewer multiple systems for primaries of lower mass and later spectral types, which stretches down all the way to the substellar mass-regime. However, at the very bottom of the stellar and substellar initial mass function, binarity and multiplicity is not very well-constrained. Recent efforts in associating low-mass members to young moving groups have provided much sought means to constrain ages for substellar objects, which otherwise prove difficult to do. As such, we are now at a point where we can compare the multiplicity rates for both older and younger samples of substellar brown dwarfs, which provide insight to their formation channels and dynamical evolution. This is of particular interest as very low-mass brown dwarfs are analogous to directly imaged exoplanets, which when resolved can be studied in high detail. We present the results from observations of 14 young low-mass substellar objects using the VLT/SINFONI integral field spectrograph with laser guide star adaptive optics, which we employ to detect and characterize 3 new binary systems. These results indicate for higher multiplicity frequencies for the younger populations of brown dwarfs, and that older systems may have undergone dynamical interactions disrupting the primordial binaries. By utilizing substellar theoretical models and the resolved brightnesses we obtain from our astrometric techniques, we discover some of these companions to be of planetary-mass. Furthermore, we find that the binary systems have small separations, which translates to orbital periods of just a few decades. As such, dynamical masses can be obtained within just a few years of astrometric monitoring, making these systems excellent benchmarks for calibrating evolutionary models in an otherwise scarcely probed mass-regime.

328.05 — Revealing the Turbulent, Cloudy Nature of Young Giant Exoplanet Analogs

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An apparent correlation between enhanced clouds and youth has emerged as an important insight into cool-temperature atmospheres. Spitzer variability monitoring allows us to trace the presence of inhomogeneous clouds in brown dwarf and exoplanet atmospheres. This method is particularly sensitive to the high-altitude clouds that are suspected in low-gravity atmospheres. In this talk I will present preliminary results from our ongoing survey for Spitzer variability in an age-calibrated sample of young (20-130 Myr), low-gravity objects that share a striking resemblance with the directly-imaged planets. Combining our sample with similar variability studies of old brown dwarfs (3-5 Gyrs) will unequivocally reveal the extent of turbulent clouds in the atmospheres of young, exoplanet analogs, while also providing crucial information on the angular momentum evolution and atmospheric dynamics of young, isolated exoplanet analogs.

328.06 — Atmosphere and Evolutionary Models for Brown Dwarf and Giant Exoplanets

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The study of brown dwarfs and giant exoplanets is rapidly evolving as ever-improving instrumentation becomes sensitive to cooler objects. Accurate and reliable atmosphere and evolutionary models are important for placing mass and age constraints on these newly discovered objects, and understanding the rich chemistry and physics taking place in their atmospheres. We are expanding on the widely used COND evolutionary models by developing a grid of model atmospheres (T_{eff}=200-2000K, log(g)=2.5-5.5) with our state-of-the-art 1D radiative-convective equilibrium code ATMO. ATMO includes the latest opacities for important molecular absorbers such as H_2O, CH_4 and NH_3, and the latest line shapes for the collisionally broadened Na and K resonance lines. These model improvements allow us to follow the evolution of 1-75M_{Jup} objects down to the coolest effective temperatures (T_{eff}=200K). We present comparisons of this new model set to those previously published, illustrating how the evolutionary tracks and the substellar boundary have changed due to improved opacities and the usage of a new equation of state. We also compare our model grid to observational datasets in colour-magnitude diagrams and investigate the impact of our new Na and K line shapes in reproducing brown dwarf spectra. Our future work will involve expanding on this initial grid, to investigate the effects of metallicity, C/O ratio and non-equilibrium chemistry in cool brown dwarfs and giant exoplanets.

328.07 — Moderate Resolution Spectroscopy of Directly Imaged Planets

Kielan Kathryn Wilcomb[1]; Quinn Konopacky[1]; Travis Barman[2]; Christopher Theissen[1]; Laci S. Brock[2]; Bruce Macintosh[3]; Jean-Baptiste Ruffio[3]; Christian Marois[4]

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Recent direct imaging of exoplanets has revealed a population of Jupiter-like objects that orbit at large separations (∼10-100 AU) from their host stars. These planets, with masses of ∼2-14 M_{Jup} and temperatures of ∼500-2000 K, remain a problem for the two main planet formation models—core accretion and gravitational instability. We present results from our ongoing survey of directly imaged planets with moderate (R∼4000) spectral resolution. We are making use of OSIRIS on the W.M. Keck I 10 meter telescope, which offers some of the best spectra to-date for directly imaged substellar companions. Thus far, we have observed eight companions in the K band (∼2.2 μm), including the "super-Jupiter" Kappa Andromeda b. Our spectra reveal resolved molecular lines from water and CO, allowing for the derivation of atmospheric properties such as temperature, surface gravity, metallicity, and C/O ratio. In particular, we confirm that Kappa And b has a low surface gravity, consistent with a young age and mass near the deuterium burning limit. We also find that Kappa And b potentially has a sub-solar metallicity. We compare our spectra of the companions in K band to those of other brown dwarfs and gas giant planets, and to each other. Our survey will improve our knowledge of the intricate atmospheres of young, substellar objects.

328.08 — Detecting a substellar high-contrast companion to an M-dwarf with CARMENES

Maritza Soto[1]
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M-dwarf stars are the most abundant type of star in the galaxy, but not very studied due to their low temperatures and radiation mostly in the infrared. The CARMENES spectrograph was created with the aim of studying these objects, by observing both in the visible and infrared wavelengths, and delivering high resolution spectra. Here we study the spectra obtained for one M dwarf observed with CARMENES, and attempt to detect the high contrast brown dwarf companion using cross-correlation techniques. We combine the spectra obtained to create a template, which is then removed from each individual spectrum. The spectra are shifted to the companion's restframe, and the residuals are cross-correlated with model spectra of different temperatures. We show that a companion with a contrast level of 0.001 at 1 micron is detectable. This makes this target a good candidate for future direct imaging efforts.

328.09 — Directly-imaged atmospheric characterisation with TauREx retrievals.

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Inverse methods have become a fundamental analysis technique for modelling exoplanetary atmospheres. This technique explores a variety of potential bulk and atmospheric model parameters that combine to best-fit an observed spectrum. TauREx (Tau Retrieval of Exoplanets) is a Bayesian retrieval suite designed to be applied to spectroscopic observations of extrasolar planetary atmospheres. We have adapted TauREx for analysis of near-infrared spectrophotometry from a variety of directly-imaged gas giant exoplanets and brown dwarfs. This includes the HR 8799 system and 51 Eri b observed using instruments such as SPHERE and GPI. This analysis returns estimates for target mass, radius, surface gravity and temperature-pressure structure, as well as confirming and constraining the presence of a variety of molecular species including H_2O and CO. This project aims to help bridge directly-imaged exoplanet observations with robust, efficient and precise characterisation. The development and adaptation of this retrieval tool is very timely and relevant given the upcoming launch of JWST.

328.10 — High Spatial Resolution Thermal Infrared Spectroscopy with ALES

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The Arizona Lenslets for Exoplanet Spectroscopy (ALES) mode of the Large Binocular Telescope Interferometer is the first adaptive-optics-fed integral field spectrograph capable of delivering 3-5 micron spectral data cubes of directly imaged exoplanets and substellar companions. By extending spectroscopic wavelength coverage of the spectral energy distributions of companions beyond near-infrared spectrophotometry, we become more sensitive to the ensemble of atmospheric processes that shape their thermal emission. ALES exists as a precursor instrument to the proposed third generation Keck instrument, SCALES, and the red channel of the proposed second generation TMT instrument, PSI. Through detailed instrument simulation, we evaluate the sensitivity of the integral field spectrograph modes of the three instruments for LBTI, Keck, and TMT, respectively, for various science cases.

328.11 — A new look at the solar neighborhood: distances and atmospheres of the coldest planetary mass brown dwarfs

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The coldest brown dwarfs, late-T and Y dwarfs, are testbeds for atmospheric studies of the extremely cold atmospheres of free-floating planetary-mass objects and provide insights into the lowest mass end of the star formation process. Using Spitzer/IRAC imaging, we present new and updated parallaxes for >140 late-T and Y dwarfs in the nearest ~20 pc (Martin et al. 2018, Kirkpatrick et al. 2019). In this talk, I will present an updated understanding of the physical properties of the coldest brown dwarfs based on these parallaxes. I will also present a new look at the substellar field mass function, which shows that the star formation process does not have a physical cutoff at the deuterium burning limit, and if a low-mass cut-off exists, it is likely below 5 Jupiter masses. Finally, I will present the first-ever Keck/NIRES spectra of Y dwarfs; the highest resolution near-infrared spectra of Y dwarfs to date (Martin et al, in prep). These spectra combined with our new parallaxes give us a detailed look at the coldest, free-floating, planetary mass objects.

328.12 — Gemini Planet Imager Spectroscopy of the Reddest Known Substellar Companion HD206893 B

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From the Gemini Planet Imager Exoplanet Survey, we present new near-infrared spectroscopy of HD206893 B, a substellar companion orbiting within the debris disk of an F5V star. New J, H, K1, and K2 spectra with GPI demonstrate the extraordinary red color of the object, presenting a challenging atmosphere to model with existing model grids. We present comparison with field and young L-dwarfs to assess whether the NIR spectra are consistent with upper atmosphere sub-micron hazes. Multi-epoch astrometric monitoring of the system suggests a probable semimajor axis of 10 au, well within the estimated disk inner radius of ~50 au. As only the second brown dwarf imaged within the innermost region of a debris disk, the properties of this system offer important dynamical constraints for companion-disk interaction and a useful benchmark for brown dwarf and giant planet atmospheric study.

329 — Planetary Atmospheres — Theory, Poster Session

329.01 — Towards a more complex description of chemical profiles in exoplanets retrievals: A 2-layer parameterisation

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State of the art spectral retrieval models of exoplanet atmospheres assume chemical profiles which are constant with altitude/pressure. This assumption is justified by the information content of currently available datasets which do not allow, in most cases, for the molecular/atomic abundances as a function of atmospheric pressure/altitude to be constrained. In the context of the next generation of space telescopes, a more accurate description of chemical profiles with additional levels of flexibility may become crucial to interpret observations and gain new insights into atmospheric physics. We explore here the possibility of retrieving pressure-dependent chemical profiles from transit spectra as recorded by future space observatories, without injecting any priors from theoretical chemical models in the retrieval algorithms. The "2-layer" retrieval parameterisation presented here allows for the independent extraction of molecular/atomic abundances above and below a certain atmospheric pressure. By simulating various cases, we demonstrate that this evolution from the assumption of constant chemical abundances is justified by the information content of transit spectra provided by future space instruments. Comparisons with traditional retrieval models show that assumptions made on chemical profiles may significantly impact retrieved parameters, such as the atmospheric temperature, and justify the attention we give here to this issue. We find that the 2-layer retrieval is able to accurately capture discontinuities in the vertical chemical profiles, which could be caused by disequilibrium processes — such as vertical mixing or photo-chemistry — or the presence of clouds/hazes. The 2-layer retrieval could also help to constrain the composition of clouds and hazes by exploring the correlation between the chemical changes in the gaseous phase and the pressure at which the condensed/solid phase occurs. The 2-layer retrieval presented here therefore represents an important step forward in our ability to constrain theoretical chemical models and cloud/haze composition from the analysis of future observations.

329.02 — The Formation of Zonal Flow and a Hot-spot Shift on Tidally Locked Planets

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The global atmospheric circulation and temperature distribution of tidally locked exoplanets is key to interpreting observations such as phase curves, eclipse maps, and atmospheric retrievals. The dominant dynamical process in their atmospheres is a super-rotating zonal equatorial jet. The meridional circulation on tidally locked planets is rarely investigated, as it is assumed to be secondary to the zonal day-night circulation. This poster will show that the meridional circulation is in fact vital to the formation of the zonal flow, via the same "Gierasch-Rossow-Williams" mechanism that operates on Venus. It will show how the meridional circulation adds eastward angular momentum to the atmosphere and transports this angular momentum upwards. This mechanism will then be used to explain the scaling behaviour of the zonal jet position and speed in a suite of GCM simulations, by predicting how the various terms in the zonal momentum equation scale with stellar flux and rotation rate.

Finally, I will link this to our recently published study using a rotating shallow-water model linearized about this eastward zonal flow. I will show that the response to day-night forcing is modified by this jet, producing the distinctive eastward hot-spot shift that appears in observations. The key result is that the shift is not produced by advection of heat, but rather is a result of interactions between forced stationary waves and the mean flow. This theoretical prediction of the equilibrium zonal flow and the resulting temperature distribution could be useful for interpreting observations of tidally locked planets.

329.03 — Atmospheric Mass Loss due to Giant Impacts

Almog Yalinewich[1]
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Exoplanet systems (especially Kepler 36b/c and Kepler 107b/c) exhibit large density variations between neighbouring planets. This difference is attributed to atmospheric content. One mechanism that is usually implicated in atmospheric mass loss is photoevaporation, but this mechanism cannot explain the Kepler 107b/c dichotomy, for which the planet with the atmosphere is closer to the host star and less massive. Another explanation is giant impacts that occur shortly after the dispersal of the protoplanetary disc. In this talk I will present new results from a state of the art, moving mesh, hydrodynamic simulations of such collisions. These simulations capture the propagation of the shock wave through the interior of the planet. Using these results it is possible to calculate the amount of atmospheric mass loss from a wide range of parameters. In contrast to other atmospheric loss processes, giant impacts can remove both the primordial and secondary atmospheres with a larger molecular weight. In this talk I will present new, yet unpublished results that include the effects of an oblique collision and take into account the finite speed of sound in the interior of the target planet. With these more realistic simulations I will show that under the right circumstances, giant collisions can account for the differences in atmospheric content in Kepler 36b/c and Kepler 107b/c.

329.04 — Do Magnetic Fields Prevent Atmospheric Escape?

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Atmospheric escape is capable of shaping a planet's atmospheric composition and total mass, and thus the planet's long-term habitability. Loss to space of atmospheric particles has played a key role in the atmospheric evolution of both Mars and Venus. Intrinsic planetary magnetic fields like the Earth's have long been thought to shield planets from atmospheric erosion via stellar winds; however, recent arguments have suggested that a magnetic field will increase the interaction area with the solar wind, collecting correspondingly more energy that can be used to drive increased escape.

Using a set of global three-dimensional hybrid plasma simulations validated via observations at Mars and Venus, we find that neither of these paradigms are complete descriptions. Rather than solely inhibiting or driving ion escape, there is a value of magnetic field strength associated with maximum ion outflow. For weaker magnetic fields, ion escape is enhanced due to shielding of the southern hemisphere from "misaligned" ion pickup forces. For stronger magnetic fields ion escape decreases due to trapping associated with closed magnetic field lines. The peak escape rate occurs where the intrinsic magnetosphere (caused by the planetary magnetic field) reaches the induced magnetosphere (caused by ionospheric conductivity). As the size of the intrinsic magnetosphere is determined by pressure balance between the incoming solar wind and the planetary magnetic field, the magnetic field associated with peak escape is critically dependent on the solar wind pressure.

Where possible we have fit power laws for the variation of fundamental parameters (escape rate, escape power, polar cap opening angle and effective interaction area) with magnetic field, and assessed upper and lower limits for the relationships. Such power laws can be used in generalized studies of atmospheric escape and potential habitability to better characterize a wide variety of systems.

329.05 — THOR version 2: a GPU-enabled, non-hydrostatic general circulation model for extrasolar planets

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We present the first major update to THOR, a non-hydrostatic, GPU enabled 3D general circulation model, which is the culmination of 8 years of work in the Heng group in Bern. THOR is the first GCM that has been built from the ground up for the study of exoplanets. Thus, it is entirely free of tunings toward solar system planets and contains as few assumptions as possible. It is also publicly available and we actively encourage the community to become involved in further development. With this model, we have the capability to model atmospheres with or without the hydrostatic approximation, independent of the additional approximations that lead to the primitive equations of meteorology. We use the model to study whether the climate structures of exoplanets are robust to the assumption of hydrostatic equilibrium. We demonstrate that the hydrostatic approximation alone is sufficient to significantly alter the zonal and vertical winds of hot jupiters. This implies that aerosol sizes derived from spectra may be miscalculated, if the wind velocities are based upon hydrostatic GCMs. The divergence between hydrostatic and non-hydrostatic simulations appears to be a function of temperature. We further discuss improvements and additions to the model that have been implemented since the release of version 1.0, including grey radiative transfer, chemical tracers, and an insolation scheme that allows for arbitrary orbits and rotation parameters. We have begun adapting the model for terrestrial planets with the goal of studying atmospheric collapse on tidally-locked worlds. Additionally, we reproduce a number of benchmark tests for dynamical cores.

329.06 — Effect of disequilibrium chemistry on the spectra of exoplanet atmospheres

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Recently, transmission and/or emission spectra of exoplanet atmospheres have been observed by both space- and ground-based telescopes. Forthcoming space missions such as JWST and ARIEL are expected to enable high-precision observation of these spectra. Most of the current retrieval models used to derive the atmospheric properties from observed spectra assume the abundance profiles of chemical species in the atmospheres to be thermochemical-equilibrium or constant ones throughout the atmosphere for simplicity. However, in reality, the abundance profiles can depart from the thermochemical equilibrium ones by the disequilibrium processes such as quenching effect. In this study, we examine how the quenching process affects the spectra of exoplanet atmospheres for some atmospheric properties such as temperature and eddy diffusion coefficient. For this purpose, we have developed 1-D model to simulate the abundance profiles considering both thermochemical reactions and eddy diffusion transport with the use of the chemical timescale for each species derived by Tsai et al. (2018). We discuss the conditions in which we can assume equilibrium chemistry or disequilibrium chemistry.

329.07 — A coherent disentanglement of the fingerprints of physics, chemistry and dynamics of exoplanets on their atmospheric spectra

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Characterization of planetary atmospheres has been always a challenge. While the next generation of facilities, such as E-ELT, JWST, and ARIEL, will help to improve the status, the number of well-characterized exoplanet atmospheres will still be limited. Large-scale simulations could assist us by predicting the diversity of the planetary atmospheres, and pointing toward the regions on the parameter space where we have a higher chance of finding interesting targets with desired properties.

We present the results of an extensive investigation, with a three-step strategy, to understand the fingerprints of physics, chemistry and dynamics of exoplanets on their atmospheric spectra. In the first step, we study the synthetic spectra of 28,224 self-consistent cloud-free models; assuming effective temperature, surface gravity, metallicity, C/O ratio of the planet, and host star's stellar type as the free parameters. We propose a new classification scheme and find a region (Methane Valley) between 800 and 1500 K, where a greater chance of CH_4 detection is expected. The first robust CH_4 detection on an irradiated planet places HD102195b within this region; supporting our prediction.

We then investigate the fingerprints of disequilibrium chemistry on the atmospheric spectra by performing 84,672 full chemical network kinetic simulations with ChemKM. We find that the quenching pressure decreases with the effective temperature of planets, but it also varies with other atmospheric parameters. We show that the atmospheric mixing does not change the shape of the two main color-populations in the Spitzer color-maps and thus any deviation of observational points from these populations are likely due to the presence of clouds and not disequilibrium processes. However, we find some colder planets (T_{eff}<900 K) with very low C/O ratios (<0.25) that show significant deviations; making these planets interesting cases for further investigations.

We further present the results of 38,500 self-consistent cloudy models to demonstrate how this picture changes when the radiative feedback of clouds is included in the models.

329.08 — Retrieving Exoplanet Spectra using deep learning

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The field of exoplanetary spectroscopy is as fast moving as it is new. Analysing currently available observations of exoplanetary atmospheres often invoke large and correlated parameter spaces that can be difficult to map or constrain. This is particularly true for the theoretical modelling of their atmospheres and the atmospheric parameter retrieval from observed data. Issues of low signal-to-noise data and large, non-linear parameter spaces are nothing new and commonly found in many fields of engineering and the physical sciences. Recent years have seen vast improvements in statistical data analysis and machine learning that have revolutionised fields as diverse as telecommunication, pattern recognition and medical physics. In this talk, I will discuss the use of machine and deep learning in inverse retrievals of exoplanetary atmospheres. I will present the ExoGAN retrieval framework, which learns the intrinsic likelihood surface of a radiative transfer retrieval using generative adversarial networks (GANs) and compare this approach to other classical and machine learning solutions in the recent literature. As we firmly move into the era of 'big data' and increasing model complexities in the era of JWST, ELTs and ARIEL, intelligent algorithms will play an important part in facilitating the analysis of these rich data sets in the future.

329.09 — Nucleation of TiO_2molecular clusters in the context of cloud formation on hot Jupiters

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Clouds form when a super-saturated gas condenses on small dust grains, leading to an optically thick gas-liquid mixture. On rocky planets like earth the processes are well-understood, as small dust grains are easily transferred from the surface to the upper atmosphere by winds. On hot Jupiters however, there is no solid surface that supplies dust grains to act as condensation cores. Yet, clouds have been observed in the atmospheres of hot Jupiters. The current understanding of the formation process is that the required condensation cores are formed through nucleation of molecular clusters of highly refractory molecules, similar to the nucleation of dust in stellar outflows.

In this work we investigate the cluster-formation of Titanium dioxide (TiO_2) as a potential candidate for the seed-nucleus. In order to establish a selfconsistent nucleation pathway, it is crucial to obtain the bond-energies for all isomers and geometries of the clusters with high accuracy. We achieve this by using quantum chemical density functional theory (DFT) calculations. We found that the B3LYP/cc-PVTZ level of theory comes closest to the experimental values from the Janaf-Nist tables. Since the DFT calculations quickly get too computationally expensive with cluster size, we employ a force-field approach to approximate the energies of larger clusters as accurate as possible. Using an interatomic buckingham pair potential we find new cluster-geometries and their respective energies using a simulated annealing technique. We use the new clusters and their energies as input for a kintetic nucleation model that serves as the basis of a cloud formation code. Finally, we investigate the impact of the cluster geometries and energies on the nucleation process and thereby on the cloud formation on hot Jupiters.

329.10 — The effect of internal gravity waves on cloud evolution in sub-stellar atmospheres

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Substellar objects exhibit photometric variability which is believed to be caused by a number of processes such as magnetically-driven spots or inhomogeneous cloud coverage. Recent substellar models have shown that turbulent flows and waves, including internal gravity waves, may play an important role in dust cloud evolution. The aim of this paper is to investigate the effect of internal gravity waves on dust cloud nucleation and dust growth, and whether observations of the resulting cloud structures could be used to recover atmospheric density information. For a simplified atmosphere in two dimensions, we numerically solve the governing fluid equations to simulate the effect on dust nucleation and mantle growth as a result of the passage of an internal gravity wave. Furthermore, we derive an expression that relates the properties of the wave-induced cloud structures to observable parameters in order to deduce the atmosphere density. Numerical simulations show that the density, pressure and temperature variations caused by gravity waves lead to an up to 600-fold increase of the dust nucleation rate and an up to 80% increase of the dust growth rate in the linear regime. These variations lead to banded areas in which dust formation is much more pronounced. We show that internal gravity waves in substellar atmospheres lead to banded cloud structures similar to those observed on Earth. Using the proposed method, potential observations of banded clouds could be used to estimate the atmospheric density of substellar objects.

329.11 — Atmospheric escape: new windows, longer baselines and demographic influences

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We present new quasi-global 3-D radiative-hydrodynamic simulations of close-in exoplanets undergoing atmospheric escape. By tracking the ionization state of outflows driven by ionization heating, we produce self-consistent synthetic observations. The resulting synthetic Lyman-α observations find several distinct large-scale features of atmospheric escape, which we classify into three regimes dependent upon the properties of the interplanetary medium (e.g., stellar wind, ionizing flux, orbital separation). Several of these new features produce substantial obscuration of the star many hours outside of transit. We therefore demonstrate that long-baseline transit observations in Lyman-α and other non-optical lines are needed to constrain mass loss mechanisms. We compare to the several observations of known systems undergoing atmospheric escape, and discuss which aspects of the theory are still missing. By incorporating recent developments in transit observations of escaping exospheres, such as ground-based observations in H-α and Helium 10830, we expand our models and probe the core of hydrodynamic escape missed in Lyman-α. We conclude by discussing how our results inform our understanding of the evaporation valley evident in super-Earth demographics.

329.12 — Planetary Interior Physics from Near Infrared Spectroscopy

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The atmosphere can often be a window into processes happening within a planetary interior. Indeed, in some cases for rocky planets, and in most cases for giant planets, the properties of the radiative atmosphere entirely regulate the cooling of deeper planetary layers, including any surface or deep interior. Often this atmosphere/interior interface is hidden from view. However, at near-infrared wavelengths, where atmospheric opacity sources (such as water vapor) are often at their minima, one can see relatively deeply into a planet's atmosphere. In some particular cases, this gives us access to the physics of the deeper atmosphere or interior. The first example: In hot Jupiters, the mechanism that causes inflated radii, a long-standing problem, is still open. Through the use of 1D models we show that in the NIR one can sometimes observe flux that emerges from below the radiative-convective boundary, which is a direct probe of the interior entropy of these planets, which will place new constraints on the radius inflation mechanism. The second example: Planets on eccentric orbits have this eccentricity damped, in which orbital energy is converted to thermal energy in the planetary interior. This thermal flux can heat interiors well in excess of that expected for simple cooling models, by orders of magnitude, leading to detectable fluxes from the deep interior. Inferring these fluxes from spectra can lead to a direct constraint on a planet's tidal quality factor, Q, which is typically not a measurable quantity. We show an example for well-studied transiting Neptune-class planet GJ 436b, and generalize this work for other planets, giant and rocky, on eccentric orbits.

329.13 — Investigating the Mineralogy of Clouds in Substellar Atmospheres

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Brown dwarfs, substellar objects not massive enough to fuse hydrogen, have cool atmospheres with the temperatures of giant planets. Their atmospheres are cool enough to form clouds and their temperature determines which species condense. Thick layers of dust, likely made of silicates, blanket L dwarf atmospheres, limiting the depths probed by spectra; these clouds clear dramatically at the L/T transition. Cloud chemistry and microphysics is challenging to model from first principles; clouds clearly form, but the specific species that condense are not well-constrained from theory. This uncertainty is a major barrier to understanding exoplanet atmospheres. The next key step in understanding these clouds is to empirically determine which clouds form using mid-infrared spectroscopy to identify mineral species. Currently there is tentative evidence from Spitzer that silicate features are present in L dwarf spectra. JWST could allow us to measure these features in many L dwarfs. Before these observations are made, we need to understand in detail at what wavelengths the strongest cloud absorption features will be, and predict which objects will have the largest amplitude signals. We present our results exploring the impact of individual cloud species, including how particle sizes and cloud mineralogy change spectral features. We investigate which objects are most ideal to observe, exploring a range of temperatures and surface gravities. We find that silicate, corundum and perovskite clouds have a strong cloud absorption feature for small particle sizes (<1 um). Silicate clouds strongly absorb at 10 um while corundum and perovskite absorb at 11.5 um and 14 um respectively. We simulate time-series observations with the MIRI instrument on JWST for a range of nearby, cloudy, and photometrically variable brown dwarfs. Our predictions suggest that with JWST, by measuring spectroscopic variability inside and outside a mineral feature (eg. the silicate feature), we can uniquely identify a range of clouds species. Mid-infrared time-series spectroscopy can therefore be used to empirically constrain the complex cloud condensation sequence in substellar atmospheres

329.15 — Help or Hinder? Assessing the Role of Clouds on the Spectra of Exoplanet Atmospheres

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As we move toward a more detailed reconnaissance of exoplanet atmospheres, the role of clouds will become more apparent. Self-consistent treatments of clouds in the reflection, emission, and transmission geometries will be necessary to interpret multiwavelength observations for a more complete understanding of a breadth of planetary atmospheres. Here we present analytic toy models for understanding how clouds can alter the information within a planetary spectrum. This "information content" is characterized by the column density of a given absorber in reflection and emission spectra, and the transit depth amplitudes for features in transmission spectra. We produce parameterizations for the information content of a range of planet types in the three main observing modes as a function of bulk cloud properties. The effects of cloud optical depth, height, vertical extent, patchiness, coverage, and albedo, are important in shaping the information content and are often inherently degenerate. We show how clouds can increase the atmospheric signal in reflection spectra, decrease the signal in transmission spectra, and produce a wider range of behavior in emission spectra. This work provides an approachable introduction for understanding the results of more sophisticated numerical models, and highlights how cloud geometry can add nuance to exoplanet atmosphere characterization.

329.16 — Extreme Storms on Synchronized Exoplanets

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We propose to present the latest results from an extensive set of numerically converged and validated simulations of global atmospheric dynamics on tidally-synchronized exoplanets. Significantly, the simulations are the highest resolution, best 'conserving' (e.g., angular momentum, energy, and enstrophy) simulations to date. These characteristics permit highly energetic, long-lived storms that chaotically stir and redistribute hot and cold temperatures on a wide range of scales, including the planetary scale (roughly planetary radius). Here, the emergence, morphology, and life-cycle of the storms are carefully studied in a hot-Jupiter context, as a generic example, with a major focus on how the storms affect the three-dimensional temperature structure and observable temporal variability. For example, tropical modons (cyclone-pairs) transport heat (cold) from day (night) side to night (day) side and produce discernable quasi-periodic signatures in the time series of disk-integrated temperature flux over many thousands of orbits. Modeling and characterizing such behaviors with fidelity are critical for understanding the nature of extreme planetary atmospheres, in which the large-scale flow speeds (characterized by the Mach number) are high, as well as for interpreting and guiding current and future observations.

329.17 — Salt Clouds, Metal Rain and Rock Storms in the Deep Atmosphere of Jupiter and Implications on Exoplanets and Brown Dwarfs

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Salts, silicates and metals, such as KCl, ZnS, TiO_2, Mg_2SiO_4, MnS, Fe, and Al_2O_3, condense as clouds in the deep atmosphere of Jupiter and greatly affect its chemical and dynamical structure. This new study has three motivations: (1) convective (rock) storms might trigger the observed internal mode oscillations of Jupiter (e.g., Gaulme et al. 2011; Markham and Stevenson 2018). (2) Salt grains could chemically modify the local plasma environment and produce possible signals for the JUNO microwave observations (Jansen et al. 2017). (3) Those high-temperature condensates are direct analogs of the clouds detected on hot Jupiters (e.g., Sing et al. 2016), directly imaged exoplanets (e.g., Zhou et al. 2016) and brown dwarfs (e.g., Apai et al. 2013), where the clouds form high in their photospheres. We first use a 1D microphysics model, CARMA (Gao et al. 2018; Powell et al. 2018), to simulate multiple cloud layers of salts, silicates and metals above 10^4 bar. TiO_2 and KCl self-nucleates to form condensation nuclei for the other vapors to condense. Iron droplets can grow up to sub-milimeter size and rain down and evaporate at $\sim 10^4$ bar. Mg_2SiO_4 is the most abundant cloud species, extending from 10^3 bar to ~ 1 bar. The micron-sized silicate and salt grains might serve as the seeds for the water cloud formation. We then use a dynamical model, SNAP (Li and Chen 2018), to simulate the silicate thunderstorm. Latent heat release from the silicate condensation and deep convective flux drive the cloud-level moist convection. Jupiter's silicate "hydrological cycle" is found to be several orders of magnitude larger than the water hydrological cycle on Earth. We consider the convective storm as a heat engine and use the CAPE (convective available potential energy) to estimate the mechanical work done by the storm. The total available energy of a single rock storm can reach $\sim 10^{26}$ erg but it depends on the area fraction of the convection. Our ongoing 3D convection simulations will shed more light on the power from the storm to excite possible seismic modes on Jupiter.

329.18 — Assessment of Machine Learning for Analysing Exoplanet Atmospheres

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Recently several attempts have been made to use machine learning algorithms either to complement or replace existing techniques used to study the atmospheres of exoplanets. However, these attempts have often led to predictions that do not capture the inherent uncertainties and degeneracies that we expect to be present in both observed data and in forward models. In this project we independently reproduce previous results and discuss the differences between results of machine learning retrieval and traditional methods. We subsequently exploer a new supervised machine learning approach and apply this method both to a previously examined case, as well as to the atmosphere of another hot giant planet, HD 209458b. In the latter case we use a fully numerical forward model. Our method leads to a closer match to traditional retrievals than other machine learning-based approaches. Finally we discuss the benefits and drawbacks of incorporating machine learning into the analysis of exoplanetary atmospheres.

329.19 — The Accuracy of Mass Measurements Required for Robust Atmospheric Characterization

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TESS discoveries have already become fruitful targets for HST follow up, and this will undoubtedly continue through the JWST era. In addition to providing targets for atmospheric characterization, TESS' Level One Science Requirement is to measure masses for 50 transiting planets smaller than 4 Earth radii. A full suite of ground based facilities will be working together to optimize the TESS science yield. Somewhat surprisingly though, no study has quantified the accuracy of mass constraints required to yield robust atmospheric properties of small planets. Previous work showed that the mass of a transiting exoplanet could be inferred from its transmission spectrum alone. The method leverages the effect of the planet's surface gravity on the atmospheric scale height, which in turn influences the transmission spectrum. However, significant degeneracies exist between transmission spectra of planets with different masses and compositions, making difficult to unambiguously determine the planet's mass and composition in many cases. I will present the first quantitative answer to this pressing question. Our analysis places definitive limits on how accurate mass constraints need to be in order to unambiguously determine atmospheric composition for a diverse array of planets ranging from terrestrial-size (TRAPPIST-1-like) to mini-Neptunes and hot Jupiters. These results broadly impact the community of scientists working on exoplanets — from the full breadth of ground based observers conducting TESS follow-up, to those studying planet populations, and finally to those planning atmospheric investigations. This is particularly timely as the STScI Director charged the HST-TESS Advisory committee to report to the Space Telescope Users Committee on how HST can best support follow-up observations of TESS exoplanet discoveries. The community needs to determine optimal strategies for maximizing the rapid scientific return from TESS targets.

330 — Future Missions and Instrumentation, Poster Session

330.01 — GLINT, a pathfinder instrument for exoplanets characterization through nulling interferometry

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High angular resolution (of order milliarcseconds) at high contrast (fractional flux of order 10^{-6} or fainter) is required to directly detect exoplanets light, revealing their intrinsic atmosphere and surface properties. Here we present the GLINT (Guided Light Interferometric Nulling Technologies) instrument, a pathfinder developed at the University of Sydney in Australia to tackle this task. It employs nulling interferometry to actively reject the light of a host star through destructive interference. Such advanced control and processing of starlight is accomplished

by way of photonic technologies fabricated into integrated optical chips. This platform immediately offers versatile and complex optical layouts all miniaturized onto highly stable and low-loss components. The first GLINT prototype was demonstrated on sky at the 4m Anglo Australian Telescope. Our current testbed on the 8m Subaru telescope boasts significantly expanded capabilities including multiple input array elements feeding a spectrally-dispersed interferometer delivering multi-channel nulling and complex visibility data.

330.02 — An Updated Study of Potential Targets for Ariel

Billy Edwards[1]*; Lorenzo Mugnai*[2]*; Giovanna Tinetti*[1]*; Enzo Pascale*[2,3]*; Subhajit Sarkar*[3]

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Thousands of exoplanets have now been discovered with a huge range of masses, sizes and orbits. However, the essential nature of these exoplanets remains largely mysterious: there is no known, discernible pattern linking the presence, size, or orbital parameters of a planet to the nature of its parent star. We have little idea whether the chemistry of a planet is linked to its formation environment, or whether the type of host star drives the processes controlling the planet's birth and evolution. Progress with these science questions demands a large, unbiased spectroscopic survey of exoplanets and Ariel has been selected as ESA's M4 mission for launch in 2028. By studying a large and diverse population of exoplanetary atmospheres, Ariel will provide insights into planetary formation and evolution within our galaxy. I will present the latest study of potential targets for Ariel in which we assessed the suitability of currently-known exoplanets and predicted TESS yields. This list of planets has been utilised to form an example Mission Reference Sample (MRS) to demonstrate that Ariel's mission goals could be met from this planetary population. I will also present the results from the latest studies into the expected scientific capability of Ariel.

330.03 — Measuring the Stellar Drivers of Exoplanet Habitability with the ESCAPE Mission (-or- Why are those solar systems so extreme???)

Kevin France[1]

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The long-term stability of exoplanetary atmospheres depends critically on the extreme-ultraviolet (EUV) flux from the host star. The EUV flux likely drives the demographics of the short-period planet population as well the ability for rocky planets to maintain habitable environments long enough for the emergence of life. In this talk, I will present the Extreme-ultraviolet Stellar Characterization for Atmospheric Physics and Evolution (ESCAPE) mission, an astrophysics Small Explorer proposed to NASA. ESCAPE employs extreme- and far-ultraviolet spectroscopy (70 - 1800 Angstroms) to characterize the high-energy radiation environment in the habitable zones (HZs) around nearby stars. ESCAPE provides the first comprehensive study of the stellar EUV environments that control atmospheric mass-loss and determine the habitability of rocky exoplanets. ESCAPE's prime mission is driven by two spectroscopic surveys: 1) a broad survey of EUV and FUV flux from 200 nearby (d < 100 pc) A, F, G, K, and M stars, providing direct input into atmospheric evolution models. The mission targets stars with a range of ages and activity levels, and places an emphasis on stars with known exoplanets. 2) A deep monitoring survey (~2 weeks per star) of 24 targets-of-interest to measure the stellar flare frequency distribution and constrain the CME rate and high-energy particle fluence from these objects. Together, these surveys provide the crucial stellar drivers that regulate habitable environments on planets targeted by upcoming atmospheric characterization missions, from JWST to LUVOIR.

330.04 — A Fabry Perot Instrument for Oxygen Searches in Exoplanet Atmospheres

Surangkhana Rukdee[1]*; Sagi Ben-Ami*[1]*; Mercedes Lopez-Morales*[1]*; Juliana Garcia-Mejia*[1]*; David Charbonneau*[1]*; Andrew Szentgyorgyi*[1]

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The large light-gathering capacity of upcoming Giant Segmented Mirror Telescopes are expected to have enough collecting area to start searching for potential biosignature gases, notably molecular oxygen O2, in the atmospheres of small planets around nearby stars. Recent simulations have shown that spectral resolutions of 300,000 - 400,000 are optimal to detect O2 in the atmosphere of an earth analog. In order to increase detection capabilities, we have developed a Fabry perot Interferometer for Oxygen Searches (FIOS), an interferometer array coupled to a high resolution spectrograph. FIOS can achieve a spectral resolution of 500,000 at the O2 A-band (760

nm). It is optimal for O2 detection, while maintaining a higher throughput compared to instruments with similar spectral resolving power. We describe the instrument concept, a simulation of its sensitivity, and preliminary results from our lab prototype.

330.05 — The Tierras Observatory: An Ultra-Precise Photometer to Characterize Nearby Terrestrial Exoplanets

Juliana Garcia-Mejia[1]; David Charbonneau[1]; Dan Fabricant[1]; Jonathan Irwin[1]

[1] *Astronomy, CfA | Harvard & Smithsonian (Cambridge, Massachusetts, United States)*

We are currently building the *Tierras* Observatory, a 1.3m ultra-precise fully-automated photometric observatory located atop Mt. Hopkins, Arizona dedicated to following up nearby transiting planets discovered by TESS and other surveys, refine estimates of their radii, and find the longer period (and hence more temperate) worlds. *Tierras* will regularly achieve a photometric precision of 700 ppm, enough to measure the transit of Earth-sized planets orbiting 0.1– $0.3R_{\odot}$ stars with 3σ significance. I will provide an overview of the current state of the observatory, as well as the design choices that will enable its science goals. These include: (i) a custom designed four-lens focal reducer and field-flattener to increase the field-of-view (FOV) of the telescope from a 12′′ to a 0.5° diagonal; (ii) a 4K × 4K pixel deep-depletion low read noise CCD operated in fast frame transfer (shutterless) mode with 80% quantum efficiency at the wavelength of observation (compared to 35% for regular CCDs); (iii) a custom narrow (50 nm) bandpass filter centered at 865 nm to minimize precipitable water vapor errors, known to limit ground-based photometry of red dwarfs; and (iv) a custom-made nano-fabricated beam-shaping diffuser to mold the focal plane image star into a broad and stable top-hat shape, increasing the dynamic range of our observations while minimizing flat-fielding, guiding, and phase-induced errors due to seeing. *Tierras* will be on-sky by January of 2020, in time to carry out plenty of follow-up observations of TESS targets in the northern hemisphere. This work is supported by the National Science Foundation, the Ford Foundation, the John Templeton Foundation, and the Harvard Origins of Life Initiative.

330.06 — Correcting instrumental systematics in Spitzer transit light curves using probabilistic Long Short Term Memory networks

Mario Morvan[1]; Ingo Waldmann[1]; Angelos Tsiaras[1]

[1] *Department of Physics & Astronomy, UCL (London, United Kingdom)*

The instrument systematic errors associated with the various space-based transit detectors remain only partly understood. Yet, they condition the whole subsequent analysis of transit light curves, from signal detection up to the planet characterization. In particular, the retrieval of atmospheres from *Spitzer*'s IRAC or *Hubble*'s WFC3 data require precise measurements of the transit depths at several wavelengths, and it is widely believed that a better correction algorithm might allow to improve the quality, robustness and complexity of the retrieval. Here I present a machine learning approach to correcting the instrument systematics and photon noise, aiming at disentangling the instrument signal from the transit signal. The algorithm makes use of the individual pixel light curves as well as the centroid position time series, and try to learn the instrument behaviour from the out-of transit parts while assuming an analytical form for the transit shape. While the first results are shown on *Spitzer* transit light curves, such an approach is widely adaptable to most of present or future space-based detectors.

330.07 — Correcting Transiting Exoplanet Light Curves for Stellar Spots: A Machine Learning Challenge for the ESA Ariel Space Mission

Nikolaos Nikolaou[1]; Ingo Waldmann[1]; Subhajit Sarkar[1]; Angelos Tsiaras[1]; Billy Edwards[1]; Mario Morvan[1]; Kai Hou Yip[1]; Giovanna Tinetti[1]

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The field of exoplanet discovery and characterisation has been growing rapidly in the last decade. However, several big challenges remain, many of which could be addressed using machine learning methodology. For instance, the most successful method for detecting exoplanets, transit photometry, is very sensitive to the presence of stellar spots. The current approach is to identify the effects of spots visually and correct for them manually or discard the data. As a first step to automate this process, we are organising a competition for the 2019 European Conference of Machine Learning (ECML) on data generated by ArielSim, the simulator of the European Space Agency's upcoming Ariel mission, whose objective is to characterise the atmosphere of 1000 exoplanets. The data consists of pairs of light curves corrupted by stellar spots and the corresponding clean ones, along with auxiliary observation information. The goal is to correct light curves for the presence

of stellar spots (multiple signal denoising). This is a yet unsolved problem in the community. In this talk we will discuss the problem, the impact of a solution, introduce the basics of machine learning and present the outline of the competition as well as initial baseline solutions.

330.08 — Exoplanet direct detection and characterization with the ELT/HARMONI integral field spectrograph

Mathis Houllé[1]; Arthur Vigan[1]; Alexis Carlotti[2]; Elodie Choquet[1]; Mickaël Bonnefoy[2]; Niranjan Thatte[3]; Benoit Neichel[1]

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[3] *Department of Physics, University of Oxford (Oxford, United Kingdom)*

High-contrast imaging is a unique method to probe the outer regions of young exoplanetary systems, and thus gives insight into the formation, composition and evolution of young giant exoplanets. Current high-contrast instruments, such as VLT/SPHERE, Gemini/GPI or Subaru/SCExAO, provide spectro-imaging capabilities at low spectral resolution (R = 30-100) that allow the detection and first-order characterization (temperature, surface gravity) of giant planets, but significantly higher resolutions would be required for more detailed estimations (abundances, orbital and rotational velocities). The next generation of instruments on extremely large telescopes (ELTs) will be ideal for this task. HARMONI will be one of the first-light instruments mounted on ESO's ELT, currently planned for 2025. It is a medium-resolution (up to R = 17,000) integral field spectrograph in the optical and the near-infrared, which will be equipped with a single-conjugated adaptive optics system to reach the diffraction limit of the ELT in the H- and K-bands. For direct exoplanet detection and characterization, HARMONI will include a high-contrast module that will provide unprecedented contrast limits at separations between 50 and 400 mas, i.e. down to 1 AU for a star at 20 pc. Exoplanet detection will be further facilitated by the medium spectral resolution of HARMONI, which allows detection based on the expected planetary spectral features. In this poster, we will present an estimation of HARMONI capabilities for exoplanet detection, based on realistic simulated data for the high-contrast mode and new analysis tools exploiting the spectral information, such as "molecule mapping" techniques (e.g. Hoeijmakers et al. 2018). We will also show preliminary estimations of HARMONI performances for orbital and atmospheric characterization of exoplanets.

330.09 — Following up TESS's temperate terrestrials with MAROON-X

Jacob Bean[1]

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MAROON-X is a new high precision radial velocity instrument that is currently being commissioned on the Gemini North telescope. MAROON-X is optimized in terms of its wavelength coverage, efficiency, stability, and pairing with a large telescope for following up TESS's habitable zone planet candidates. I will give an update on the status of MAROON-X, including commissioning progress, performance of the instrument, and how the community can use it for their own science. I will also discuss my group's plans for using the instrument for both radial velocity and atmospheric characterization work.

330.10 — The Search for Biosignatures and Exo-Earths with the LUVOIR Mission Concept

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The Large Ultra Violet-Optical-Infrared (LUVOIR) Surveyor is one of four mission concepts being studied by NASA in preparation for the 2020 Astrophysics Decadal Survey. LUVOIR is a general-purpose space-based observatory with a large aperture (8-15 m) and a total bandpass spanning from the far-UV to the near-infrared. One of LUVOIR's main science objectives is to directly image temperate Earth-sized planets in the habitable zones of Sun-like stars, measure their spectra, analyze the chemistry of their atmospheres, and obtain information about their surfaces. LUVOIR can also observing potentially habitable exoplanets transiting nearby M dwarf stars. Such observations will allow us to evaluate these worlds' habitability and search for the presence of remotely detectable signs of life known as "biosignatures." We will discuss the strategies for Exo-Earth detection and characterization, including specific observational requirements for astrobiological assessments of exoplanetary environments with LUVOIR. The survey of the atmospheric composition of dozens of potentially habitable worlds would bring about a revolution in our understanding of planetary formation and evolution, and may usher in a new era of comparative astrobiology.

330.11 — Lessons Learned for JWST Transiting Planet Time Series from Ground-based Studies of the NIRCam Detectors and Control Electronics

Everett Schlawin[2]; Karl Misselt[2]; Tom Greene[1]; Jarron Leisenring[2]; Thomas Beatty[2]; Marcia Rieke[2]

[1] *NASA Ames (Mountain View, California, United States)*

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JWST transmission and emission spectra of transiting exoplanets will provide invaluable glimpses at exoplanet atmospheres. These spectra will reveal atmospheric compositions and temperature structures at a level never achieved before. This promising science from JWST, however, will require exquisite precision and understanding of systematic errors that can impact the time series of planets crossing in front of and behind their host stars. This is especially true if JWST is used to probe the atmospheres of temperate Earth-sized planets. Here, we discuss the lessons learned from ground-based characterization of the NIRCam H2RG detectors and ASIC control electronics, which will be used in the slitless grism time series mode for exoplanet spectra. These detectors are the same type used in JWST's NIRISS and NIRSpec spectrographs as well as ground-based near-infrared instruments. Ground-based tests provide new understandings of the crosshatching on the detectors that trace to the crystallographic structure of the HgCdTe. We show that the crosshatching behavior extends to the subpixel level and can be modeled in the Fourier domain. We provide models that estimate the impact of subpixel crosshatching when subject to pointing jitter of the telescope. Ground-based tests also reveal that correlations in the read noise (1/f noise) can strongly affect time series apertures. If uncorrected, these correlations can rival photon noise on short integrations. 1/f noise correction algorithms are of special importance to targets where only a few samples may be read per integration and exquisite precision (sub 50 ppm) is desired. We discuss several strategies for removing correlated read noise. We summarize the lessons learned from ground-based testing of flight detectors and electronics at NASA Goddard, NASA Johnson as well as flight-like electronics and detectors at the University of Arizona detector labs.

330.12 — Design and Performance of NEID Ultra-Stable Environmental Control System

Emily Lubar[2]; Paul Robertson[1]; Frederick Hearty[2]; Gudmundur Kari Stefansson[2]; Andrew Monson[2]; Suvrath Mahadevan[2]; Jason Wright[2]; Shubham Kanodia[2]; Chad Bender[3]; Joe Ninan[2]; Arpita Roy[4]; Sam Halverson[4]

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NEID is a NASA & US NSF funded ultra-stable, optical spectrometer designed to achieve Radial Velocity (RV) precision on the order of 10cm/s. Achieving this level of measurement precision requires extreme thermo-mechanical stability within the instrument which we achieve by maintaining a vacuum on the order of microTorr as well as sub-milliKelvin temperature stability. In this poster, we will outline NEID's Environmental Control System (ECS) and Temperature Monitoring and Control (TMC) System, which were both inherited and improved upon from that of the Habitable-zone Planet Finder (HPF) infrared spectrograph. We have achieved our target stability by demonstrating < 0.4mK RMS temperature variability over the course of a 30 day stability run in the lab. We expect our stability to improve at the observatory as the WIYN instrument room is more stable than our instrument development lab at Penn State. NEID will be commissioned in Fall 2019 at Kitt Peak National Observatory on the 3.5m WIYN Telescope. It will serve the exoplanet community as a vital resource for the detection and confirmation of low-mass exoplanets.

330.13 — Creating realistic synthetic observations of transiting exoplanets with JWST introducing instrumental systematics

Marine Martin-Lagarde[1]; Pierre-Olivier Lagage[1]; René Gastaud[1]; Alain Coulais[2,1]; Christophe Cossou[3]; Daniel Dicken[1]

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The launch and commissioning of the James Webb Space Telescope (JWST) in 2021 will provide game-changing astronomical observations, in particular for exoplanets. The Mid-InfraRed Instrument (MIRI) with its Low-Resolution Spectrometer (LRS) will carry out transit spectroscopy of the exoplanet atmospheres with unprecedented precision. The Early Release Science (ERS) program of JWST includes a complete light-curve spectroscopy of WASP43-b hot-Jupiter. In order to prepare the analysis of the observations, several pieces of software have been developed to create synthetic data of such observations. The instrument consortium has created MIRISim, a simulator reproducing as accurately as possible the instrument behaviour, including its noise and systematics, for imaging and spectroscopy modes of MIRI. The consortium made it publicly available. Complementary to MIRISim, we have developed ExoNoodle, a Python tool to generate time-series spectra of star-planet systems, varying over time as the planet orbits around the star. It aims at providing MIRISim with Time-Series Observations (TSO) input files. MIRISim does not include a TSO mode. Changing the source spectrum over time means to restart a new computation, therefore getting rid of the systematics evolution. Here, we present how we applied post-processing to MIRISim data to generate realistic MIRI-LRS observation of the WASP43 system, including the instrument systematics. These simulated data are used to test and improve the data reduction and retrieval techniques the community is building. They will be used in the framework of MIRI exoplanet data challenge to be conducted to prepare the exoplanet ERS program.

330.14 — Connection between free-floating and ice-giant exoplanets

Radoslaw Poleski[1]

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Gravitational microlensing technique has already provided first-order estimate of the occurrence rate of free-floating planets and detections of a few ice-giant planets. These objects are detected as, respectively, very short single-lens single-source microlensing events and short anomalies that are well-separated from otherwise single-lens events. However, some very short events that look like single-lens can be caused by bound planets which host stars were not closely approached by the sources. To constrain the existence of host we can use three lines of evidence: microlensing signal by the host, anomalous shape of the planetary sub-event, or host light detection (using adaptive optics or Hubble Space Telescope imaging). In some cases, none of these will give definite answer and this fact leads to possible misidentification of free-floating and bound planets. The chances of this misidentification are higher if the population of the wide-orbit planets is large. Thus, full inference of occurrence rate of free-floating planets has to take into account the false-positive bound planets. In a few years, large samples of both free-floating and ice-giant exoplanets will be found by the NASA flagship WFIRST mission and these samples have to be analyzed jointly. Full understanding of the origin of free-floating planets requires measuring their masses, but this can be efficiently done only if Euclid satellite conducts microlensing survey concurrently with WFIRST. In contrast, for the bound planets the mass can be measured in two additional ways. First, the microlensing parallax detection is enabled by timing of the planet and host events. Second, the host light detection constrains the mass-distance relation. Either of these can be combined with source size measurement to give direct measurement of the lens mass and distance.

330.15 — 'Alopeke, Zorro, and NESSI: Three dual-channel speckle imaging instruments at Gemini-North, Gemini-South, and the WIYN telescopes.

Nicholas Jon Scott[1]

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Zorro is the newest in a line of three speckle imagers built at NASA's Ames Research Center for community use at the WIYN and Gemini telescopes. The three instruments are functionally similar and include the capability for wide-field imaging in additional to speckle interferometry. The diffraction-limited imaging available through speckle effectively eliminates distortions due to the presence of Earth's atmosphere by 'freezing out' changes in the atmosphere by taking extremely short exposures and combining the resultant speckles in Fourier space. This technique enables angular resolutions equal to the theoretical best possible for a given telescope, effectively giving space-based resolution from the ground. Our instruments provide the highest spatial resolution available today on any single aperture telescope. The instruments have been installed and commissioned and are in regular use at these observatories. In addition to diffraction-limited speckle imaging, they are equipped with standard Sloan filters and can perform extremely high cadence photometry in either a narrow speckle field-of-view of less than 10 arcseconds or a one-arcminute wide field-of-view.

A primary role of these instruments is exoplanet validation for the Kepler, K2, TESS, and many RV programs. Contrast ratios of 6 or more magnitudes are easily obtained in speckle mode. The instruments use two emCCD cameras providing simultaneous dual-color observations help to characterize detected companions. High resolution imaging enables the identification of blended binaries that contaminate many exoplanet detections, leading to incorrectly measured radii. In this way small, rocky systems, such as Kepler-186b and the TRAPPIST-1 planet family, may be validated and thus the detected planets radii are correctly measured.

330.16 — Small Satellites for Extreme Systems: Upcoming Space Missions and Concepts for Exoplanet Exploration

Brian Fleming[1]*; Kevin France*[1]
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Extreme solar systems are often dynamic, orbit active stars, and require dedicated facilities for monitoring and characterization. The ultraviolet (UV; 100 – 300 nm) bandpass offers sensitive probes of atmospheric mass loss, protoplanetary disks, and the interplay between exoplanet atmospheres and the stellar radiation field, yet resources remain elusive. The UV can only be accessed from large, shared-use, space observatories. Small satellites and cubesats offer a new paradigm for studying transient systems. We present three missions under development at the University of Colorado that will demonstrate the potential of dedicated, low cost space instruments. The Colorado Ultraviolet Transit Experiment (CUTE) is a near-UV (250 - 330 nm) spectrograph in a 6U cubesat set to launch in mid-2020 to study atmospheric mass loss in close-orbiting giant exoplanets. The SPRITE cubesat is also a 6U spectrograph, but operates in the far-UV (100 - 200 nm) in a bandpass currently only accessible to Hubble and UVIT. The SPRITE instrument is a pathfinder for future far-UV cube- and smallsats. Finally, we present a concept for such a smallsat, COMPASS; an ESPA-class missions that could deliver unprecedented sensitivity in the deep FUV (100 - 115 nm) for a fraction of the cost of an Explorer-class mission. COMPASS measures the FUV irradiance of host stars and proxies for impulsive particle outbursts to assess the habitability of orbiting exoplanets. These missions represent part of the first step towards a new era of exoplanet surveys and characterization from space-based platforms.

330.17 — Exoplanet Host Star Characterization with QWSSI

Gerard van Belle[1]*; Catherine Clark*[2,1]*; Elliott Horch*[3,1]*; David Trilling*[2]
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[3] *Southern Connecticut State University (New Haven, Connecticut, United States)*

QWSSI, the Quad-camera Wavefront-Sensing Speckle Imager, is a next-generation speckle imager that is being developed for Lowell Observatory's 4.3-meter Discovery Channel Telescopes. The principle behind QWSSI is to extend the capabilities of the speckle camera currently resident at Lowell, the Differential Speckle Survey Instrument (DSSI), in two ways. First, while DSSI currently observes in two visible channels, QWSSI will simultaneously observe in six narrow-band channels: four in the visible (0.5-0.9um), and one each in J- and H-band (1.2 and 1.6um). Second, the visible light unused for speckle imaging is carefully preserved and feeds a wavefront sensor (WFS), which is also run simultaneously with the speckle imaging. Simulations by Löbb (2016) indicate WFS data will provide significant gains in exploring stellar multiplicity, with marked improvements in primary-secondary contrast ratios and inner working angle (Horch et al. 2018). QWSSI will also be mountable on one of the three 1-meter telescopes being installed on the NPOI Array for engineering tests and preliminary science observations. QWSSI will expand on the already considerable exoplanetary work of the speckle imagers DSSI, NESSI (@ WIYN), Alopeke (Gemini-N), and Zorro (Gemini-S), improving the discovery space for existing targets, as well opening up new regions of that discovery space with its NIR channels.

330.18 — Progress on Starlight Suppression Technologies for NASA Direct Imaging Missions

Gary Blackwood[1]*; Nicholas Siegler*[1]*; Brendan Crill*[1]*; Karl Stapelfeldt*[1]*; Eric Mamajek*[1]*; Kendra Short*[1]*; Phillip Willems*[1]
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Extensive interest in exoplanet research is motivated in part by the search for evidence of life on a subset of these worlds. This scientific search relies on measurements of star spectra, and upon the planet spectra, photometry, and mass. The ability to measure these planet properties at the required sensitivity has been the focus of sustained technology investments by NASA for the past decade, investments which are now achieving milestones and sensitivity thresholds that for the first time enable mission concepts capable of a search for evidence of life on exoplanets. Most notably, broadband contrast levels for coronagraphs and starshades have recently been demonstrated to meet better than 4×10^{-10} and 10^{-11}, respectively — thresholds required for spectral characterization of exo-earths in the habitable zones of sun-like stars.

NASA's Exoplanet Exploration Program (ExEP) identifies technology gaps pertaining to possible exoplanet missions and works with the community to identify and track technologies to prioritize for investment, and ultimately to close the gaps. The Decadal Survey Testbed, a NASA ExEP facility for testing next-generation coronagraphs, has recently demonstrated contrast performance at better than 4×10^{-10}. A sub-scale starshade validation demonstration has met the 10% broadband visible contrast threshold of better than 10^{-10} contrast. A technology readiness level 5 milestone was recently met with a laboratory demonstration of a novel formation flying sensor that demonstrates the required lateral position sensitivity.

This poster describes the recent technology breakthroughs and the enabling impact on mission concept studies being submitted to the 2020 Astro Decadal Survey for direct imaging of exoplanets and spectral characterization to search for evidence of life.

330.19 — The WFIRST Coronagraphic Instrument's Role in the Direct Imaging of Planetary Systems

John Debes[1]; Vanessa Bailey[3]; Jeremy Kasdin[5]; Nikole Lewis[2]; Bruce Macintosh[4]; Bertrand Mennesson[3]; Jason Rhodes[3]; Aki Roberge[6]; Margaret Turnbull[7]; Margaret A. Ferking[3]; Feng Zhao[3]

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The Wide Field Infrared Survey Telescope (WFIRST) coronagraphic instrument (CGI) is predicted to be capable of high contrast imaging and spectroscopy of exoplanets and circumstellar dust in reflected visible light. CGI will be a technology demonstration of five main areas that aid future direct imaging missions such as LUVOIR and HabEX: exquisite wavefront control through a pair of deformable mirrors, suppression of an on-axis star's diffraction pattern through occulting masks or shaped pupils, the use of photon counting visible detectors and post-processing techniques at high contrast in space, and high contrast spectroscopy. We will present an overview of CGI's design and of its predicted scientific capabilities. The technology demonstration phase of CGI operations will include the spectroscopic characterization of at least one known giant planet, as well as a photometric characterization of several additional known giant exoplanets orbiting nearby stars. Additionally, CGI will be sensitive to a wide range of circumstellar disks around main sequence stars, from protoplanetary disks to tenuous exozodiacal disks that may interfere with the detection of Earth analogs. These observations will provide constraints on the atmospheric and cloud chemistry of giant planets and will characterize the physical properties of circumstellar disks over several orders of magnitude in dust mass. CGI will retire many of the risks currently associated with attempting to directly image and characterize Earth-like planets during its technology demonstration phase. If the CGI performance during the technology demonstration phase warrants it, additional science campaigns may be undertaken by a competitively selected Participating Scientist Program team during later phases of the WFIRST mission.

330.21 — The Next decade (or two) of X-ray Exoplanet Studies.

Scott Wolk[1]

[1] *High Energy, Harvard-Smithsonian Center for Astrophysics (Cambridge, Massachusetts, United States)*

High energy photons and particles create some of the most extreme environments for exoplanets. I highlight the contributions to exoplanet science made by XMM-Newton and Chandra X-ray observatory over the last two decades. This research has included many individual exceptional system such as CoRoT-2, HD17156 and GJ436. Conversely, So many X-ray bright exoplanet hosts have been identified that statistical analysis, such the distribution of exoplanet masses in the presence of X-ray irradiation, are possible. As an example recent results that suggests that planet atmospheres have been eroded by their host star coronal emissions. I discussion of prospects for observations with future X-ray missions XRISM, SEEJ, Athena and Lynx.

330.22 — The NASA Exoplanet Exploration Program: Update and Prospects for the 2020's and Beyond

Eric E. Mamajek[1]; Gary Blackwood[1]; Kendra Short[1]; Karl Stapelfeldt[1]; Nicholas Siegler[1]; Brendan Crill[1]; Keith Warfield[1]; John L. Callas[1]; Phillip Willems[1]; Anya Biferno[1]; Douglas Hudgins[2]; Martin Still[2]; Shahid Habib[2]; Chas Beichman[3]

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The NASA Exoplanet Exploration Program (ExEP) is responsible for implementing NASA's plans for discovering and characterizing exoplanets, and identifying candidates that could harbor life. ExEP manages concept studies, technology development programs, precursor and follow-up ground-based science programs that aim towards achieving the science goals of current and future NASA missions (and that enable the design of next generation exoplanet missions), and communicates the excitement of exoplanet research to the public. We will review recent activities in the NASA-NSF Exoplanet Observational Research (NN-EXPLORE) partnership, progress in the characterization of exozodiacal light, the status of ongoing studies of future exoplanet flagship missions, and recent technology milestones — including updates on the progress of starshade and coronagraph technology capable of imaging and characterizing nearby habitable exoplanets.

330.23 — The Oxyometer: A Novel Instrument Concept for Characterizing Exoplanet Atmospheres

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With TESS and ground-based surveys searching for rocky exoplanets around cooler, nearby stars, the number of Earth-sized exoplanets that are well-suited for atmospheric follow-up studies will increase significantly. For atmospheric characterization, the James Webb Space Telescope will only be able to target a small fraction of the most interesting systems, and the usefulness of ground-based observatories will remain limited by a range of effects related to Earth's atmosphere. Here, we explore a new method for ground-based exoplanet atmospheric characterization that relies on simultaneous, differential, ultra-narrow-band photometry. The instrument uses a narrow-band interference filter and an optical design that enables simultaneous observing over two 0.3 nm wide bands spaced 1 nm apart. We consider the capabilities of this instrument in the case where one band is centered on an oxygen-free continuum region while the other band overlaps the 760 nm oxygen band head in the transmission spectrum of the exoplanet, which can be accessible from Earth in systems with large negative line-of-sight velocities. We find that M9 and M4 dwarfs that meet this radial velocity requirement will be the easiest targets but must be nearby (<8 pc) and will require the largest upcoming Extremely Large Telescopes. The oxyometer instrument design is simple and versatile and could be adapted to enable the study of a wide range of atmospheric species. We demonstrate this by building a prototype oxyometer and present its design and a detection of a 50 ppm simulated transit signal in the laboratory. We also present data from an on-sky test of a prototype oxyometer, demonstrating the ease of use of the compact instrument design.

331 — Habitability and Biosignatures, Poster Sessopm

331.01 — Dying to Live: Post-Main Sequence Habitability

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During the post-main sequence phase of stellar evolution the orbital distance of the habitable zone, which allows for liquid surface water on terrestrial planets, moves out past the system's original frost line, providing an opportunity for outer planetary system surface habitability. We use a 1D coupled climate/photochemistry code to study the impact of the stellar environment on the planetary atmospheres of Earth-like planets/moons throughout its time in the post-main sequence habitable zone. We also explore the ground UV environments of such planets/moons and compare them to Earth's. We model the evolution of star-planet systems with host stars ranging from 1.0 to 3.5 M_{Sun} throughout the post-main sequence, calculating stellar mass loss and its effects on planetary orbital evolution and atmospheric erosion. The maximum amount of time a rocky planet can spend continuously in the evolving post-MS habitable zone ranges between 56 and 257 Myr for our grid stars. Thus, during

the post-MS evolution of their host star, subsurface life on cold planets and moons could become remotely detectable once the initially frozen surface melts. Frozen planets or moons, like Europa in our Solar System, experience a relatively stable environment on the horizontal branch of their host stars' evolution for millions of years.

331.02 — Exploring Giant Planets & Exomoons in the Habitable Zone.

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While the search for exoplanets has been focused primarily on trying to find Earth like planets, there have been discoveries of many different worlds that have caused us to revise our ideas as to what could be a potentially habitable planet. Interestingly a significant number of giant exoplanets (>3 earth radii) have been detected in the habitable zone of their star. These giant planets are likely gas giants and thus are not considered habitable on their own, but they each could potentially be host to large rocky exomoons which would also exist in the habitable zone. These moons, should they exist, will offer new ways to understand the formation and evolution of planetary systems, and widen the search for signs of life out in the universe. The occurrence rates of these moons are related directly to the occurrence rates of giant planets in the habitable zone of their star, thus we estimated the frequency with which we expect giant planets to occur in the habitable zones. We then compiled a proposed exoplanet target list to be used in the search for detectable exomoons and for performing more detailed follow-up studies. We identified 121 giant planets whose orbits lie within either the optimistic habitable zone (OHZ) or the conservative habitable zone (CHZ). As well as the potential existence of exomoons, these giant planets in the HZ of their star raise questions as to the formation and evolution of these systems. As giant planets are thought to form beyond the snow line these planets likely migrated inwards during their formation in order for them to reside in the HZ today. One possible explanation as to why these planets stopped migrating once they reached the HZ is that of orbital resonance with other planets. Thus we fit each of the 121 HZ giant planets radial velocity (RV) data to confirm their orbital solution and look for linear trends to determine if there were indications for additional planetary companions. Of the 121 giant planets tested, 51 showed indications of additional companions (> 3σ). Highlights of our calculations will be presented along with up to date results from ongoing RV observations of the most promising of these systems.

331.03 — Predicting the UV Emission of M dwarfs with Exoplanets from Ca II and H-α

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Given the current capabilities of exoplanet detection methods, M dwarf stars are excellent candidates around which to search for temperate, Earth-sized planets. The UV wavelength regime is important to evaluate the photochemistry of the planetary atmosphere because many molecules have highly wavelength dependent absorption cross sections that peak in the UV (900-3200 Å). M dwarfs are highly active stars with unique spectra that can drive the abiotic production of key planetary biosignatures. We seek to provide a broadly applicable method of estimating the UV emission of an M dwarf, without direct UV data, by identifying a relationship between non-simultaneous optical and UV observations. Our work uses the largest sample of low-mass star UV observations yet assembled, including data from the MUSCLES and Mega-MUSCLES Treasury Surveys (Measurements of the Ultraviolet Spectral Characteristics of Low-mass Exoplanetary Systems), the FUMES survey (Far Ultraviolet M-dwarf Evolution Survey), and the HAZMAT survey (HAbitable Zones and M dwarf Activity across Time). We measure Hα equivalent widths and the Mount Wilson CaII H&K S and R'_{HK} indices using ground-based optical spectra from the HARPS, UVES, and HIRES archives and new HIRES spectra. Archival and new Hubble Space Telescope COS and STIS spectra are used to measure line fluxes for the brightest chromospheric and transition region emission lines between 1200-2800 Å. Our results show a correlation between UV line luminosity and CaII R'_{HK} with standard deviations in the range of 0.25-0.54 dex about

the best-fit lines. Correlations between UV luminosity and Hα or the S index are weak. The results presented in this talk will be important for near-future allocations of competitive Hubble time as well as the post-Hubble era. We demonstrate that with a precise R'_{HK} measurement obtained from the ground (e.g., 5-10% precision), the estimate of the intrinsic Lyα luminosity is ~12-20%, which is typically better than what can be achieved with direct, low-to-medium S/N Hubble spectra. After we gather more data this summer, we will also be able to detail dependencies on age and spectral type.

331.04 — 3-D Climate Models For Characterizing Habitable Terrestrial Extrasolar Planets

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While the recently discovered extrasolar planets have both challenged our imaginations and broadened our knowledge of planetary systems, perhaps the most compelling objective of exoplanet sscience is to detect and characterize habitable and possibly inhabited terrestrial worlds around other stars. In our quest to characterize habitable worlds, three-dimensional (3-D) general circulation models (GCMs) should be used to evaluate the potential climate states and their associated observable signals. 3-D models allow for self-consistent and realistic simulations of the climates of terrestrial extrasolar planets around a variety of stellar spectral types. Future observatories have the capability to deduce transmission, thermal emission, and reflectance spectra as a function of orbital phase. A complete understanding of terrestrial exoplanetary atmospheres, gained through comprehensive 3-D modeling, is critical for interpreting spectra of exoplanets. In this presentation, we will highlight the recent advances in 3-D climate model studies of habitable climates, and their impact on observables. We show that the current assumption of a (modern) Earth-analog as a template for a habitable planet around other stellar spectral types is not a representative model for important features in the observed spectrum. Improving upon our models of habitability is particularly relevant for planets within the habitable zones of low-mass stars (late-K and all M-dwarfs), which might be amenable for characterization in the near future either with JWST or large ground-based telescopes or the mission study concept OST. Such improvements will also be equally important for planets around Sun-like stars due to different evolutionary and planetary system history, which can be studied by mission studies like LUVOIR and HabEX. The presentation will include potential synergies that can be fostered between theorists and observers, with a common goal of finding an inhabited exoplanet.

331.05 — Geochemistry of Carbon Cycles on Rocky Exoplanets

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The long-term carbon cycle (also known as the silicate-carbonate cycle) acting on a timescale of the order of hundreds of thousands of years provides the essential negative feedback to maintain temperate climates on Earth. With the discovery of almost a thousand rocky exoplanets and ongoing hunts for an Earth-twin, it is imperative to understand the working of the carbon cycle on such planets. The aim is to investigate the factors of the Earth's carbon cycle that are critical to stabilize and destabilize carbon cycles on rocky exoplanets. These factors could be dependent on the orbital, planetary and stellar parameters as well as planet-specific properties such as rock composition, land and ocean fractions, among other factors. In this study, we focus on modeling the chemical kinetics of rock-water interaction for different rock types (depending on the planet's surface composition), as well as pH. We incorporate a set of silicate weathering reactions leading to the formation of carbonates. In addition to continental silicate weathering, we explore the effects of seafloor weathering especially in the context of varying landmass fractions, and shallow and deep ocean fractions. Other components of the carbon cycle such as subduction, ridge and arc volcanism are parameterized based on previous studies. The effects of planet size, oxidation states, and tidal locking are also investigated.

331.06 — Stellar Flares and Habitable (?) M-dwarf Worlds: Exploring a New Sample with TESS

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Finding and characterizing small exoplanets transiting small stars naturally poses the question of their habitability. A major contributing factor to this might be stellar flares, originating from powerful magnetic reconnection events on the star. While too powerful flaring can erode or sterilize exoplanets' atmospheres and diminish their habitability, a minimum flare frequency and energy might be required for the genesis of life around M-dwarfs in first place. Here, I will highlight our study of stellar flares from the Transiting Exoplanet Survey Satellite (TESS). In the first year of TESS data, we already identified thousands of flaring M-dwarfs, most of which are rapidly rotating and of late spectral types. Our sample includes superflares that showed over 30× brightness increase in white light. I will link our results to criteria for prebiotic chemistry, atmospheric loss through coronal mass ejections, and ozone sterilization. Expanding this with upcoming TESS sectors, stellar flare studies will ultimately aid in defining criteria for exoplanet habitability.

331.07 — Abiotic Oxygen on Venus-Like Exoplanets Around M-Dwarfs

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Terrestrial exoplanets in the habitable zones of nearby M dwarfs represent the first targets for the search for life outside of the Solar System. It has been long thought that one of the most obvious biosignatures on alien worlds would be the spectroscopic detection of O_2 and/or O_3, created by a global biosphere of photosynthetic life forms (Meadows et al., 2018). However, modeling has suggested that large amounts of O_2 can be created abiotically—especially on terrestrial planets around M dwarfs. In particular, Gao et al. (2015) showed that desiccated worlds with CO_2-rich atmospheres can build up ~15% O_2 via CO_2 photolysis. Venus, nonetheless, has little atmospheric O_2, despite ongoing CO_2 photolysis. This has been attributed to catalytic cycles involving ClO_x and SO_x that regenerate CO_2 from CO and O (Mills et al., 2007; Yung & DeMore, 1999). We seek to ascertain how these cycles behave on Venus-like planets around different types of stars.

We have constructed a 1-D photochemical model based on Zhang et al. (2012) to study the atmospheric chemistry of Venus-like exoplanets. The model simulates an atmosphere primarily composed of CO_2 (~90 bars) and N_2 (~3 bars) with trace amounts of H_2O, SO_2, HCl, and other constituents composed of H, C, O, N, S, and Cl, which contribute the HO_x, ClO_x, SO_x, and NO_x catalysts that can recombine photochemically generated CO and O into CO_2. We compare the effect of G- and M-dwarf spectral energy distributions on Venus-like worlds, placing the planets at orbital distances with the same total incident flux as Venus.

We find that Venus-like worlds are rich in catalysts that can recombine CO and O into CO_2. Around both G and early M dwarfs, as the catalytic ClO_x chemistry is sufficient recombine CO and O. We identify catalytic cycles involving Cl–S molecules that control the buildup of large amounts of photochemical O_2 around late M dwarfs. Specifically, around TRAPPIST-1, low SO_2 mixing ratios significantly reduces the action of Cl–S catalysts that scrub O_2 and reconstitute CO_2. This implies that Venus-like planets around late M dwarfs must maintain some amount of active SO_2 outgassing to be robust against abiotic O_2 production.

331.08 — A laboratory-to-model approach to understanding exoplanet biosignatures

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The assessment of exoplanet habitability is predominantly based on the measurement of biosignature gases, usually in the form of triplicate sets of CH_4, O_2, CO_2, and O_3, among other molecules indicative of life. Because exoplanets are distant, this is predicated on the ability to characterize atmospheres that would contain these gases at detectable limits for remote telescopes. However, this methodology often lacks a mechanism relating atmospheric detections to the potentially biogenic sources that emit these gases at the planetary surface. This can lead to misinterpretations between abiotic signatures and truly biotic sources. Here we present a study to quantitatively link surface processes and atmospheric chem-

istry for potentially habitable exoplanets using actual microbiological experiments. We will measure gas outputs from actual field samples of microbial communities that are from various ecosystems in which a multitude of major biogenic gases can be quantified. These measurements will serve as exoplanet surface inputs to the Atmsopheric-Rock-Ocean-Chemistry (AROC) model, which couples an aqueous geochemistry code and KINETICS (a photochemistry code) to trace surface-to-atmosphere chemistry. In this way, we can to bridge the gap between exoplanet biosignatures and the very biology and metabolisms found in nature. The results from this study can help guide the design of future ground- and space-based telescopes (e.g., JWST, ARIEL, ELTs, HabEx, LUVOIR, Origins) by identifying additional biosignatures that would help distinguish between atmospheric conditions that may or may not be conducive to life.

331.09 — Stellar Energetic Particle-induced radiation dose as a constraint on the habitability of terrestrial exoplanets

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Space weather has a profound impact on planetary atmospheres and has the potential to disrupt hospitable environments on exoplanets. The effect is more significant in case of close-in exoplanets around active stars. In addition to X-rays and EUV from stellar flares, energetic charged particles can ionize the atmosphere leading to photochemical changes, result in atmospheric erosion and can enhance radiation dose on the planetary surface. Charged particles of GeV energies undergo hadronic interactions in the atmosphere producing secondary particles, a fraction of which traverse down to the surface with harmful biological effects. Using data from 70 major SPEs (Solar Particle Events) over the past century as a proxy, and using GEANT4 (CERN) Monte Carlo model, we simulate radiation dose induced by Stellar Energetic Particles on presently known habitable exoplanets for various atmospheric and magnetospheric conditions. This is the first comprehensive study to quantify the effects of SEPs on exoplanets. We compare the results with experimental radiobiology data and discuss its implications on constraining the habitability of terrestrial exoplanets.

331.10 — Transition from Eyeball to Snowball Driven by Sea-ice Drift on Tidally Locked Terrestrial Planets

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Background: Among the ≈4000 confirmed exoplanets, most of them are orbiting around M dwarfs because they are relatively easy to detect and M dwarfs are the most common type of star in the galaxy. About 15 exoplanets are most likely to have rocky compositions and meanwhile in the habitable zone within which the surface is temperate to maintain liquid water. These planets are the prime targets for future atmospheric characterizations of potentially habitable systems, especially the three nearby ones–Proxima b, TRAPPIST-1e, and LHS 1140b. Previous studies suggest that if these planets have surface ocean they would be in an eyeball-like climate state: ice-free in the vicinity of the substellar point and ice-covered in the rest regions. However, an important component of the climate system–sea ice dynamics has not been well studied in their work.

Fundamental question: Would the open ocean of the eyeball-like climate be stable against a globally ice-covered snowball state? Or, could sea-ice drift close the open ocean?

Methods: Through a series of climate experiments, we investigate the effects of oceanic heat transport and sea-ice drift on the surface ice coverage of tidally locked terrestrial planets. Hundreds of numerical experiments were performed in order to clearly know the robustness of the results.

Conclusion: Ocean dynamics trend to expand the open-ocean area, but more importantly wind-driven sea-ice drift toward the substellar point shrinks the open-ocean area and even drives some of them to a snowball state. This works for both a synchronous orbit and a resonance orbit. The dominated mechanism is that sea-ice drift cools the sea surface through absorbing heat during ice melting when the ice flows to the warmer substellar region.

Implication: Previous studies have shown that stellar radiation, atmospheric composition and evolution, atmosphere dynamics, clouds, and ocean dynamics are important for the climate and habitability of tidally locked planets. Here, we show that another critical factor—sea ice dynamics, which is able to drive an eyeball-like climate state to a globally ice-covered snowball state.

331.11 — TETH: Towards Extra-Terrestrial Habitats

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The discovery and characterisation of new extrasolar planets (exoplanets) is ongoing, but to date only a handful of low-mass planets have been found orbiting in the habitable zone of sun-like stars. The next generation of major facilities (e.g. TESS and PLATO) aimed at the systematic search for Earth-like planets orbiting solar-like stars will be operational in the coming years, and some of the planets they will find may orbit stars close enough for atmospheric characterisation, including the possible detection of biosignature gases. Studies on the formation and evolution of the Earth reveal that an Earth-like habitat is characterised by a N-dominated atmosphere and could be detected by measuring the relative atmospheric abundances of N, O, C, and H (NOCH). However, N, which is the main fingerprint of an Earth-like habitat, is extremely difficult to detect and may be possible only in the ultraviolet, a wavelength range that has not been studied for low-mass exoplanets. Before starting the search for bio-signatures with future facilities (e.g. ELTs, LUVOIR), we need to explore our capabilities to detect Earth-like habitats. Here, we present several synthetic transmission spectra for the Earth's atmosphere, for the wavelength range 915 to 11000 Å, at a spectral resolution of R = 100,000. We focus on both atomic and molecular features, and discuss the detectability of N.

331.12 — Assessing the Potential of Volatile Organic Compounds as Exoplanet Biosignatures

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Remotely detectable signs of life, or biosignatures, are being widely studied for future exoplanet observations. While the majority of the studies focus on simplest molecules such as Oxygen, Ozone, or Methane, Earth's biosphere emits a significantly broader range of gaseous species into the atmosphere, including what is called Volatile Organic Compounds (VOCs). The specific inventory of these relatively complex molecules would have more limited possibilities to be produced by abiotic processes on terrestrial planets, making them potentially useful, complementary biosignatures. A drawback is that they are photochemically vulnerable and less likely to be accumulated in the atmosphere. In our presentation, we make a general assessment of VOCs as exoplanet biosignatures by studying the characteristics of their spectral features and the conditions in which VOCs may accumulate in planetary atmospheres to a detectable level. We show that for an Earth-like atmosphere the mixing ratio of larger than $\sim$1 ppm would be necessary to be able to identify the infrared spectral features of VOCs. This level of accumulation could be possible around late M-type stars due to the reduced OH and O3 production. We also discuss how to distinguish VOC worlds from abiotic hydrocarbon worlds.

331.13 — Identifying Potential Venus Analogs from Exoplanet Discoveries

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With a radius of 0.95 Rearth and a mass of 0.85 M_{earth}, Venus is the most analogous planet to Earth in the solar system. Study of Venus and Venus-like exoplanets is invaluable in understanding factors that determine a planet's habitability throughout its evolution. Fortunately, many Venus-analogs are expected to soon be discovered as the recently launched Transiting Exoplanet Survey Satellite (TESS) mission is sensitive to planets in close proximity to their host stars. TESS is predicted to discover hundreds of terrestrial planets within the inner boundary of their host star's Habitable Zone (HZ), placing them in the 'Venus Zone' (VZ), defined by Kane et al. (2014). TESS in tandem with the launch of the James Webb Space Telescope in the coming years will allow for the characterization of these planets' atmospheres, providing a better understanding of atmospheric compositions of planets inside the VZ. This will help delineate the primary factors that determine whether a planet develops sustainable temperate surface conditions, or if it would be pushed into a runaway greenhouse state, leading to a more well-defined outer boundary for the VZ. Here we provide a progress report on discoveries from the TESS mission, identification of planets in the VZ, and methods used to determine runaway greenhouse scenarios. The observed properties of these planets will be applied to Global Climate Models, such as ROCKE-3D, to better constrain the boundaries of the HZ and VZ, and study the atmospheric demographics of terrestrial planets.

331.14 — A Matter of Time: The Coupled Role of Stellar Abundances, Exoplanet Radiogenic Heat Budgets and Climatic Evolution

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A planet's heat budget is a complex combination of the heat of formation, the energy released during core formation, and decay of the long-lived radionuclides U, Th and ^{40}K. A planet's radiogenic heat budget is solely a function of the total amount of these elements present. Observations of Solar twins show a range of Th abundances between 60 and 250% of the Sun's (Unterborn et al., 2015). We show similar ranges are expected for U and K. If this range is indicative of the span of exoplanet radiogenic heat budgets, an exoplanet's thermal and chemical evolution may be quite different from the Earth's.

We present results of geodynamical models from Foley & Smye, 2018 for stagnant lid planets with varying radiogenic heat budget. We compile a range of observed radionuclide abundances reported from the literature, adopting a Monte-Carlo approach for determining input abundances in individual models. We focus on stagnant lid planets, as stagnant lid convection is likely to be more common than plate tectonics. We show that changes in a planet's radiogenic heat budget affect the rates of volcanism, surface weathering, and volatile degassing from the interior. This allows us, through the measurement of the host star's abundances of radionuclides, to constrain a planet's thermal history and quantify the timescale over which it can maintain a temperate climate.

In general we find those stagnant lid planets with a greater starting abundance of radionuclides are temperate for a longer period of time. We calculate a conservative estimate of degassing lifetimes for a 1 Earth mass stagnant-lid planet of 1.6±0.6 Gyr across our observationally constrained range of radionuclide abundances. We argue those non-tidally-locked planets orbiting stars older than this are unlikely to be actively degassing in the absence of plate tectonics, including both TRAPPIST-1 (7.6±2.2 Gyr; Burgasser & Mamajek, 2017) and Kepler 444 (10±1.5 Gyr; Mack et al., 2018). These planets therefore are unlikely to have temperate climates, and instead likely lie in a snowball climatic regime, limiting their potential to be habitable and "Earth-like."

331.15 — Detecting Pre-Biosignatures in the Atmospheres of Earth-like Planets Around Other Stars

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When we observe the first terrestrial exoplanet atmospheres, we expect to find planets at a wide range of geological conditions and evolution including planets that may be in the early stages of biological development or failed biospheres that reached only a certain point of pre-biotic chemistry.

Understanding the UV environment of the host star is particularly important for contextualizing the habitability of an exoplanet. Depending on the intensity, UV radiation can be both useful and harmful to life as we know it. UV radiation from 180 - 300 nm can inhibit photosynthesis and cause damage to DNA and other macromolecule damage (e.g. Kerwin & Remmele 2007). However, these same wavelengths also drive several reactions thought necessary for the origin of life (e.g. Ritson & Sutherland 2012; Patel et al. 2015).

Molecules such as HCN, NH_3, CH_4, and C_2H_6 would be interesting to detect in an exoplanet atmosphere since they are known to be useful for key prebiotic chemical pathways. We find that some of these molecules could be produced abiotically in a $CO_2/CH_4/H_2$ rich atmosphere with lighting and photochemistry. HCN, for example, is present at each of the initial photochemical reactions that produce lipids, amino acids and nucleosides, the three building blocks of life. Reactions to form HCN can be accomplished via photochemistry, lightning, impacts, or volcanism. As well, the C/O ratio of the planet will greatly influence the likely dominate reactions in that planet's atmosphere. We discuss the chemical mechanisms by which HCN can be formed and destroyed on rocky exoplanets with Earth-like N_2 content and surface water inventories, varying the oxidation state of the dominant carbon-containing atmospheric species.

We finally examine the plausibility of detecting prebiotically interesting molecules, such as HCN, NH_3, CH_4, and C_2H_6 in an early-Earth type atmosphere around stars with different UV environments using early Earth, a flaring M dwarf, and a quiescent

M dwarf as a range of host stellar types and UV environments.

331.16 — Near-UV transmission spectrum of Earth-as-an-exoplanet obtained during a lunar eclipse

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We performed UV spectroscopy with the Hubble Space Telescope of the January 2019 lunar eclipse to obtain the first UV observation of Earth as a transiting exoplanet. The observatories and instruments that will be able to perform transmission spectroscopy of exo-Earths are beginning to be planned, and characterizing the transmission spectrum of Earth is key to ensuring that key spectral features (e.g., ozone) are appropriately captured in mission concept studies. Ozone is photochemically produced from O_2, a product of the dominant metabolism on Earth today, and it will be sought in future observations as critical evidence for life on exoplanets. Ground-based lunar eclipse observations have provided the Earth's transmission spectrum at optical and near-IR wavelengths, but the strongest ozone signatures are in the near-UV. We describe the observing strategy and the methods used to extract a transmission spectrum from Hubble lunar eclipse spectra. Finally, we identify spectral features in the transmission spectra and compare them to Earth models to determine if current models accurately capture key transmission features of the Earth in the near-UV.

331.17 — Prospects for detecting extraterrestrial O_2 with the ELTs

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High-dispersion transmission spectroscopy using the upcoming extremely large telescopes (ELTs) has the potential to probe the atmospheres of temperate, Earth-like exoplanets transiting nearby, late-type stars. Such observations may reveal the presence of biomarkers like molecular oxygen (O_2), which could indicate the presence of extraterrestrial life. Previous studies performed simulations with purely synthetic noise distributions to estimate the detection feasibility of the O_2 A-band at 7600 Å. We improve on these simulations by incorporating real data with real white and red noise, specifically, archival, time-series spectra taken of the M-dwarf Proxima Centauri with the Ultraviolet and Visual Echelle Spectrograph (UVES) on the Very Large Telescope (VLT). Since the expected flux difference between Proxima and the brightest transiting M-dwarf systems is similar to the difference in collecting area between the VLT and the European ELT (E-ELT), these UVES data should have noise characteristics similar to future E-ELT observations. By injecting oxygen transmission signals into the UVES data of Proxima, we determine that an A-band detection with the E-ELT will require 20-50 transits for an Earth-twin transiting a nearby (d≈7 pc) M5V star. This result from simulations with a more realistic noise distribution is similar to previous estimates.

331.18 — Evryscope flares as probes of the habitability of Proxima b and the nearest rocky exoplanets

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In March 2016, the Evryscope observed the first superflare from Proxima Centauri. The Evryscope array of small optical telescopes recorded the superflare as part of an ongoing survey of all bright southern stars, monitored simultaneously at 2 minute cadence since 2015. Evryscope flares act as probes of the space weather environment and potential habitability of nearby exoplanets in three ways: by constraining their UV surface environments, by looking for planetary magnetic fields via star-planet interaction and flares that phase up with planet orbits, and by monitoring optical counterparts to radio flare observations. We will illustrate each of these probes for Proxima Centauri, and go on to discuss the first results from our ongoing program to measure the long-term flare behavior of all TESS planet-search targets. By modeling the photochemical effects of particle events accompanying large flares, we find Proxima's repeated flaring is sufficient to reduce the ozone column of an Earth-like atmosphere at the orbit of Proxima b by 90% within five years. Surface UV-C levels during the Evryscope superflare reached $\sim$100× the intensity required to kill simple UV-hardy microorganisms without ozone, suggesting that life would struggle to survive in the areas of Proxima b exposed to these flares.

Across the sky, we report ~2× the previous largest number of 10^{34} erg high-cadence flares from nearby cool stars. We find 8 flares with amplitudes of 3+ magnitudes, with the largest reaching 5.6 magnitudes and releasing 10^{36} erg. We measure the superflare rate per flare-star and quantify the superflare properties of TESS-planet-search stars as a function of spectral type. We observe 14.6±2% of the stars around which TESS may discover temperate rocky planets emit flares large enough to significantly affect the potential habitability of those planets. We found 17 stars that may deplete an Earth-like atmosphere via repeated flaring, and we will discuss observations of a superflare with sufficient energy to photo-dissociate all ozone in an Earth-like atmosphere in a single event.

331.19 — Investigating the Habitability of Exoplanets Orbiting High-Mass Stars

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High-mass stars ($M_* \geq 1.3M_{Sun}$) provide fundamentally different environments for planets than Sun-like and smaller stars. Their outer-most layers are radiative rather than convective, and therefore typically do not emit flares that make habitability around M-dwarfs questionable. High-mass also stars commonly rotate near their breakup speeds, resulting in pole-to-equator temperature gradients that can vary by more than a thousand Kelvin. Additionally, planets orbiting high-mass stars commonly misalign into highly inclined or even retrograde orbital configurations, causing planets to vary in exposure between their host stars' hotter poles and cooler equators throughout their orbits. In this presentation I will show how the stellar and orbital properties commonly seen in A/F-type systems can combine to produce insolation patterns unlike anything seen for planets orbiting Sun-like stars, and I will discuss their implications for climate and habitability.

331.20 — How surface albedo shapes a planet — inside our Solar System and out.

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Different planetary surfaces can strongly influence the climate, atmospheric composition, and remotely detectable spectra of planets and exoplanets. From highly reflective ice, cooling a planet's surface, to dark oceans, absorbing most of the incident light each surface type needs careful study. Our own Solar System contains a diverse set of bodies (planets and moons) with a wide range of rocky, icy, and gaseous surfaces that can be used as a reference catalog for comparison against exoplanet observation. We show how this spectral reference catalog of 19 Solar System objects, can be used to initially characterize different surface types using color filters, which can assist in the prioritization of exoplanets for time-intensive follow-up with next-generation Extremely Large Telescopes (ELTs) and space-based direct observation missions. The feedback between surface and climate is a large factor when modeling terrestrial exoplanets. We further explore the changes to a planetary environment for different surfaces around a wide range of host stars using a wavelength dependent surface albedo. This allows us to create a database of high-resolution spectra (R>100,000) of remotely detectable atmospheric features, including biosignatures, for exoplanet observations with upcoming telescopes. The feedback between planetary surfaces and climate is critical to understanding the environment of potentially habitable worlds.

331.21 — Comparitive exo-Planetology with Polarimetry for Detecting Habitability Markers

Kimberly Bott[1,2]; *Lyan Guez*[2]; *Victoria Meadows*[2,1]; *Andrew Lincowski*[1,2]; *Jeremy Bailey*[3,4]; *Lucyna Kedziora-Chudczer*[3,4]

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We present results from research on the use of polarimetry to distinguish between planet types and detect key features of habitability. This work explores the signatures of planets with realistically modelled surfaces and atmospheres in orbit around G and M dwarfs to determine which features in a polarized light curve are easiest to detect. We model terrestrial type planets as well as mini-Neptunes with volatile envelopes. For terrestrial planets, our models include different ground types, oceans, species dependent Rayleigh scattering (based on environmentally dependent chemical evolution), and clouds. In some key areas such as distinguishing glint from cloud and disentangling the effect of cloud heights polarimetry provides a powerful tool. With upcoming larger aperture ground based telescopes polarimetry could enable observations of planets that would be within the inner working angle of a coronagraph, complementing space based telescopes. We find that, although the signatures of some planet types are distinct, considerations of "secondary effects" (subtle changes in the reflectivity of contaminated ices for example) need to be considered. The presentation will portray this work in the context of the broader work of the Virtual Planetary Laboratory to understand exoplanet habitability and biosignatures, showcasing work by our students. We examine observational strategies with current and future instruments to assess the likelihood of detection and compare the utility of polarimetry to other observation techniques.

331.22 — Prospects for Biosignature Detection with JWST

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The James Webb Space Telescope (JWST) may provide the first opportunity to characterize the composition of atmospheres of M dwarf terrestrial planets. Due to the character of M dwarf host stars' UV spectra, atmospheric biosignatures may build up to higher abundances than for planets orbiting G dwarfs, potentially making them more detectable. Krissansen-Totton et al., (2018) argue that the simultaneous detection of CO_2 and CH_4 could constitute a disequilibrium biosignature in an anoxic environment. However, whether JWST will have the sensitivity to detect biosignatures from oxygenic photosynthesis, or other plausible metabolisms, remains an open question. To provide a comprehensive exploration of the potential detectability of different types of biosignatures with JWST, we have used coupled 1-D climate-photochemical and radiative transfer models to generate synthetic spectra of simulated planetary environments for TRAPPIST-1 d and e that support a range of different biospheres. We then simulate JWST observations for these environments, and identify optimal observing modes, exposure times, and retrieval methods for detecting biosignatures and environmental context. We simulate Archean-Earth-like environments with either a dominant sulfur- or methane-producing biosphere for clear, cloudy and hazy cases, as well as modern Earth analogs with photosynthetic oxygen-producing biospheres for clear and cloudy cases, and also assess the habitability of these environments. We quantify the detectability of the $CO_2$and CH_4 biosignature. We find that other biosignatures, including the ethane signature of sulfur biospheres, and oxygen and ozone for photosynthetic biosignatures, will be extremely challenging to detect. We also explore the detectability of other possible biosignatures, including methyl chloride, which is predominantly produced by tropical plants on Earth, and could serve as an alternative indicator of oxygenic photosynthesis.

331.23 — Low-Cost Inference of Terrestrial Climates With Broadband Photometry

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A universal aspect of exoplanet science is that the information available is very limited, and the sample of planets we can study in situ is very small. Detailed, informative observations of exoplanets are observationally resource-intensive and technically difficult, and a growing body of numerical simulations of planet formation, evolution, and climate shows that inference from these limited observations is fraught with numerous observational and physical degeneracies. At a time when the number of observational targets is large but the resources available to study them are limited, we need low-cost techniques which nonetheless permit robust classification. Critically, these techniques must be developed in advance to prevent wasted resources. The particular challenge of classifying rocky exoplanet climates in the habitable zones of Sun-like stars has in the past been frustrated by many potential degeneracies, particularly the possibility of widespread clouds. Using hundreds of full 3D climate models, each with detailed simulated reflectance spectra, we present a new technique to uniquely identify cold, ice-covered 'snowball' planets through broadband visible and infrared photometric colors. The occurrence rate of snowball planets in the habitable zone is sensitive to planets' geophysical properties, so this low-cost technique for identifying snowball planets in observed populations represents a possibly unique way to test geophysical theories of planet formation and evolution. While in our models serious degeneracies prevent the ultimate goal of easy and robust identification of temperate, Earth-like climates, this technique could permit pre-screening of

potential follow-up targets. We identify several useful observing bands that will be accessible to planned instruments on upcoming large ground-based telescopes, and which may guide future instrument design. Our work shows low-SNR broadband photometry can distinguish between different climates on Earth-like planets, which permits informative survey science and potentially provides a roadmap for improving other exoplanet inference problems.

331.24 — Constraining the Water Loss Histories of the TRAPPIST-1 Exoplanets

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JWST is poised to detect and characterize terrestrial exoplanet atmospheres in the search for biosignatures (Morley et al., 2017, Lustig-Yaeger et al., 2019), but the correct interpretation of those observations is predicated on understanding the system's long-term evolution. A well-known example, TRAPPIST-1, harbors 7 planets that received significant high-energy fluxes during the 1 Gyr stellar pre-main sequence, likely driving water loss (Luger & Barnes 2015, Wheatley et al., 2017). We describe and employ two new software tools, VPLanet and approxposterior, to derive probabilistic constraints for TRAPPIST-1's XUV luminosity evolution and estimate the probability that these planets could have water today. We use VPLanet, a general purpose planetary system evolutionary code (Barnes et al., 2019), to simulate stellar evolution and water loss and apply approxposterior, a machine learning Python package for Bayesian inference (Fleming & VanderPlas, 2018), to compute accurate approximations of posterior distributions for how much water the planets could have lost, accounting for observational uncertainties and correlations between parameters. approxposterior obtains nearly identical results as traditional Markov Chain Monte Carlo methods (e.g. Foreman-Mackey et al., 2013), but requires 500× less computational time. We find that there is a 46% chance that TRAPPIST-1 is still in the saturated phase today, potentially causing TRAPPIST-1e to lose about 8 Earth oceans, releasing ∼1400 bars of O_2, a false biosignature. We define the Exoplanet Habitability Index (EHI) to quantify the probability that a planet possesses water, given our model, and therefore may be a viable target for JWST biosignature observations. TRAPPIST-1e is likely a good candidate with an EHI ∼1, depending on the assumed initial water distribution. As new nearby transiting planets are discovered, our framework can be applied to efficiently identify those that could possess liquid water today and can be readily generalized to account for additional physical processes to gain insights and generate predictions for potentially-habitable and uninhabitable worlds.

331.25 — Planetary Magnetism as a Parameter in Exoplanet Habitability

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Evidence from the Solar system suggests that, unlike Venus and Mars, the presence of a strong magnetic dipole moment on Earth has helped maintain liquid water on its surface. Therefore, planetary magnetism could have a significant effect on the long-term maintenance of atmosphere and liquid water on rocky exoplanets. We use Olson & Christensen's (2006) model to estimate magnetic dipole moments of rocky exoplanets with radii $R_p \leq 1.23$ R_{earth}. Even when modelling maximum magnetic dipole moments, only Kepler-186 f has a magnetic dipole moment larger than the Earth's, while approximately half of rocky exoplanets detected in the circumstellar habitable zone have a negligible magnetic dipole moment. This suggests that planetary magnetism is an important factor when prioritizing observations of potentially habitable planets.

331.26 — An Astroecological Model for Characterizing Exoplanet Habitability

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A primary objective of astrobiology is to identify worlds outside of our own which are capable of supporting life. Here, an integrative approach is applied to characterize the habitability of rocky exoplanets in the habitable zone of their host stars. We explore the relationship between modeled alien environments and terrestrial life with a novel astroecology model which can be used as a tool to asses habitability on exoplanet surfaces. In this model, simulated exoplanet environments from real

derived exoplanetary parameters are convolved with a biological layer derived from laboratory experiments. The general circularization model (GCM), ROCKE-3D (Way et al. 2018), a fully-coupled 3-dimensional oceanic-atmospheric model is used to generate exoplanet environmental parameters. The GCM output is coupled in the astroecology model in the agent-based modeling software, NetLogo, with empirically-derived thermal performance curves of 1,627 cell strains representing extremophiles from all six Kingdoms. This dataset, termed the Biokinetic Spectrum for Temperature (Corkrey et al., 2016), arises from a meta-analysis of cellular growth rate as a function of temperature. In this agent-based model, the survivability of a biological organism is determined by its thermal response to simulated local and global exoplanet temperatures. This work produces a list of exoplanets with the highest probability of having temperate surface conditions compatible with terrestrial-based thermophysiology. Life, however, is dependent upon multiple variables including the presence of liquid water, nutrient content, and an energy source. Caveats of the methodology and application of our results are discussed with implications for extraterrestrial evolution.

331.27 — Habitability of the Teegarden's Star Planets

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We study the habitability of the two 1.5±0.4 Earth-mass planets, recently detected by the CARMENES collaboration, around the ultra-cool nearby M dwarf Teegarden's Star. With orbital periods of 4.9 and 11.4 days, both planets are likely to be within the Habitable Zone and tidally locked. They are among the most Earth-like exoplanets yet discovered. We find (Wandel and Tal-Or 2019, ApJL) that one or both planets are likely to support liquid water on at least part of their surface for a wide range of possible atmospheres, characterized by their atmospheric heating factor (i.a. the greenhouse effect) and global circulation. At least one of the TG planets may be habitable for atmospheric heating in the range 0.3-15 that of Earth. As demonstrated by detailed numerical calculations of similar planets, Teegarden's Star present calmness and old age favor the retaining or reproduction of a sufficiently massive atmosphere, within the habitability range. The demonstrated habitability of the Teegarden's Star planets for a wide range of atmospheres, combined with their small distance (3.85 pc) and highest similarity to Earth (ESI=0.94) makes them most attractive targets for bio-signature searches.

332 — Other — Theory, Poster Session

332.03 — Machine Learning and Big Data for Exoplanets and Astrobiology: Results from NASA Frontier Development Lab

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We present results from NASA's Frontier Development Lab 2018, an Artificial Intelligence/Machine Learning incubator tackling challenges in various fields of space sciences. Herw we focus on the results of the Exoplanet and Astrobiology teams: planet candidate classification in survey data and modeling and retrieval of exoplanet atmospheres and spectra in the context of life detection. A particular focus will be on two data sets produced: a set of 3 million exoplanet spectra calculated with the GSFC Planetary Spectrum Generator (PSG) and a set of 150.000 exoplanet atmospheres computed with *ATMOS*. The Exoplanet team used state-of-the-art deep learning models to automatically classify Kepler and TESS transit signals as either exoplanets or false positives (Ansdell et al. 2018, Osborn et al. 2019). Their *Astronet* code expanded upon work of Shallue & Vanderburg 2018 by including additional scientific domain knowledge into the models to significantly increase overall performance . The Astrobiology team 1 project demonstrated how cloud computing capabilities can accelerate existing technologies and map out previously neglected parameter spaces (Bell et al., 2019). They succeeded in modelling tens-of-thousands of atmospheres over a few days, using the software *ATMOS* that was originally intended for use in single run applications. In Soboczenski et al., 2018 and Cobb/Himes at al., 2019 the Astrobiology 2 team presented a ML-based retrieval framework called *INARA* that consists of the first Bayesian deep learning model for retrieval and a data set of 3, million synthetic rocky exoplanetary spectra generated using *PSG* (Zorzan et al, in prep.; Himes et al., in prep.). References: *Bell, A., et al. 2018, NIPS 2018 CiML workshop; Soboczenski, F., et al. 2018, NeurIPS Workshop on Bayesian Deep Learning, arXiv:1811.03390; Ansdell, M., et al. 2018, ApJL, 869 (1), L7; Shallue, C. J.,*

& Vanderburg, A. 2018, AJ, 155, 94 Cobb A., Himes M. et al. 2019, AJ, in press, arXiv:1905.10659 ; Osborn H. et al. 2019, A&A, in press, arXiv:1902.08544

332.04 — Magnetic field effects on the motion of charged dust in rings and discs, motivated by Saturn's spokes.

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Spokes are a transient feature in Saturn's rings. Widely accepted to be charged dust levitated away from the main ring plane, the exact mechanisms and physical environment leading to their formation and propagation is still shrouded in mystery. Several theories have been proposed, including micrometeoroid impacts and lightning. However, none can fully explain the appearance of spokes.

This study is an ongoing exploration into charged dust motions in rotating tilted dipole magnetic fields. A systematic investigation of the orbital dynamics and resonances in Saturn's rings has been performed with simulations. The numerical method used is flexible and allows a comparison to the other non-diffuse ring systems of our solar system, where spokes are not observed. The aim is a greater understanding of why spokes are only observed in Saturn's B ring. Extending the work beyond planetary rings, predictions can be made about the existence of spoke-like features in more extreme solar systems, which are analogous in structure — a central body and disc, such as white dwarfs.

332.05 — Persistent Homology of Flows on Extrasolar Planets

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High-resolution simulations and observations generate copious amounts of high dimensional, large volume, heterogeneous datasets, which are increasingly difficult (if not prohibitive) for analysis by traditional (statistical, spectral, or graphical) methods alone. Persistent homology is a novel computational method for practically ascertaining the topological 'shape' of such data. Here the shape is characterized by tallying the number of connected elements and n-dimensional 'holes' (e.g., closed loops, three and higher dimensional voids, etc.), as well as 'coves' (depressions or protrusions on the holes), in the data. An example is the recent high-resolution, long-duration simulations of hot-Jupiter atmospheres that produce highly complex flow and temperature fields, containing up to many thousands of storms across a wide range of spatial and temporal scales. To clearly demonstrate the efficacy of the homology analysis method, we use it to analyze an idealized vortex model of these storms, focusing on the nonlinear evolution of such storms at the extremely high Reynolds number associated with planetary flows. Features, such as the number of storms and filaments around their periphery, their 'tubular' or 'blobby' morphologies, and periodic bursts of instability are captured and quantified. Understanding such features is crucial for validating theory and numerical models, as well as for interpreting and guiding observations. Broadly, homological analysis is a widely applicable tool that can help to directly address the large data problem faced in many areas.

332.06 — Extreme Solar Systems and the Fermi paradox : limits to growth?

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The amazing data we now have on exoplanets allows us to estimate that our Galaxy hosts about 50 billion terrestrial exoplanets. On the other hand, on our own planet, life appeared very quickly, then developed slowly, until a remarquable acceleration in the last 500 million years that lead to mankind. In the developement of our civilisation, a similar exponential acceleration is observed, with the distance fled by man made objects multiplied roughly by 10 every ten years since the first plane flew accross a field at the dawn of the XXth century. At this pace, we should conquer the whole Milky Way by the end of this century. But although our planet formed nine billion years after the first stars, none of the many exoplanets seems to be just a century ahead of us : they have not sent their flying saucers to Earth.

This paradox, first coined by E. Fermi, shows that something must be wrong in the above reasoning. In fact, it is obvious to every participant of this conference that the laws of physics forbid to cross a hundred thousand light-years in just a hundred years, so that exploring the whole Galaxy can not be done so fast. This illustrates that any exponential process reaches its limits quickly : the distance we explore can not keep being multiplied by ten every ten years. This is also true for the economic growth, which is also exponential, and based on the use of ressources and the emission of pollution in a finite world ...

The CO2 emissions already change the Earth's climate, in such a way that they represent a threat for our future developement. Have all the other extraterrestrial lives destroyed their environment by trying to conquer the Galaxy? Have they spontaneously decided to stop their exponential growth in order to preserve their planet? The fact that none of them succeeded to come here forces us to think about our own behaviour. In particular, this conference will certainly be fantastic, and I will be enjoying it a lot. But is it reasonable that we all fly here? Should our community start thinking about how to do science with less greenhouse gasses emission?

332.07 — Formation and evolution of short-period planets around magnetized host stars

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During the formation and early evolution of short-period planets, kiloguass fields persist on their host stars. Their interaction with planets' evolving natal disks determines not only the amount of building block grains and the orbital destiny of protoplanets, but also emerging stars' spin rate. After the disk depletion, the relative motion between the stellar spin and the planets' orbit leads to unipolar induction and Lorentz force which can cause significant orbital evolution, Ohmic dissipation, and low-frequency radio emission. I show how this effect may enable remote sensing of super Earths' surface composition. I also show how to generate analogous magnetic field in proto-Jupiters and how these process may have determined the spin rate of Jupiter and the orbits of its Galilean moons.

332.08 — Forget Limb Darkening Laws: Transit Modeling Using Stellar Atmosphere Intensities

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Limb darkening (LD) laws are ubiquitous in their use in exoplanet transit modeling. They provide a fast and easy way to parameterize the changing intensities across the disk of the star, allowing transit models to be quickly computed and compared with observations. However, we know that LD laws are a poor representation of the stellar intensities, particularly at the limb where the intensities drop off extremely quickly. This is especially important when considering subtle effects such as planet oblateness, since these effects are most pronounced at the limb. In spite of the shortcomings, researchers often do not use the LD laws that match stellar models. Instead, they fit for the coefficients of a LD law. This further removes the transit modeling from actual stellar physics. While the fit to the transit may be better when solving for LD coefficients, it is no more than a consequence of (i) allowing more freedom in the models; (ii) a re-statement that LD laws are not realistic representations of the stellar intensities.

It would be far more advantageous to use an actual model atmosphere to give the specific intensities, and we provide a fast method to do so, using tabulated model intensities from ATLAS models to compute the transit. The code is only slightly slower than the one using ad hoc LD laws. By using actual model atmosphere intensities, there are no free parameters to solve for (given the stellar properties). Comparison of this method with the traditional method using ad hoc LD laws shows the derived planet radius is systematically wrong by 0.1% or more, depending on the impact parameter. In addition to improving the accuracy (rather than precision) of transit modeling, we note an area where our method may be extremely fruitful: transit spectroscopy. The wavelength-dependent transit depth is a function of both the planet's atmosphere and the stellar LD variation. By eliminating the use of parameterized LD laws we (i) completely remove any degeneracy between transit depth and LD coefficients; (ii) include astrophysical knowledge of the star's intensity distribution, which varies strongly as a function of both position and wavelength.

333 — Other — Observational, Poster Session

333.01 — Endeavours towards precise M-dwarf properties: Activity robust multi-line modeling in the visual and near-infrared

Vera Maria Passegger[1]; *Andreas Schweitzer*[1]; *Denis Shulyak*[2]; *Evangelos Nagel*[1]; *Peter H. Hauschildt*[1]; *Ansgar Reiners*[3]; *Pedro J. Amado*[4]; *José A. Caballero*[5]; *Miriam Cortés-Contreras*[5]; *Alejandro J. Domínguez-Fernández*[6]; *David Montes*[6]; *Andreas Quirrenbach*[7]; *Ignasi Ribas*[8,9]

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A precise characterisation of planet-hosting stars is very important to derive and constrain the physical properties of orbiting planets. The CARMENES instrument, which is searching for habitable planets around M dwarfs, provides us with high-resolution spectra in the visual (0.52–0.96 μm) and near-infrared wavelength range (0.96–1.71 μm). We fit the most recent PHOENIX-SESAM stellar atmosphere models simultaneously to both wavelength ranges to determine effective temperature, surface gravity, and metallicity for 282 M dwarfs. With these temperatures we also derive stellar masses and radii using luminosities and Gaia DR2 parallaxes. Although stellar activity is widely unconsidered in stellar parameter determination, we show the importance of taking into account this property by carefully selecting magnetically insensitive lines, especially for the near-infrared wavelength range. For the first time, we directly compare stellar parameters such as effective temperature, surface gravity, and metallicity derived from multiple wavelength ranges for the same spectra. We recommend using a combination of the visual and near-infrared wavelength ranges for parameter determination in order to maximise the amount of spectral information and minimise possible effects due to model imperfections.

333.02 — Optical/Near-IR Microwave Kinetic Inductance Detector-based Integral Field Spectrographs for High-Contrast Observations

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I will present an overview of the high-contrast imaging techniques achievable with Microwave Kinetic Inductance Detector (MKID)-based instruments. Optical/Near-IR MKIDs are low noise detectors which can resolve both the energy and arrival time of individual photons, returning microsecond-accurate time-tagged photon lists. These lists allow for post-processing techniques that take full advantage of photon spectral and arrival time information, such as photon-counting Stochastic Speckle Discrimination (SSD), a technique which enables direct observations of exoplanets at small separations from their host star, and Spectral Differential Imaging (SDI), a technique which exploits the chromatic behavior of speckles to model the stellar Point-Spread Function (PSF). These techniques enable the subtraction of the speckle background approaching the photon noise limit. Active feedback techniques using the MKIDs as a focal plane wavefront sensor promise to further improve instrumental sensitivity. I will also present results from the MKID Exoplanet Camera (MEC). MEC is a 20,440 pixel MKID infrared camera that interfaces with the SCExAO planet finding instrument on the Subaru Telescope at Mauna Kea. MEC received first light in June 2018 and has been used to image young massive planets and debris disks.

333.03 — Capturing the Now — the AAS Oral History Project

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The Oral History Project of the American Astronomical Society is in its sixth year. It is part of the activities of the Historical Astronomy Division. What is an oral history? Oral histories are interviews with individuals that are meant to capture some aspect of their, if not their entire, life. For the AAS project, we spend up to two hours with each person gathering background information, noting career moves, highlighting mentors, but also touching on current issues relevant to our community such as diversity, sexual harassment, data science, queue observing, tenure, and getting individual recognition for collaborative research. We have interviewed over 150 sci-

entists, technicians, family members, and STEM support staff. Some of these interviews can be found on the AIP archive of oral history interviews. The AAS Oral History Project is unique in that we interview anyone who volunteers to be interviewed: You do not need to be old and famous (like Doug Lin, but we do want to interview him, too!). Our interviews include undergraduates to emerita. The poster shares the full list of our interviewees and some of our preliminary analysis of trends. Finally, if you would like to be interviewed contact Jarita (jholbrook@uwc.ac.za).

333.04 — A Fresh Look at Red Giant Planet Hosts Using TESS: A Study of Stellar Mass and Surface Gravity

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A detailed understanding of even the most basic parameters of planetary systems requires accurate knowledge of the host star's bulk properties. Historically, measuring accurate masses for field red giant stars has been especially difficult because stars of a wide range of masses evolve through similar parameter space on the Hertzsprung Russell diagram, sometimes passing through the same phase space multiple times. For a given luminosity and temperature, the star's surface gravity must also be known. Until recently, surface gravity was predominately measured spectroscopically, requiring the abundances of metals inferred from both neutral and singly-ionized species to agree (ionization balance). Such measurements tend to suffer from systematic uncertainties that are difficult to fully quantify, resulting in independent gravities measured for the same star that differ by much more than the quoted (random) uncertainties. Asteroseismology has provided the key to solving this problem. High precision, long baseline photometric monitoring yield detailed oscillation spectra, and the frequency of maximum oscillation power is directly proportional to surface gravity. TESS is collecting such data over the whole sky, and here we present preliminary measurements of asteroseismic log g from a sample of red giant planet hosting stars in the Southern Hemisphere. Our sample has been observed by TESS in 2-minute cadence, and we have spectroscopic log g measurements both from heterogeneous sources in the literature and measured homogenously by us. We discuss the frequency with which asteroseismic log g's differ substantially from the asteroseismic ones (even when spectroscopic measurements agree) and we explore the implications of revised stellar log g and masses on the interpretation of the planetary companions around these stars.

333.05 — Machine Learning for the Identification of Exomoon Candidates in Kepler

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Convolutional neural networks (CNNs) are well suited for image classification problems, particularly when the data volume is too large for by-eye classification. They have recently been applied with great success to the problem of distinguishing genuine planets from false positives in the *Kepler*, K2, and TESS datasets. In this work we apply a CNN to the *Kepler* data for the purpose of identifying candidate exomoon signals. We train the CNN on ~200,000 artificial light curves — real *Kepler* light curve segments with injected planet/moon signals — to achieve ~95% accuracy for moon signals of sufficient SNR in the validation set. We apply the CNN to every transit of every KOI to identify potential exomoons in the data, after which we will vet the most promising candidates with a full photodynamical moon fit and Bayesian model selection.

333.06 — Eclipse Mapping: Creating Two- or Three-Dimensional Images of Exoplanets

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Eclipse mapping is a method that can be used to resolve an image of the day side of an exoplanet. As the planet passes into secondary eclipse, the stellar limb blocks successive slices of the planet disk, while a different set of slices are revealed as the planet comes back out of eclipse. If we measure the detailed change in flux during these partially obscured times of ingress and egress, we can reconstruct the brightness distribution across the planet disk. If we take spectra during these times, then different wavelengths are probing different depths into the atmosphere and so these data contain three-dimensional information about the planet's atmosphere. In practice, eclipse mapping is a nuanced technique, subject to various sources of uncertainty and degeneracy. Here we present a mathematically optimized method for retrieving the maximum possible spatial information from an eclipse mapping dataset. We can also use this method to evaluate whether significant orbital-mapping degeneracies exist, for any particular system and observational set-up. We then introduce a way to extend this framework to include multi-wavelength observations, by using machine learning methods to identify dominant spectral components and group them into spatial regions. We show applications of this new spectral-spatial mapping method to test-case toy models, with various artificial atmospheric states, demonstrating its ability to retrieve correct information. Finally, we estimate the scientific return when this method is applied to upcoming JWST data.

333.07 — The Starchive – An Extreme Open Access Archive

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The Starchive (starchive.org) is an open access, open source stellar database and web application like no other. We have designed an interface which is intuitive, comprehensive and adaptable. Currently, the database contains multiple stellar samples including all stars within 30pc, all known brown dwarfs and white dwarfs, stars with planets and circumstellar disks and stars in young stellar associations. We have plans to incorporate the WDS, Gaia and TESS catalogs. The web app allows users to search the database using coordinates, names or an ADS reference code. A search can include a single star or multiple stars (batch mode). If users search for information on a single star, the result page contains all published measurements and derived physical parameters on that star, a Vizier image as well as any available high contrast images via js9. If the star is in a multiple system, there is a clear hierarchical tree with live links to the other members of the system. If available, users will have access to wavelength calibrated spectra and time series of that star all in one location. If a user submits a list of stars or utilizes the rank list search option, the web app provides a dynamic table of multiple stars with links to each individual star page. Users are able to download a text, .csv or latex file of that table. Directly from the multi-star web page application users will be able to use adaptable plotting tools to visualize the resulting data set. It is the goal of the Starchive that the plots be publication quality thus eliminating the need to download and then replot data for presentations and papers. Registered users will be able to upload data into the database. To ensure the fidelity of the data, we will highly regulate and constantly validate any uploaded data sets. There will be an API available for users to access the database directly from their own code. The front-end scripts will be placed on github and users will be encouraged to contribute new plotting tools.

333.08 — Sonifying Solar Systems: New Tools for Research and Outreach

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Sonifying planetary transits and the possible chemical contents of their atmospheres; ALMA's public Soundbank of molecular data from new star birthing regions; discerning the harmonic resonances between planets in distant solar systems; and Kepler Space Telescopes' "Stellar Choir", demonstrating with a unique soundscape, playable by the inquirer, the location of known exoplanetary systems: All of these are now offering sonified data for a unique encounter with exo-planetary science both by the public and research scientists, seeking insights about the universe beyond the visible spectrum. We have found new insights about the solar corona from sonified data which the ear could discern though invisible to the eye. Sonification is opening an entirely new window for communication with the public, students, and understanding our universe. It is providing those who are visually impaired the ability to explore the universe, experience it, and as well to become astrophysicists. This presentation explores some of the unique things being done at this frontier for outreach, blending culture and science, and research in the realm of Extreme Solar Systems and the quest for other life in the cosmos.

333.09 — Exoplanets in the Antarctic Sky: from Searching to Characterizing

Yu Zhouyi[1]*; Zhang Hui*[1]
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Thanks for the wide-field exoplanet surveys on the ground and in the space, thousands of exoplanet samples have been found in the last two decades. From Dome A, the highest point of the Antarctic plateau, we have also contributed over 100 candidates using the AST3 telescopes in 2018. Now, besides searching, we are progressing forward to study special exoplanet systems in details to reveal their dynamics and physics properties. I will first introduce our recent works on searching exoplanets with the help from deep learning methods. And I'll present some results on characterizing Proxima Cent b, the nearest potential habitable world, using AST3-II. We find a temporary solar-like oscillation in Proxima. We know that M dwarf stars are dominated by advection layer, there should be some kinds of Solar-like oscillation. But the oscillation won't be stable so although believed, no positive detection was made. This may be the first observation proof. This is an excellent example to show the advantages of monitoring high-value targets from Dome A. To further utilize these advantages I'll also introduce the KISS (Kunlun Infrared Sky Survey) project and its usage on exoplanet characterization. We also monitored Beta Pictoris a couple of hours each day during the twilights (when the weather was permitting), using AST3 II telescope, in 2017. At the end of the polar winter, we had acquired around 70,000 frames on this target at a cadence of 3.5 sec. Although no obvious eclipse was found, we've found some new pulsating frequencies, e.g. around 14.3, 20.6, 58.98/day , and some ultra-high-freqency signals, which are not mentioned before. We think this phenomena can reveal some properties of Beta Pictoris b's circumplanetary environment.

333.10 — The Terrascope: Turning Planets into Telescopes

David Kipping[1]
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As our knowledge of exoplanets grows, so to does our thirst for ever more data. Photometric precision has been gradually improving from percent level with photographic plates, to mmag with ground-based surveys and now in the parts per million with space-based facilities. It is timely to consider where the next order of magnitude gain might come from then, to reach parts per billion precision. In this talk, I'll discuss the idea of using the Earth as a giant lens of distant starlight exploiting atmospheric refraction — a "terrascope". By placing a one-meter aperture at the Earth-Sun L2 point, distant point sources are shown to be amplified by a factor of ∼45,000 with a lensing timescale of ∼20 hours, effectively turning a one-meter telescope into a ∼200 meter class telescope. I show how the effects of atmospheric extinction and clouds are small provided the terrascope is placed at a large separation from the Earth, such as L2. The terrascope concept is certainly challenged by seeing, turbulence and airglow and I'll discuss some possible strategies to mitigate these effects.

333.11 — The Mysterious Activity of TRAPPIST-1

Brett Morris[1]*; Eric Agol*[2]*; James Davenport*[2]*; Suzanne Hawley*[2]
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TRAPPIST-1 is one of the most tantalizing exoplanet systems discovered to date, with seven Earth-sized transiting exoplanets in a resonant chain orbiting an ultra-cool dwarf star. To make robust inferences about the properties of the exoplanets orbiting TRAPPIST-1, we must first identify any stellar surface inhomogeneities which will confound exoplanet transmission spectroscopy (Morris et al. 2018, Rackham et al. 2018, Ducrot et al. 2018). TRAPPIST-1 is the first M8V star to be scrutinized with long-term ∼1% precision photometry in multiple wavebands, and preliminary analyses of the surface features of the host star are full of surprises. There is no definitive evidence for coverage of the stellar surface by dark starspots, but there is photometric and spectroscopic evidence for bright, hot regions on the surface of the star. Furthermore, the occurence of flares seems to be correlated with the optical flux of the star, perhaps suggesting that the apparent rotational modulation of the star could instead be evolution of bright active regions. We will discuss the available evidence for activity and rotation of the host star, and conclude with a discussion of the implications for transmission spectroscopy of the exoplanets.

333.12 — The Transiting Exoplanet Survey Satellite (TESS): Mission Operations and Instrument Performance

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[1] *MIT Kavli Institute for Astrophysics and Space Science, Massachusetts Institute of Technology (Cambridge, Massachusetts, United States)*

The Transiting Exoplanet Survey Satellite (TESS) is performing a near-all-sky survey to detect exoplanets around the nearest and brightest stars in the sky. TESS began performing science observations of the southern ecliptic hemisphere in July of 2018. As TESS begins the survey of the northern ecliptic hemisphere, we review the performance of the instrument and spacecraft during the first year of the science mission. We also discuss flight operations in Year 2, including instrument pointing and target selection.

333.13 — Extreme Stellar Systems: Towards Improved Stellar Parameters with Single-lined Eclipsing Binaries

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The precision and accuracy with which we characterize exoplanets discovered via transit and radial velocity (RV) techniques are no better than the precision and accuracy with which we know their host stars. This relationship is most stark for planets around M dwarfs. The most precisely and accurately determined stellar parameters have come from double-lined eclipsing binaries (EBs), and M-M EB studies suggest that low-mass stellar models under-predict radii and over-predict effective temperatures by 5-10%, — thus determining how precisely and accurately we can characterize planets around M dwarfs.

While studies of the "M dwarf discrepancy" are limited both by the small sample of well-studied M-M EB and their typically short orbital periods, single-lined EBs — and the advent of precise Gaia parallaxes — provide one avenue to circumvent these problems. We will present results from our ongoing campaign to measure few-percent masses, radii, and temperatures for single-lined EBs — specifically, the M dwarf secondaries. our total sample of ∼200 single-lined EBs extends the parameter space out to longer orbital periods (dozens of days) and different binary configurations. As such, we can better distinguish between radius and temperature discrepancies inherent to low-mass stellar models and the effects of increased stellar activity caused by a nearby stellar companion.

We will highlight a few key characterizations of A-M and F-M EBs from joint analyses of primary and secondary eclipses, optical radial velocities (RVs), and spectral energy distributions. We will also share our exciting discovery of unique EB consisting of a fully convective, likely pre-main sequence M star and a late-B dwarf. We will discuss prospects for improving the precision of the inferred parameters and compare parameters inferred from these "global analyses" to those inferred from modeling the out-of-transit flux variations.

333.14 — Exoplanetary Atmospheric Retrieval via Bayesian Machine Learning

Michael Himes[1]; *Adam Cobb*[2]; *Frank Soboczenski*[3]; *Simone Zorzan*[4]; *Molly O'Beirne*[5]; *Atilim Gunes Baydin*[2]; *Yarin Gal*[9]; *Shawn Domagal-Goldman*[7]; *Giada Nicole Arney*[6]; *Daniel Angerhausen*[8]
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Atmospheric retrieval, the inverse modeling technique whereby atmospheric properties are inferred from observations, is computationally expensive and time consuming. Recently, machine learning (ML) approaches to atmospheric retrieval have been shown to provide results consistent with traditional approaches in just seconds to minutes. We introduce plan-net, the first ensemble of Bayesian neural networks for atmospheric retrieval. Our novel likelihood function captures parameter correlations, improving uncertainty estimations over standard likelihood functions common in ML. We replicate the results of Marquez-Neila et al. (2018), and we demonstrate plan-net's improvement in accuracy over their random forest regression tree when applied to their synthetic data set of hot Jupiter WFC3 transmission spectra. We apply a trained plan-net ensemble to the transmission spectrum of WASP-12b and find results generally consistent with the literature. We also apply plan-net to our data set of over 3 million synthetic terrestrial exoplanet spectra generated using the NASA Planetary Spectrum Generator. AC is sponsored by the AIMS-CDT and EPSRC. FS and MH acknowledge the support of NVIDIA Corporation for the donation of the Titan Xp GPUs used for this research. AGB is funded by Lawrence Berkeley National Lab and EPSRC/MURI grant EP/N019474/1.

333.15 — Planets are Shaped by their Past: Reconstructing the Early XUV Emission of Exoplanet Host Stars

Parke Loyd[1]; Evgenya L. Shkolnik[1]; Adam Schneider[1]; Tyler Richey-Yowell[1]; Travis Barman[2]; Sarah Peacock[2]; Isabella Pagano[4]; Victoria Meadows[3]

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X-ray and extreme ultraviolet (XUV) radiation is likely shaping the observed population of short period exoplanets by powering blow-off of their atmospheres. The amount of atmosphere an individual planet might lose to XUV erosion depends on the history of its XUV irradiation, which could be 10-1000× higher when it formed than at present day. This can explain two classes of "missing" planets: sub-Jovians with short orbital periods (<5 d) and planets with radii between super-Earths and sub-Neptunes out to longer periods (< 25 d), colloquially known as the "sub-Jovian desert" and the "radius gap," respectively. However, a star's present XUV flux is likely not a good tracer of its XUV past. In consequence, we found correlating the properties of planets with their present-day XUV irradiation yielded no clear dependence in the location of the desert or the gap. We will present this test, along with simulations determining whether such correlations could be detected in yet-to-be-discovered TESS planets in this talk. Accurate knowledge of a individual stars' XUV histories could permit a robust test of the photoevaporation hypothesis for the missing planets and constrain the timespan over which photoevaporation is most effective. We will synthesize the current state of knowledge regarding the evolution of stellar XUV emission from the time of planet formation onwards for F-M stars, outlining the obstacles and opportunities for revealing the past lives of highly irradiated planets.

333.16 — Results from the W-Band survey: Searching for planetary-mass brown dwarfs

Sophie Dubber[1]

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The W-Band survey has found multiple young, M/L-type dwarfs in the Taurus and Serpens star-forming regions, spectroscopically confirmed using a custom 1.45 micron filter to identify water absorption features. Here, I present examples of the spectra of these objects, and details of the 27 sq. degree survey. I also discuss the difficulties in determining spectral types for objects in young, star-forming regions, due to the degeneracy caused by interstellar reddening.

333.17 — The search for radio emission from exoplanets using LOFAR beam-formed observations

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The detection of exoplanetary magnetic fields is one of the most elusive hunts in exoplanet science today. Observing the magnetic field of an exoplanet will give valuable information to constrain their interior structure, atmospheric escape, and the nature of any star-planet interactions. Additionally, the magnetic fields on Earth-like exoplanets might help contribute to their sustained habitability by deflecting energetic stellar wind particles.

The most promising method to detect exoplanet magnetic fields is radio emission observations since this method is not susceptible to false positives. All the magnetized planets and moons in our Solar System emit in the radio using the Cyclotron Maser Instability (CMI) mechanism. To date, many ground-based observations conducted to find exoplanet radio emission have resulted in non-detections.

In this talk, we discuss our ongoing observational campaign searching for exoplanetary radio emissions using beam-formed observations with the Low

Band of the Low-Frequency Array (LOFAR). To date we have observed three exoplanetary systems: 55 Cnc, Upsilon Andromedae, and Tau Boötis. These planets were selected according to theoretical predictions, which indicated them as among the best candidates for an observation. Data analysis is currently ongoing.

In order to test, validate, and quantify the sensitivity reached with our LOFAR pipeline, we apply it to a LOFAR observation of Jupiter's magnetospheric radio emission in which the signal from Jupiter is attenuated. The idea is simple: we observe Jupiter, divide its signal by a fixed factor before adding it to an observation of sky background, thereby creating an artificial dataset best described as "Jupiter as an exoplanet". We then run our pipeline and check whether the (attenuated) radio signal from Jupiter is detected. The maximum factor by which we can divide Jupiter's signal and still achieve a detection gives the sensitivity of our setup. We find that circularly polarized exoplanetary radio bursts can be detected up to a distance of 20 pc assuming the level of emission is 10^5 times stronger than the peak flux of Jupiter's decametric burst emission.

400 — Atmospheres – I

400.01 — The Galilean Satellites Observed by Cassini: a testbed for icy terrestrial exoplanets

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For terrestrial exoplanets with thin atmospheres or no atmospheres, the surface will dominate to the reflected light signal of the planet. Direct observation of the disk-integrated brightness of bodies in the Solar System, and the variation with illumination angle, wavelength, and planetary longitude, is essential for both planning imaging observations of exoplanets and interpreting the eventual datasets. We will present our analysis of approximately 5,000 Cassini observations of the Galilean satellites through an exoplanet lens and show their longitudinal and illumination variations. The data span a range of wavelengths from 400-950 nm and predominantly phase angles from 0-25 degrees with some constraining observations near 120 degrees. Restricted to observations at the same illumination angle, we show that we can clearly detect the spin period of each of the four moons. We invert these light curves to reconstruct maps of the surfaces and we present comparisons of these maps to direct images. In the case of Io, we detect a clear color variation that can be traced to geologic features with varying quantities of sulfur compounds and silicates across the surface. Despite the similarity in size and density between the moons, surface inhomogeneities result in significant changes in the disk-integrated reflectivity with planetocentric longitude and phase angle. This implies that future exoplanet observations could exploit this effect to deduce surface variations, determine rotation periods, and potentially infer surface composition. Furthermore, the Galilean satellites are all distinctly non-Lambertian with steep phase functions, implying that icy exoplanets will be fainter than expected at quadrature and more demanding to characterize by direct imaging.

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400.02 — Prospects for Using H-α Transits to Probe Escaping Atmospheres

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The recently-observed dearth of super-Earths with radii ∼1.8 times that of Earth is a member of a rare class of discoveries: observational confirmation of a clear theoretical prediction. Two separate groups predicted this feature using models of photoevaporative atmospheric loss. Since the discovery of the super-Earth radius gap, these models have been used to constrain properties of this planetary population such as the core mass distribution, with exciting results. As the quantitative results of photoevaporation models become more important (and as photoevaporation is compared to core-powered mass loss, a new competing theory for the source of energy driving escape), improved observational constraints on photoevaporation models are sorely needed. I will present new results showing that, though transits in hydrogen's H-α line have thus far provided limited information about escaping atmospheres, for thoughtfully-chosen planetary samples, this line has exciting potential. Most direct observations of photoevaporation in action have been conducted using transits in hydrogen's Lyman-α line. Because this line's center is obscured by ISM absorption, these observations primarily provide information about outflowing gas far from the planet, making mass loss rate calculations model dependent. For most planets currently observed to have escaping gas, the fraction of escaping hydrogen in the n=2 state is too small for significant H-α absorption. I will present new theoretical calculations showing that for planets experiencing a larger XUV flux, recombination cascades can populate the n=2 state at an observable level. I will comment on these results in the context of A-stars such as Kelt 9, flaring M-stars, and young stars, and attempt to convince conference attendees that additional observational campaigns are warranted in the conveniently accessible from the ground H-α line.

400.03 — A Sub-Neptune Exoplanet with a Low-Metallicity Methane-Depleted Atmosphere and Mie-Scattering Clouds

Björn Benneke[1]; Heather Knutson[2]; Joshua Lothringer[3]; Ian Crossfield[4]; Julianne I. Moses[5]; Caroline Morley[6]; Laura Kreidberg[7]; Benjamin Fulton[8]; Diana Dragomir[4]; Andrew Howard[2]; Ian Wong[4]; Jean-Michel Desert[9]; Peter McCullough[10]; Eliza Kempton[10]; Jonathan Fortney[11]; Joshua Kammer[12]; Drake Deming[10]

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The discovery of thousands of exoplanets with masses and radii intermediate between Earth and Neptune was one of the biggest surprises of exoplanet science. These super-Earths and sub-Neptunes likely represent the most common outcome of planet formation. Mass and radius measurements indicate a diversity in bulk composition much wider than for gas giants; however, direct spectroscopic detections of molecular absorption and constraints on the gas mixing ratios have largely remained limited to planets more massive than Neptune. In this talk, we present the main results from an unprecedented HST/Spitzer data set (12 transits and 20 eclipses) of a sub-Neptune exoplanet, whose mass of 12.6 Earth masses places it near the half-way point between previously studied exo-Neptunes (22-23 Earth masses) and exoplanets known to have rocky densities (7 Earth masses). Obtained over many years, our data set provides a robust detection of water absorption (> 5 σ) and a thermal emission detection from the lowest irradiated planet to date. We reveal a low-metallicity, hydrogen-dominated atmosphere similar to a gas giant, but strongly depleted in methane gas. The low, near-solar metallicity (O/H=0.2-18) sets important constraints on the potential planet formation processes at low masses as well as the subsequent accretion of solids. The low methane abundance indicates that methane is destroyed much more efficiently than previously predicted, suggesting that the CH4/CO transition curve has to be revisited for close-in planets. Finally, we also find a sharp drop in the cloud opacity at 2-3 μm characteristic of Mie scattering, which enables narrow constraints on the cloud particle size and makes the planet a keystone target for mid-IR characterization with JWST.

400.04 — Meteorite Outgassing Experiments to Inform Chemical Abundances of Super-Earth Atmospheres

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At present, there is no first-principles understanding of how to connect a terrestrial planet's bulk composition to its atmospheric properties. Since terrestrial exoplanets likely form their atmospheres through degassing (Elkins-Tanton & Seager 2008), a logical first step to build such a theory for super-Earths is to assay meteorites, the left-over building blocks of planets, by heating them to measure the outgassed volatiles. Our Solar System presents a wide variety of meteorite types, including chondrites which are primitive unaltered rocks believed to be representative of the material that formed the rocky planets. We present the current results of our meteorite outgassing experiments in which we heated a variety of chondritic meteorite samples, at carefully controlled rates to temperatures from 200 to 1200 °C and measured the partial pressures and relative abundances of the outgassed volatile species (e.g., CO_2,

H_2O, CH_4, H_2, O_2, S, Na) as a function of temperature and time. Our experimental set-up consisted of a residual gas analyzer connected to a furnace to heat samples at specified rates. We compare the results of these experiments to Schaefer and Fegley's prior theoretical chemical equilibrium and kinetics calculations which modeled thermal outgassing for a wide variety of chondrites to predict the composition of terrestrial atmospheres formed via outgassing of specific types of meteorites (Schaefer & Fegley 2007, Schaefer & Fegley 2010). In addition to testing and validating Schaefer and Fegley's models, the results from our experiments inform the phase space of chemical abundances used in atmospheric models of super-Earth exoplanets.

400.06 — Helium-Enhanced Planets at the Edge of the Radius Gap

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Primordial hydrogen-helium envelopes surrounding sub-Neptune-sized planets are susceptible to mass loss driven by ionizing radiation from their host star. The effect of mass loss is imprinted on observed exoplanet populations in the form of a "photo-evaporation desert" and a "gap" at 1.6 Earth Radii in the planet radius distribution. To date, models of the mass-loss evolution of exoplanets have assumed that the planetary envelope composition stays constant over time. However, after an initial ~0.1 Gyr phase of rapid hydrodynamic mass loss, sub-Neptunes may experience a subsequent phase of thermal escape modulated by diffusive separation between hydrogen and helium wherein they gradually become enhanced in helium and metals (relative to hydrogen) over billions of years. We predict that planets on the large radius edge of the "radius gap" in planet occurrence rates could be significantly enhanced in helium (or depleted in hydrogen) relative to solar composition. We have performed the first self-consistent calculations of the coupled thermal, mass-loss, and compositional evolution of hydrogen-helium envelopes surrounding sub-Neptune mass planets. Our simulations consistently produce planets with envelope helium mass fractions in excess of Y=0.5 (at planet ages of 5 Gyr) near the upper edge of the radius gap. Our results have important implications for the interpretation of atmospheric transmission and emission spectra of low-density sub-Neptune-size planets, which are prime targets for atmospheric characterization with HST and eventually JWST. Enhancement in helium relative to hydrogen will affect both the scale height and equilibrium chemical abundances in the atmosphere (e.g., CO relative to CH_4). To date, most atmospheric retrieval analyses have fixed the ratio of hydrogen and helium to solar abundances; this assumption must now be relaxed. Our prediction further provides a new observational test for the extent to which the radius gap is caused by atmospheric mass loss versus an intrinsically bimodal outcome of planet formation.

401 — Population Statistics and Mass-Radius Relations

401.01 — Frequency of Gaseous Planets Beyond the Ice Line

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The occurrence distribution of long-period planets is a key unknown left in our understanding of exoplanetary demographics. The presence of Jupiter and Saturn in our solar system likely facilitated the formation of Earth and the other terrestrial planets, yet we do not have a clear picture of the intrinsic frequency of gas giant planets orbiting beyond ~5-10 AU in exoplanetary systems. Here we analyze a massive dataset of over 35,000 archival Keck/HIRES and Lick radial velocities collected over the past 30 years for a sample of 785 nearby stars. This groundbreaking study provides direct measurements of the mass, period, and eccentricity distributions of Jupiter and Saturn-mass planets beyond 5 AU and Neptune-mass planets out to the location of the ice line (~3 AU for sun-like stars). We are finally able to unify, compare and contrast planet population statistics from direct imaging surveys with those of radial velocity and transit surveys. This will have a profound impact on the planning of future direct imaging campaigns, potentially providing them with targets to observe and yield predictions. We examine the period distribution of gas giant planets beyond 10 AU to look for the fall off in the planet occurrence rate required to reconcile the tension between radial velocity studies and direct imaging studies. We measure the mass distribution of Neptune to Jupiter mass planets orbiting beyond 3 AU to look for an enhancement in the frequency of sub-Jovian planets near the ice line as is observed for Jovian and super-Jovian mass planets. We compare the mass-distribution of planets beyond 3 AU to those orbiting inside 1 AU to look for the signatures of planet migration and shepherding of the multitude of small, low-mass planets discovered by Kepler. The results of this study will have profound impact on the planning of future direct imaging campaigns, potentially providing them with targets to observe and yield predictions. By connecting the regimes of exoplanetary demographics explored by all of the various detection techniques we provide a unified view of the end product of planet formation across the entire protoplanetary disk.

401.02 — Masses and Radii of Exoplanets from Kepler, K2, and TESS

David Winslow Latham[1]; Samuel N. Quinn[1]
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The population of planets orbiting solar-type stars is dominated by planets smaller than 4 Earth radii, the size of Neptune. Mass determinations for transiting planets identified by Kepler and K2 have suggested that most planets smaller than about 1.8 Earth radii have bulk densities that are consistent with internal structures and compositions similar to the terrestrial planets in the Solar system. One of the primary goals of the TESS mission is to determine masses and bulk densities for more than 50 planets smaller than 4 Earth radii, to improve our understanding of the transition between rocky planets and those more like Neptune. We will highlight the progress towards meeting that goal.

401.03 — On the hunt for Trappist-1 siblings

Didier Queloz[1]; Michaël Gillon[2]
[1] *U. Cambridge (Cambridge, United Kingdom)*
[2] *U. Liege (Liege, Belgium)*

The TRAPPIST-South 60cm telescope at La Silla (ESO) is famously known for its detection of the extraordinary TRAPPIST-1 planetary system. A discovery made during the prototype phase of our ultra-cool dwarf transit survey SPECULOOS (Search for Planets EClipsing ULtra-cOOl Stars). This talk will first report on the self-consistence transit occurrence analysis of all observations of 42 bright ultracool dwarfs made with TRAPPIST-South during a period ranging from 2011 to 2017. On the basis that, with the exception of the discovery of TRAPPIST-1 planets, we didn't detect any other significant transiting event, we concluded on a 10% lower limit for the occurrence of planets similar to TRAPPIST-1b in this sample. The outcome is very sensitive to the size and period of the planet considered. A comprehensive statistic will be presented. Finally, performance obtained with our recently commissioned SPECULOOS Southern facility installed at Paranal will be presented. The lower occurrence limit measured with TRAPPIST survey will be compared with early results from 6 months of continue SPECULOOS core survey operations

401.04 — 'Oumuamua and DSHARP Point to 10^{11} Hidden Planets

Malena Rice[1]; Gregory Laughlin[1]
[1] *Astronomy, Yale University (New Haven, Connecticut, United States)*

The discovery of the first interstellar asteroid, *'Oumuamua*, strongly suggests an enigmatic abundance of free-floating asteroids whose ejection into galactic space is entirely unexplainable by the current population of known exoplanets. Remarkably, it signals the existence of a vast undiscovered population of wide-separation (~5+ AU) planets of Neptune's size or larger that are capable of directly ejecting debris from their environments. The ALMA Disk Substructures at High Angular Resolution Project (DSHARP) recently returned 20 ultra high-resolution images of protoplanetary disks, illustrating a ubiquity of substructures among the protoplanetary disk population. We present new results demonstrating for the first time that the planets suggested by radial gaps in the DSHARP sample are consistent with the undiscovered exoplanetary population required to produce a significant flux of interstellar objects. There are a number of compelling near-term prospects for detecting the population of planets that we have inferred, with which we conclude.

401.05 — Peas in a Pod: Planets in Kepler's Multiplanet Systems are Similar in Size and Regularly Spaced

Lauren Weiss[1]
[1] *Institute for Astronomy, University of Hawaii at Manoa (Honolulu, Hawaii, United States)*

As part of the California Kepler Survey, we have established precise planet radii, semimajor axes, incident stellar fluxes, and stellar masses for 909 planets in 355 multi-planet systems discovered by Kepler. In this sample, we find that planets within a single multi-planet system have correlated sizes: each planet is more likely to be the size of its neighbor than a size drawn at random from the distribution of observed planet sizes. In systems with three or more planets, the planets tend to have a regular spacing: the orbital period ratios of adjacent pairs of planets are correlated. Furthermore, the orbital period ratios are smaller in systems with smaller planets, suggesting that the patterns in planet sizes and spacing are linked through formation and/or subsequent orbital dynamics. The regular sizes and spacing of the Kepler planets are among the most common outcomes of planet formation, suggesting that our solar system is not among the majority of planetary system architectures. New theories of planet formation might be required to reproduce the patterns in the Kepler planetary systems.

401.06 — Planets do not show intra-system uniformity

Wei Zhu[1]
[1] *Canadian Institute for Theoretical Astrophysics (Toronto, Ontario, Canada)*

Recent works claim that planets in the same system should have similar properties (namely, mass and radius) and be regular spaced. These patterns, if true, would have significant implications for theories of planet formation and evolution. In this talk, I will show that this so-called intra-system uniformity can be largely, if not entirely, explained by detection biases. The universal signal-to-noise threshold that is used in Kepler transit detections corresponds to different thresholds in planetary parameters for different stars. I will show that it is this variation in detection threshold that is responsible for the majority of the claimed correlation in planet properties. With a more robust statistical approach, I find that the presence and the size of the smaller planets is independent of the presence and size of their largest sibling, arguing against the so-called "intra-system uniformity." Theoretical implications of these findings will also be discussed.

401.07 — Kepler planets: a uniform population

Yanqin Wu[1]
[1] *University of Toronto (Toronto, Ontario, Canada)*

In this talk, I will discuss recent progress regarding the masses of Kepler planets, and how they seem to make up a surprisingly uniform population. This uniformity is unpredicted, and challenges theories of planet formation. As an aside, Kepler planets appear to have interesting connections to the formation of stellar binaries.

402 — Planets in and around Binaries

402.01 — The Role of Stellar Multiplicity in the Formation of Massive Close-In Giant Planets and Brown Dwarf Desert Members

Clémence Fontanive[1]*; Ken Rice*[1]*; Mariangela Bonavita*[1]*; Eric Lopez*[2]*; Koralijka Muzic*[3]*; Beth Biller*[1]
[1] *University of Edinburgh (Edinburgh, United Kingdom)*
[2] *NASA Goddard Space Flight Center (Greenbelt, Maryland, United States)*
[3] *Universidade de Lisboa (Lisboa, Portugal)*

Stellar multiplicity is believed to influence planetary formation and migration, although the precise nature and extent of this role remain ambiguous. In this talk, I will present new results from a survey aimed at testing the impact of stellar multiplicity on the formation and/or evolution of the most massive, close-in planetary and substellar companions, which are extremely challenging to explain with current theoretical models. Using direct imaging observations and the Gaia DR2 catalogue, we searched for wide binary companions to stars hosting massive giant planets or brown dwarfs ($M > 7\ M_{Jup}$) on orbits shorter than ~1 AU. From a robust statistical analysis, we derived a very high binary fraction of ~80% on separations of 20–10,000 AU for our sample, twice as high as for field stars with a 3-σ significance. These results indicate that stellar companions greatly influence the formation or evolution of these systems. This binary frequency was also found to be larger than for lower-mass planets on similar orbits, suggesting that the effects of binary companions become more important for higher-mass planets. Our survey thus demonstrates that binarity plays a crucial role in the existence of very massive short-period giant planets and brown dwarf desert inhabitants, almost exclusively observed in multiple systems. These new results provide vital information and constraints for both theoretical studies of planet formation, and observational campaigns of exoplanets and brown dwarf companions.

402.02 — The Mutual Inclinations of the Proto-Tatooine Disks

Ian Czekala[1]*; Eugene Chiang*[1]*; Sean Andrews*[2]*; Eric Jensen*[3]

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[3] *Physics and Astronomy, Swarthmore College (Swarthmore, Pennsylvania, United States)*

Efforts to learn about the efficiency of circumbinary planet formation from the dozen circumbinary systems discovered by *Kepler* are hampered by the fact that the occurrence rate is degenerate with the underlying mutual inclination distribution (i.e., the typical misalignment between the binary and planetary orbital planes). In this talk, I will discuss our survey of 20 spatially-resolved circumbinary protoplanetary and debris disks, which includes several spectroscopic binaries (P < 40 days) whose disks we have resolved with ALMA for the first time. Crucially, these tight binaries are the only protoplanetary systems that are comparable in scale to the *Kepler* circumbinary planet hosts. Using a hierarchical Bayesian model, we infer that the disks around short-period binaries are intrinsically coplanar (< 5° mutual inclination), implying that the occurrence rate of *Kepler* circumbinary planets is similar to that around single stars (~10% for planets with radii [4,10] R_{Earth}). In stark contrast, however, the mutual inclinations of slightly wider binary systems (P > months) are much more varied: there are several strongly misaligned disks (> 40°), with even a few circumpolar disks (90°) around highly eccentric (e > 0.7) binaries. We will demonstrate that a combination of tight binary star formation mechanisms and high eccentricity oscillatory effects can explain the extremely strong trends of mutual inclination with binary period and eccentricity.

402.03 — Circumbinary Planets at the K/T (Kepler-TESS) Boundary

William F. Welsh[1]
[1] *Astronomy, San Diego State University (San Diego, California, United States)*

Eight years ago at the ESS II conference, we presented the first Kepler circumbinary planets. Since then, 11 planets in 9 systems have been discovered. In this talk we present the last two unpublished, unambiguous Kepler transiting circumbinary planets: KOI-3152 and KIC 10753734. Both systems have planets with rapidly precessing orbits and significantly spotted stars which has made their characterization difficult. The orbital periods are 28.2 and 19.4 days for the binaries, and 171 and 260 days for the planets, respectively. In both systems three transits were detected, yielding planetary radii of 3.4 and 6.0 Re. Like most of the circumbinary planets, these planets orbit near the binary (in)stability radius. KOI-3152 is a particularly interesting case: its eclipses are extremely grazing (impact parameter > 1) and thus its eclipse depths and widths are extremely sensitive to changes in the orbital inclination. A change in inclination is in fact detected, and can be modeled as the result of precession driven by a ~140 Me planet. But this mass is not consistent with the planet's 3.4 Re radius — something is wrong. After much scrutiny, we have solved the problem: The increasing eclipse depth is spurious — it is the result of increasing starspot coverage that has led to an incorrect out-of-eclipse flux normalization. This well-understood (though ignored) bias is of course not particular to binary stars. But the change in the bias is pernicious. We will put these two new planets in context and briefly discuss what the ensemble of Kepler transiting circumbinary planets has to offer exoplanet science: the most accurately known masses and radii, challenges to understanding planet formation and migration, revising the definition of the habitable zone, and why circumbinary planets are often more suitable for life than single-star planets. Finally, we close with a mention of how TESS is expected to reveal hundreds of new circumbinary planets via the "one-two punch" discovery technique, and how we are on the cusp of transitioning from detailed characterization of a handful of planets to being able to carry out statistical studies of the circumbinary planet population.

403 — Planets around White Dwarfs

403.01 — Gas giant planets evaporated by hot white dwarfs

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All known exo-planet hosts stars will evolve into white dwarfs. It is well established that many white dwarfs are accreting small planetary bodies, including asteroids and comets, indicating that planetary systems survive, at least in part, the metamorphosis of their host stars. Gravitationally scattering planetesimals towards the white dwarf requires the presence of more massive bodies, yet no planet has so far been detected at a white dwarf. We discovered a moderately hot white dwarf that is accreting from a circumstellar gaseous disc composed of hydrogen, oxygen, and sulphur. The composition of the disc is unlike all previously detected gaseous disks around white dwafs but resembles predictions for deeper atmospheric layers of icy gas giants, with H2O and H2S being major constituents. We therefore suggest that a gas giant orbiting the white dwarf is evaporated by the strong EUV irradiation from the hot white dwarf. While still indirect, this discovery represents the so far clearest evidence for the expected existance of gas giant planets around white dwarfs. We extend on this result by calculating the orbital separation at which gas giant planets will be evaporated by hot white dwarfs. We find that planets such as the gas giant planets in our solar system are expected to be located at such separations from the sun when it completed its metamorphosis into a white dwarf.

403.02 — A planetesimal orbiting within the debris disc around a white dwarf star

Christopher Manser[1]
[1] *Physics, University of Warwick (Coventry, West Midlands, United Kingdom)*

I will present the first and so far only spectroscopically detected planetesimal around a white dwarf (Manser et al. 2019, Science, 364, 66). The body orbits within a disc of rocky debris on a period of 2.06 hours, making it the closest planetary body to a white dwarf. To withstand the tidal forces this deep in the gravitational field of the white dwarf this planetesimal must have some internal strength and/or a high density, and I discuss the possibility of it being the core of a differentiated planet that has partially disintegrated.

During the talk, I will highlight the methods used to make the discovery, how I can apply this newly developed method to several other white dwarf systems, and how these extreme bodies could explain the presence of gaseous debris discs at white dwarfs.

403.03 — The Abundances of Metals in Circumstellar Gas around Polluted White Dwarfs

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Between 30 - 50% of white dwarfs (WDs) show heavy elements in their atmospheres. This "pollution" likely arises from the accretion of planetesimals that were perturbed by outer planet(s) into the white dwarf's tidal radius. A small fraction of these WDs show either emission or absorption from circumstellar (CS) gas. For example, high resolution spectroscopic observations of WD1145+017 reveal photospheric and CS absorption lines of elements heavier than helium in multiple transitions. The photospheric abundances have been measured and are similar to the bulk composition of the Earth. The CS component arises from a gas disk produced through the sublimation of a transiting, disintegrating planetesimal. Models (to date) have not yet been able to link the CS species to the total atomic abundance in gas. Here we present self-consistent models of CS gas in orbit around various types of WDs and demonstrate how we determine the abundances of CS lines arising from planetesimals. Additionally, we build a grid of models to place constraints on the gas masses needed for detection of CS gas around various WDs with current observatories. We test the grids using new discoveries and WDs with previously known CS gas, in preparation for constraining the frequency of CS gas around statistical samples of WDs. Knowing the abundances of CS gas around polluted white dwarfs will provide a key to understanding the instantaneous composition of the material accreting onto the photosphere and will allow a direct comparison to the composition of rocky bodies in the Solar System.

404 — Atmospheres – II

404.01 — The Most Extreme Case of Atmospheric Escape Detected on the Warm Neptune GJ 3470b with HST

Vincent Bourrier[1]
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Observations of exoplanets during the transit of their host star allow probing the structure and composition of their atmosphere. The intense stellar energy input into exoplanets orbiting close to their star can lead to a dramatic expansion of their upper atmosphere, and the 'evaporation' of large amounts of gas into space. UV observations of hot Jupiters revealed the extended exospheres formed by this escaping gas, and showed that these planets are too massive to lose a substantial fraction of their atmosphere. Lower-mass planets are expected to be much more sensitive to evaporation, which has long been thought to play a role in forming the desert of hot Neptunes (a deficit of Neptune-size exoplanets on very short orbits). I will present the discovery of a giant hydrogen exosphere around GJ3470b, a warm Neptune located at the border of the desert. This is the first UV result of the Panchromatic Comparative Exoplanet Treasury (PanCET) survey, a Hubble program targeting 20 exoplanets across the entire spectrum. Our numerical simulations of the resolved exospheric transit show that GJ3470b is subjected to mass losses comparable to that of hot Jupiters, making it the most extreme case of evaporation observed to date. GJ3470b could already have lost up to 40% of its mass over its 2 Gyr lifetime, bringing direct observational confirmation that evaporation shaped the population of close-in exoplanets. I will compare GJ3470b with other known evaporating planets and discuss the reasons for its dramatic escape. Our results strengthen the interest of observing the upper atmosphere of exoplanets to determine their properties and understand how they depend on their past evolution. This is particularly important for super-Earth and Earth-size planets, whose lower atmosphere could be hidden by clouds. The development of new tracers of atmospheric escape at optical/infrared wavelengths opens thrilling perspectives for the characterization of exoplanets via their upper atmosphere.

404.02 — A Novel New Method for Measuring Windspeeds on Exoplanets and Brown Dwarfs

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Within our solar system, we can directly observe the effects of rapid rotation on the atmospheric physics of the giant planets. Zonal winds, a result of rapid rotation and convection, play an important role in the bulk atmospheric flow. This, in turn, can impact atmospheric chemistry, as evidenced by Jupiter's disequilibrium PH3, which dominates its mid-IR spectrum. Similar to Jupiter and Saturn, recent studies reveal that many brown dwarfs and directly-imaged exoplanets are also fast rotators with evolving atmospheric inhomogeneities. The effects of rotation and convection are starting to be included in efforts to model the atmospheric dynamics of brown dwarfs and exoplanets. The resulting predictions of wind speed, however, remain relatively untested.

We present the first results of a novel new method for measuring wind speeds on exoplanets and brown dwarfs. Utilizing a combination of radio observations and infrared photometric variability, we present the first observational constraints on wind speed for a cool, cloudless brown dwarf. We discuss the implications of our measurement for models of atmospheric circulation. Looking to the future, we discuss the ways in which new observational facilities could extend our method of wind speed measurement to other brown dwarfs and exoplanets.

404.03 — Exoplanet atmospheres at high spectral resolution with CARMENES

Enric Palle[1]

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Transmission spectroscopy using high-resolution spectrographs is quickly becoming a major tool to detect and understand planetary atmospheres, from ultra hot Jupiters to Neptunes-size planets. The CARMENES spectrograph started operations in 2016, and since then we have been using it for the study of planetary atmospheres taking advantage of it simultaneous wavelength coverage from visible to near-infrared (0.5-1.7 micron). This has led to several innovative results, including the first ground-based detections of the He I triplet, allowing the study of exoplanetary tales and scape ratios, or the detection for the first time of the Ca triplet (together with FeII, Na I, and the Balmer series of Hα, Hβ, and Hγ) in the atmosphere of the ultra hot Jupiter (UHJs) MASCARA-2b/KELT20-b. In this talk we will update the several He detections on a sample of about a dozen planets, including various levels of stellar irradiation and planetary masses. I will also discuss CARMENES's capabilities for the characterization of UHJs atmospheres, where our results are consistent with theoretical models, predicting a rich day-side ionosphere.

For the SOC: The CARMENES team as a large sample of exoplanets observed (some published some not yet), which can for the first time provide correlations between stellar irradiation and the detectability of He I triplet and Hα lines, in some cases both, useful for both observers and modelers. I can review the overall results, currently in preparation for a number of publications. For UHJ atmospheres, we can detect several atmospheric species with both trasnmission spectroscopy and cross-correlation techniques simultanoeuly, again for a sample of hot planets. So

I think this talk will nicely summaryze several results in two important hot topics of exoplanet atmospheres.

404.04 — Unlocking the Hidden Secrets of Hot Jupiter Atmospheres through Near-Ultraviolet Spectroscopy: A Case Study of HAT-P-41b

Nikole Lewis[1]; Hannah Wakeford[2]; Ishan Mishra[1]; David Sing[3]; Natasha Batalha[4]; Mark Marley[5]; Nor Pirzkal[2]; Thomas Evans[6]; Jayesh Goyal[7]; Gregory Henry[8]; Tiffany Kataria[9]; Nikolay Nikolov[3]; Jessica Spake[7]; Kevin Stevenson[2]

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Near-Ultraviolet (NUV, 200-400 nm) spectra of planets hold rich information about the chemistry and physics at work in their upper atmospheres. In the solar system, NUV spectroscopy has been critical in identifying and measuring the abundances of a variety of hydrocarbon and sulfur-bearing species, produced via photochemical mechanisms, as well as oxygen and ozone. To date, less than 20 exoplanets have been probed in this critical wavelength range, with mixed results, limited by the wavelength coverage and sensitivity of the workhorse instrument for such studies, HST's STIS G430L and E230M gratings. In HST Cycle 25, our team embarked on a journey to explore the potential of HST's WFC3/UVIS G280 grism, which offers the highest throughput of all HST's instruments in the NUV and is up to 25 times more sensitive than its STIS counterparts at 350 nm. The WFC3/UVIS G280 grism does offer one challenge, the presence of overlapping spectral orders similar to those of JWST's NIRISS instrument, which required us to develop new data reduction and analysis techniques. The first target to be explored with this newly unlocked mode on HST was the hot Jupiter HAT-P-41b, which had been previously observed with HST's STIS G430L grism. Our high-precision spectrum of HAT-P-41b, which combines information from both the positive and negative spectral orders, has revealed features in the NUV that cannot be explained by standard equilibrium chemical models, the presence of aerosols, or stellar activity. Drawing on solar system and stellar studies, we considered dozens chemical species that are known to absorb strongly at NUV wavelengths. Through detailed atmospheric modeling and retrieval analyses we have uncovered not yet considered chemistry and physics at work in the atmosphere of HAT-P-41b, which is likely present in many exoplanet atmospheres. In this talk I will detail the opportunities that have been opened up with the HST WFC3/UVIS G280 grism in the exploration of exoplanet atmospheres and reveal the once hidden secrets of HAT-P- 41b's atmosphere.

404.05 — New Theoretical Models for Cloudy Substellar Atmospheres

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Ample evidence suggests that exoplanets of all kinds have clouds, likely made of many different materials from refractory minerals, to silicate dust, to salts, to volatile ices. Clouds are complex to model and challenging to understand from limited observations of exoplanets. Fortunately, planet-mass free-floating objects provide a key venue for understanding cloud formation in substellar atmospheres. These objects have the temperatures of planets but, critically, lack a nearby star, making high signal-to-noise, high precision measurements possible. To understand the physics and chemistry of these atmospheres, we need to compare these high fidelity observed spectra to state-of-the-art models. Recent improvements to the ingredients in substellar atmosphere models include new line lists for various important species (methane, alkali metals, water, etc.), as well as updated chemistry calculations for a range of metallicities and carbon-to-oxygen ratios. Here, we present a new set of substellar atmosphere models for objects warmer than 1000 K including clouds. We show how these models differ from previous cloudy brown dwarf models (Saumon & Marley 2008), and demonstrate how metallicity affects cloudy substellar spectra. We present results comparing these models to field brown dwarfs, free-floating planets, and directly-imaged companions, demonstrating how gravity changes cloud properties and emergent spectra. Finally, we present a new technique for understanding the compositions and mineralogy of clouds in brown dwarfs using mid-infrared spectroscopic time-series measurements with JWST. These models will publicly available and provide a critical tool for the community in the lead-up to the launch of JWST.

404.06 — Infrared Eclipses and Transits of the Best TESS Planets

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A key TESS goal is to identify the best exoplanet targets for atmospheric study. We will report on initial results from our large-scale Spitzer program to follow up TESS planets with mid-infrared transits and eclipses. Spitzer's unparalleled infrared sensitivity and photometric stability are allowing us to refine the properties of these new planets and ensure that their transits and eclipses can be recovered for many years to come — e.g., with HST and JWST. Our program focuses on the smaller (i.e., sub-Jovian) planets for which ground–based observations are impractical and for which JWST spectroscopy will have a high impact. Our most exciting results will include the only secondary eclipse measurements of these sub-Jovian planets until JWST launches. Our program includes eclipse observations of planets from 1–6 Earth radii and equilibrium temperatures from 800-2500 K. In addition, we are producing some of the only thermal phase curves known for such planets. Our program is providing the touchstone sample of TESS planets that will be studied in great detail for many years to come.

404.07 — Peering into the formation history of Beta Pic b with long-baseline interferometry

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Beta Pictoris is arguably the best-known stellar system outside of our own. 30 years of study have revealed a highly structured circumstellar disk with rings, belts, and a giant planet. But very little is known about how it came into being. In particular, the giant planet beta Pictoris b is known to have played a crucial role in the structuring of the system, but its formation history remains elusive, despite some attempts to settle the cold / hot start question. I will present the first interferometric observations of the giant planet Beta Pic b, obtained with GRAVITY, on the combined four 8.2 m telescopes of the VLTI. These observations resulted in the cleanest (S/N > 50), medium resolution (R=500), K-band spectrum of a giant planet ever obtained. I will show that this spectrum, combined with existing low-resolution data, can be used to estimate the planetary C/O ratio, which in turn can be used to trace down the formation history of the planet. In particular, I will present two interpretations of the low C/O ratio obtained, one in the gravitational collpase formation paradigm for planet formation, and one in the core-accretion paradigm.

500 — Atmospheres – III

500.01 — Non-Equilibrium Chemistry of the Coolest Brown Dwarfs: Implications for Directly Imaged Exoplanets

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The Y-dwarf spectral class is composed of only ~23 brown dwarfs with effective temperatures below 450 K and atmospheres rich in gaseous methane, ammo-

nia, and water. Y-dwarfs are colder than any current directly imaged exoplanet, offering previews into the atmospheric physics of gas giants that will be discovered and characterized in the future with JWST and SCALES. The coldest brown dwarf WISE 0855 (250 K) showed water absorption and evidence of clouds across its M-band (4.5 – 5.0) spectrum. In addition to this, WISE 0855 is also only ~100 K hotter than Jupiter, yet its lack of phosphine absorption means that it has significantly different atmospheric mixing properties than Jupiter. This difference implies that there could be a large degree of variation in atmospheric physics at extremely cool temperatures. In this work, we expand the sample of cool brown dwarf M-band spectra to cover the temperature range of 250 K – 700 K by taking low resolution Gemini/GNIRS spectra of 4 T/Y-dwarfs (50 hours, WISE 1541, WISE 2056, WISE 0313, UGPS 0722) and placing them in context to previously published spectra (WISE 0855, 2MASS 0415, Gl 570D). With the exception of Gl 570D, cloud-free, solar metallicity brown dwarf models do not accurately fit the spectral slopes of our sample and better fits are achieved when non-equilibrium abundances of carbon monoxide are added into the atmospheric models. Atmospheric mixing can bring up warmer carbon monoxide gas and our sample suggests that mixing becomes stronger at cooler effective temperatures. We discuss why these types of atmospheric analyses are essential for 1) planning and interpreting higher quality JWST Y-dwarf observations and 2) predicting what may be observable on cooler, low-gravity gas giant exoplanets.

500.02 — New signatures of Planet Formation Scenario in Gas Giant Exoplanet Atmospheres

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We present a portfolio of observational projects for which we have recently succeeded in measuring the atmospheric composition and metallicities of gas giant exoplanets. We study the atmospheric properties of giant exoplanets over a broad range of masses and equilibrium temperatures, and retrieve their their chemical and dynamical properties. We introduce novel observational techniques and diagnostics to probe exoplanet atmospheres and climates of tidally locked planets; we measure their composition at different longitudes, from their dayside to their nightside, and with multiple spectral resolution. These projects use diverse and complementary approaches to retrieve atomic and molecular abundances and the atmospheric metallicity, including new metallicity tracers (e.g. alkali metals, iron, hydrides). We present the breakthrough results but also the main challenges to overcome while making these measurements. When combined together, our findings on the measurements of atmospheric metallicity allow us to make quantitative comparisons amongst exoplanets, and with the Solar System planets, in order to test predictions from planet formation models. The first results from these projects offer the tantalizing suggestion that some of the trends seen in the Solar System are also seen in extrasolar systems, but others are not. Ultimately, I will present the implication of these new results in the context of exoplanets, and shed light on our understanding of exoplanets' formation, evolution and architectures.

500.03 — Heavy and rare-Earth metals in the transmission spectra of Ultra Hot Jupiters

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Ultra-hot Jupiters form a new class of exoplanets that tend to orbit hot early type stars in short periods. The first Ultra-hot Jupiter known to exist is KELT-9 b: A massive gas giant heated to a temperature of over 4,000K on the day-side by its 10,000K A-star. The extreme temperature dissociates all but traces of the most strongly bound molecules (CO and H_2O) into their constituent atoms. A significant fraction of the atomic gas is thermally ionised. Under these circumstances, line absorption lines by metals and continuum absorption by the hydrogen anion are the dominant sources of opacity. Clouds and aerosols are notably absent, and the timescales of chemical reactions are much shorter than those of mixing and photoionisation over most of the atmosphere at the dayside and terminator regions. This means that the interpretation of the transmission spectrum of KELT-9 b should be greatly simplified compared to planets for which aerosols and non-equilibrium chemistry are important.

We recently performed a survey of the transmission spectrum of KELT-9 b as observed with the high-resolution HARPS-N spectrograph and discovered multiple heavy metals, including iron, chromium, scandium and yttrium. We find that the absorption lines of neutral iron are almost perfectly predicted by a model of an isothermal atmosphere in hydrostatic and chemical equilibrium, but that all other lines are anomalously strong, indicating strong atmospheric inflation below millibar pressures.

We have since started analyses of high-resolution observations of a number of other, cooler hot Jupiters. During my talk I will announce new, strong detections of neutral and ionised metals in these atmospheres. The discovery of multiple metals in multiple planets at high confidence demonstrates that detailed chemical analyses of ultra-hot Jupiter atmospheres are indeed possible, and that the community can move beyond the notion of metallicity, but instead study the chemistry of individual trace metals. In addition, these spectral lines are powerful tools to constrain atmospheric dynamics and structure.

500.04 — Detection of planetary rotation and a strong East wind on a ultra-hot gas giant with ESPRESSO at the Very Large Telescope

David Ehrenreich[1]

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The stellar radial velocity anomaly measured during an exoplanet transit (the Rossiter-McLaughlin effect) allows to constrain the orbital architecture of a transiting planetary system and resolve the surface velocity structure of the transited star. Thanks to the exquisite radial velocity precision of the new ESPRESSO high-resolution spectrograph at the Very Large Telescope, we show that the Rossiter-McLaughlin effect of a highly-irradiated gas giant can also be used to diagnostic the existence of a ultra-hot atmosphere. Removing the stellar signature (known as the Doppler shadow) reveals another Doppler signature moving along with the planet, which we attribute to the planetary atmosphere. Since this absorption signal is obtained through the cross-correlation of the spectra with a stellar mask, the exoplanet must contain atomic iron, the main component of stellar cross-correlation masks. The cross-correlation function of the *planet* appears slightly redshifted at the beginning of the transit and becomes strongly blue-shifted as the East (evening) limb enters the stellar disc, indicating a strong asymmetry in the wind velocity between the two limbs. This is seen consistently at two different epochs of observation. We measure the average full-width at half maximum (FWHM) of the planetary signal and obtain the projected rotational velocity of the planet, which we compare to the expected tidally-locked rotation of the close-in exoplanet. ESPRESSO started science operations at the VLT on September 2018 and this is the first scientific result from the consortium that built the instrument. It reveals ESPRESSO, an ESO instrument open to the Community, as an outstanding characterization machine for exoplanetary atmospheres.

500.05 — The Global Climates, Clouds, and Dynamics of the Hottest Jupiters

Thomas Beatty[1]; Taylor James Bell[2]; Karen Collins[5]; Nick B. Cowan[2]; Lisa Dang[2]; Drake Deming[7]; Jonathan Fortney[4]; B. Scott Gaudi[3]; Tiffany Kataria[6]; Dylan Keating[2]; Joshua Lothringer[1]; Avi Mandell[8]; Tamara Rogers[9]; Adam Showman[1]; Keivan Stassun[10]

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The atmospheres of ultra-hot Jupiters (>3000K) exist in an extreme state of day-night disequilibrium, giving us one of the best opportunities to study the dynamic processes in giant planet atmospheres. By using orbital phase curve observations of these planets we can construct a global map of their thermal emission, and watch their atmospheres change as gas moves from day to night and back again. Besides providing us with a better understanding of hot Jupiter atmospheres, this also allows us to study what would otherwise be observationally inaccessible atmospheric processes. Specifically, we can see the formation of clouds near planetary dusk, their destruction shortly after dawn, and use this to constrain the physics of cloud formation and dissolution in both exoplanets and brown dwarfs. We can also use phase curve observations of extremely hot, cloudless, planets to directly trace the underlying dynamics and mixing in these atmospheres.

We will illustrate this using new results from our new HST/WFC3 phase curves of KELT-1b and new dual-band Spitzer phase curves of KELT-9b. For KELT-1b, our spectroscopic phase curves of KELT-1b show — for the first time — the broadband and spectroscopic signatures of the formation and break-up of these nightside clouds. Coupled with previous broadband Spitzer phase curve observations, this gives us new insight into the cloud formation timescales and cloud compositions on hot Jupiters.

We will also present new 3.6um and 4.5um Spitzer phase curves of KELT-9b, which, at 4600K, is the hottest giant planet known. Unlike all other hot Jupiters, KELT-9b shows a strongly non-sinosoidal phase curve in both Spitzer bands. Also unlike all other hot Jupiters, the extreme temperature of KELT-9b's atmosphere means that it is completely cloudless, and we will discuss how the phase curve variation we see is driven by atmospheric dynamics. The high temperature also causes molecular hydrogen to dissociate on the dayside, and by using the strong opacity difference between H and H2 in the two IRAC channels, we can use the hydrogen dissociation / recombination reaction as a direct tracer of the atmospheric gas dynamics.

500.06 — A Window into Planetary Magnetism with Exo-Aurorae

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Planetary magnetic fields influence atmospheric evaporation from space weather, yield insights into planet interiors, and are essential for producing aurorae. The most direct way of measuring magnetic fields on exoplanets is by observing exo-aurorae at radio frequencies. Our discovery of the first radio exo-aurora on the ~12.7 M_J brown dwarf SIMP J01365662+0933473 marks the beginning of an era for directly probing magnetism at planetary masses. Low-frequency radio arrays such as the Owens Valley LWA and the Square Kilometre Array will soon be sensitive to exoplanet aurorae, providing a new means of exoplanet detection and characterization. Now is a critical time to prepare for these upcoming searches by harnessing detailed studies of exo-aurorae on observationally accessible exoplanet analogs, planetary-mass brown dwarfs. I will synthesize the state of the art for searches of brown dwarf exo-aurorae, including our new results from a survey of young, planetary-mass objects and the deepest study to date of an 11-12 M_J brown dwarf. I will discuss implications for and highlight opportunities to probe exoplanet magnetism with the next generation of ground- and space-based radio facilities.

501 — Disks

501.01 — Protoplanetary disks and their dynamic host stars

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Protoplanetary disks play a key role not only in understanding planet formation, but also in unlocking the fundamental physics of transport processes given that these are some of the closest astrophysical accretion disks. The young stars hosting these disks are known to be remarkably variable, but it is not clear how the variable high-energy radiation fields of a young star impact the disk and hence planet formation and accretion processes. In order to gain insight to these dynamic systems, multi-epoch and multi-wavelength datasets are necessary. I present the first near-simultaneous multi-epoch X-ray, ultraviolet, optical, infrared, and radio observations of an accreting, young star. These data reveal the first observational evidence of the star-disk-jet connection. The observations show that an increase in the surface density in the inner disk resulted in more mass loading onto the star and therefore a higher accretion rate onto the star, which led to a higher mass-loss rate in the jet. This suggests a linked origin, presumably the stellar magnetic field, which can both channel material onto the star as well as eject it in collimated jets along twisted field lines. This showcases the possibilities for future progress in time-domain studies and emphasizes the importance of coordinated multiwavelength work of these dynamic young systems.

501.02 — Large total masses and small amounts of CO gas in protoplanetary disks

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The total mass in protoplanetary disks and the C-to-O ratio of solids and gas are critical initial conditions for understanding the speed of planet formation and planetary composition after formation. Several recent studies show that the standard assumptions for both of these quantities are likely incorrect. I will report on our new set of models that reconcile theory with observations of protoplanetary disks and create a new set of initial conditions for planet formation models. This modeling makes use of recent resolved multiwavelength observations of disks in the millimeter to constrain the aerodynamic properties of dust grains, allowing us to infer total disk mass without an assumed dust opacity or tracer-to-H2 ratio. The 7 disks modeled using this method thus far are close to the limit of gravitational stability at certain radii and raise the possibility that all disks are more massive than has been previously appreciated. This qualitative change to the initial conditions of planet formation has sweeping implications. I will present new, unpublished work that combines the microphysics of cloud formation in planetary atmospheres and our new models of protoplanetary disks to show that the observed depletion of CO in TW Hya is consistent with freeze-out processes and that the variable CO depletion observed in disks can be explained by the processes of freeze-out and particle drift. This work both solves an outstanding problem in observations of protoplanetary disks and robustly constrains the C-to-O ratio in gas and solids available for planet formation.

501.03 — Kinematic detection of embedded protoplanets

Christophe Pinte[1,2]; Gerrit van der Plas[2]; Francois Menard[2]; Daniel Price[1]; Valentin Christiaens[1]; Tracey Hill[3]; Gaspard Duchene[4]; Daniel Mentiplay[1]; Christian Ginski[5]; Elodie Choquet[6]; Yann Boehler[2]; Sebastian Perez[7]; Simon Casassus[7]; Bill Dent[3]

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We still do not understand how planets form, or why extra-solar planetary systems are so different from our own solar system. Recent observations of protoplanetary discs have revealed rings and gaps, spirals and asymmetries. These features have been interpreted as signatures of newborn protoplanets, but the exact origin is unknown, and remains poorly constrained by direct observation. In this talk, we show how high spatial and spectral resolution ALMA observations can be used to detect embedded planet in their discs. We report the kinematic detections of Jupiter-mass planets in the discs of HD 163296 and HD 97048. For HD 97048, the planet is located in a gas and dust gap. An embedded planet can explain both the disturbed Keplerian flow of the gas, detected in CO lines, and the gap detected in the dust disc at the same radius. While gaps appear to be a common feature in protoplanetary discs, we present a direct correspondence between a planet and a dust gap, indicating that at least some gaps are the result of planet-disc interactions.

501.04 — ALMA Reveals a Misaligned Inner Gas Disk inside the Large Cavity of a Transitional Disk

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Pairs of azimuthal intensity decrements at near-symmetric locations have been seen in a number of protoplanetary disks. They are most commonly interpreted as the two shadows cast by a highly misaligned inner disk. Direct evidence of such an inner disk, however, remains largely illusive, except in rare cases. In 2012, a pair of such shadows were discovered in scattered-light observations of the near face-on disk around 2MASS J16042165- 2130284, a transitional object with a cavity 60 au in radius. The star itself is a "dipper," with quasi-periodic dimming events on its light curve, commonly hypothesized as caused by extinctions by transiting dusty structures in the inner disk. Here, we report the detection of a gas disk inside the cavity using Atacama Large Millimeter/submillimeter Array (ALMA) observations with 0.2 arcsec angular resolution. A twisted butterfly pattern is found in the moment 1 map of the CO (3–2) emission line toward the center, which is the key signature of a high misalignment between the inner and outer disks. In addition, the counterparts of the shadows are seen in both dust continuum emission and gas emission maps, consistent with these regions being cooler than their surroundings. Our findings strongly support the hypothesized misaligned inner disk origin of the shadows in the J1604-2130 disk. Finally, the inclination of the inner disk would be close to −45° in contrast with 45°; it is possible that its internal asymmetric structures cause the variations on the light curve of the host star.

501.05 — Polarizing Planetary Systems: New Debris Disks Resolved on Solar System Scales by GPIES

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We will present new top-level results from our unprecedented debris disk survey of 100+ stars in near-IR, polarized scattered light with the high-contrast Gemini Planet Imager. This four-year survey is the first of its kind: a uniform probe of young planetary system environments for small dust on Solar System-like scales with polarimetry and high angular resolution. Among the 26 detected disks we will present, seven are scattered-light discoveries, over a dozen are seen in polarized intensity for the first time, and all are resolved on spatial scales of 0.5–7.0 au. On the population level, we constrain the presence of micron-sized grains at stellar separations of 1–20 au for our nearest observed stars and 20–200 au for the farthest: a prime zone for planet formation and migration. We now know the detailed morphologies of these disks, a handful of which either may be disturbed by interaction with low-mass companions or have had perturbing giant planets directly imaged. In one case, an external stellar companion may have truncated the primary star's disk. We will also link our data to ALMA observations, showing an empirical relationship between the radial locations of small and large disk grains. Going forward in a broader context, our data yield measurements of the disk-scattered light's polarization fraction, which will be a key factor in determining grain compositions, sizes, and structures that are only weakly constrained otherwise. Thus, GPIES disk data are pushing the bounds of theory and models to explain observations. In summary, we will use our ESS IV oral presentation to share with the exoplanet community the results of the most information-rich survey of scattered-light debris disks ever conducted, one that will inform the design and drive the science goals of advanced instrumentation and facilities that will see first light in the coming decade.

501.06 — The debris disk of HR 8799: do we need an extra planet?

Virginie Faramaz[1]

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HR 8799 is so far the only system where multiple planets have been directly imaged. The planetary system is surrounded by an extremely faint debris disk, which detailed observations are now within reach thanks to the sensitivity and resolution power of ALMA. Prior observations of this disk at low (~3) SNR in Band 6 (1.3 mm) led two different teams to derive two different values for the location of the disk inner edge: one result suggests that an additional planet should be present beyond the outermost planet HR 8799 b to carve this inner edge. The other one finds an inner edge location that is, on the

contrary, compatible with HR 8799 b carving this inner edge. We present here new high angular resolution observations of this debris disk in Band 7 with ALMA, the most sensitive that were obtained so far, thanks to which we derive an inner edge consistent with the largest value derived from the modeling of the Band 6 emission, and thus confirm that the inner edge of the debris disk would require an additional planet beyond HR 8799 b to have been carved at this distance.

501.07 — The presence of gas in debris discs: what does it imply?

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Gas is now discovered ubiquitously around main-sequence stars at a stage (>10Myr) where planets have already formed. This gas is always discovered in systems with planetesimal belts (debris disc stage) and is thought to being released from volatile-rich planetesimals when they collide with each other and create the observed dust. I will present the most recent gas detections and new yet unpublished ALMA data showing new detections for the first time around a G-type star (in addition to recent detections around M and F stars), showing that gas release around main sequence stars is not an A-star phenomenon as once thought. I will show what can be learned from all these new gas detections in the main sequence phase for the planetary system as a whole. The main result so far is that, as we are probing gas released from planetesimals, we have a direct access to the volatile content of these exoplanetesimals, which is fundamental as they are the building blocks of planets and may also deliver volatiles when impacting onto Earth-like planets in these systems. I will show how gas evolution models (Kral et al. 2016, 2017, 2019) can help to constrain the composition of these exoplanetesimals. From the gas models, we also derive the viscosity of these gas discs and show that it may be compatible with values given by the magnetorotational instability (MRI, see Kral & Latter 2016), which may allow to test the MRI under new conditions, in low density environments where non-ideal effects (such as the ambipolar diffusion) may be important. Last but not least, our new model is able to explain the most massive gas discs observed (with CO masses greater than 0.01 earth masses) as being of secondary origin as well (Kral et al. 2019), i.e. with gas released from planetesimals rather than being primordial (i.e. a remnant of the protoplanetary disc gas). This has important consequences concerning planetary formation and the fate of protoplanetary discs that can be studied from these gas observations.

502 — Habitability and Biosignatures

502.01 — Are Exoplanets Orbiting M Dwarfs Extreme?

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M dwarf stars have long spin-down timescales, long activity lifetimes and persistent magnetic activity, all of which have implications for the potential habitability of orbiting planets. I will present results from several research programs investigating M dwarf rotation, activity and evolution. I will discuss a new technique to measure chemical-kinematic ages of main-sequence M dwarf stars. We applied that technique to a variety of nearby M dwarfs, both planet hosts and non-planet hosts, and rapid (young) and slow (old) rotators. We find that relatively slow rotators (P$\sim$100 days) do not appear to be α enriched, indicating that they are not over 10 Gyrs old. Second, for the rapid rotators, we see clear evidence of Zeeman enhancement of Y-band Ti I lines as a function of Rossby number. While other activity indicators, such as H-α and X-ray emission, appear to saturate with low Rossby number, Zeeman enhancement does not, indicating that the saturation mechanism is confined to the chromosphere and corona. Finally, I will present new results on the M dwarf radius problem. Using spectral synthesis methods, we find that large magnetic star spot fractions are primarily responsible for observed discrepancies between model and measured stellar radii in fully convective M dwarf stars. As most M dwarfs appear discrepant, our results suggest the vast majority of M dwarfs have large spot fractions and correspondingly high localization of magnetic fields.

502.02 — Flare Statistics and High Resolution Spectroscopy of a Volume Complete Sample of Mid-to-Late M dwarfs within 15 Parsecs

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Main-sequence stars with masses less than 30% that of the Sun are fully convective and are the most abundant stars in the galaxy. The question of how fully convective stars generate their magnetic field is of intrinsic interest and also bears upon the habitability of their orbiting planets. These stars currently provide the best opportunities to study planets in the habitable zone, so it is essential we characterize their magnetic activity. We are currently undertaking a multi-epoch high-resolution spectroscopic survey in addition to obtaining (through a TESS GI program) two-minute cadence data of a volume-complete sample of stars with masses between 0.1-0.3 the solar value and within 15 parsecs. The stars in the sample are well-characterized with accurate masses and radii, and photometric rotation periods from the MEarth project. We determined the statistics of flares on all mid-to-late M dwarfs within 15 parsecs observed by TESS to-date. We use our complementary high-resolution spectroscopic measurements of rotational velocities, H-α equivalent widths, along with our galactic space motions (calculated from our measured radial velocities) to correlate the ages and activity levels of this population to the flare rates, luminosities, and durations.

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502.03 — Volatile- and Water-rich Planetary Material Accreting onto a White Dwarf

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We report the discovery of a white dwarf that has an unusually large amount of hydrogen, ~5% by mass, within its helium atmosphere. Such a mixture cannot result from the past evolution of this star alone (Rolland+, 2018). The only plausible explanation is that this white dwarf has recently accreted $\sim 10^{22}$g of water — as much as 1% of the Earth's oceans. Absorption lines of the major mineral-forming elements (O, Mg, Si, Ca, Fe, Ni) and of volatile elements (C, S, P) detected in our *VLT* and *Hubble Space Telescope* spectroscopy unambiguously demonstrate that the star is currently accreting planetary debris. Our abundance analysis indicates a comet-like nature of the disrupted planetesimal, carrying the material necessary for seeding terrestrial exo-planets with the building-blocks of life. Small traces of hydrogen are common in helium atmosphere white dwarfs, and are often found alongside pollution by planetary debris, providing clear statistical evidence that water-rich rocky bodies prevale into the final stages of stellar and planetary evolution (Gentile Fusillo+, 2017). This connection is corroborated by this spectacularly polluted white dwarf, which has accreted a sufficient amount of water to change its past and future spectra evolution.

502.04 — M-dwarf Activity Driven 3D Climate and Photochemistry of Inner Habitable Zone Tidally-Locked Planets

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Planets residing in circumstellar habitable zones (CHZs) offer our best opportunities to test hypotheses of life's potential pervasiveness and complexity. Constraining the precise boundaries of habitability and its observational discriminants is thus critical to maximizing our chances at remote life detection for future instruments. Conventionally, calculations of the inner edge of the habitable zone (IHZ) have been performed using both 1D climate models and 3D general circulation models. However, these models lack interactive three-dimensional chemistry and do not resolve the observationally-critical mesosphere and lower thermosphere (MLT). Here we employ a 3D chemistry-climate model (CCM) to simulate the atmospheres of synchronously- rotating planets orbiting at the inner edge of habitable zones of K- and M-dwarf stars (between T_{eff} = 4000 K and 2600 K) with N_2-O_2-H_2O-CO_2 atmospheres. With the inclusion of interactive chemistry, we find that simulated runaway and moist greenhouse thresholds are in good agreement with previous GCM studies. However, around quiescent stars, our prognostic hydrogen mixing ratios are orders of magnitude lower than previous diagnostic estimates, suggesting that planets in these systems are less vulnerable to desiccation via water escape. Additionally, we find that around active M-dwarfs, increases in upper atmospheric moisture and photodissociation rates allow hydrogen mixing ratios to approach that of water vapor, leading to elevated water loss efficiency via diffusion-limited escape. Using our CCM results as inputs, translated transmission and emission spectra show that both water vapor and ozone features could be detectable by future missions such as the James Webb Space Telescope.

502.05 — Dark water oceans on exoplanets orbiting cool stars

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Several thousand extrasolar planets orbiting other stars provide a first glimpse into the diversity of other worlds. We show that oceans on worlds orbiting different alien Suns will differ from Earth's oceans because the penetration depth of light can be very different, altering ocean dynamics significantly. While Sunlight can penetrate up to 250m in a water ocean, light may penetrate as little as 2m for oceans illuminated by cool red stars. Dynamics and photosynthesis in water oceans on exoplanets and exomoons orbiting other Suns can be very different from Earth's. We introduce a new paradigm for the hydrosphere-atmosphere interaction in planetary models. The idea is fundamental – when you convolute the absorption of water with wavelength with the irradiation exoplanets receive from different host stars it fundamentally changes how deep that light can penetrate water, especially for cool host star planets like the detected, potentially habitable planets around our neighboring stars Proxima-b and the planets in the Trappist-1 system. Our paper shows the huge impact the host star irradiation has on the thermal structure and resulting dynamics on water oceans on extrasolar planets. Additionally, the depth below which there is generally insufficient light for photoactive organisms in oceans on a red star will be much shallower than on Earth. Thus, photosynthetic ocean life, if it exists, will be much closer to the ocean surface, and can be more readily detected on planets and moons orbiting red stars.

502.06 — Prebiotic Planets: Evaluating Planetary Conditions for Origins of Life

Dimitar Sasselov[1]
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We often discuss exoplanet habitability, but rarely focus on the prebiotic planets – the ones with geochemical conditions conducive to the emergence of life. How could prebiotic exoplanets, if we could identify them, help us solve life's origins? In this talk I will focus on the prebiotic synthesis of the nucleotides, amino acids and lipids needed for *life as we know it* and the planetary environmental context that makes that synthesis possible. I will argue that, as we still struggle to understand life's origins on Earth, there are general predictions about the global planetary conditions that are testable with upcoming spectroscopic observations of the atmospheres of rocky exoplanets.

503 — Future Missions

503.01 — Expanding our Telescope Toolkit: Exoplanet Science Opportunities with SmallSats

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New technologies can disrupt the status quo by challenging the current assumptions and opening up new avenues of research. Small satellites, including CubeSats, have been growing in popularity in many science and technology fields, yet are only now beginning to receive attention as tools for astrophysics research. When deployed as space-based telescopes, SmallSats enable science experiments not possible with existing or planned large space missions. We trade some capabilities such as mirror size for lower cost and shorter build times for more frequent launch opportunities, with two additional and crucial advantages over large, over-subscribed telescopes: SmallSats can monitor sources for weeks or months at time, and at wavelengths not accessible from the ground such as the ultraviolet, far-infrared and low-frequency radio. Achieving high-impact astronomical research with SmallSats is becoming increasingly feasible with advances in technologies such as precision pointing and compact sensitive detectors. SmallSats may also pair well with the large space- and ground-based telescopes providing complementary data to better explain the physical processes observed. There are many possible exoplanet-focused science cases for SmallSats, several of which are already in development and more ideas yet to be proposed. I will share our experiences developing the NASA-funded SPARCS (Star-Planet Activity Research CubeSat) mission as a case study to explore the challenges and opportunities of astrophysics SmallSats.

503.02 — Exoplanet Imaging with ELTs and the TMT's Planetary Systems Imager

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The combination of high angular resolution and sensitivity will allow ELTs to image hundreds of exoplanets ranging from gas-giants to super-earths and even a handful of rocky planets. I will review the different types of exoplanets that will be observable with ELTs and also discuss how spectroscopy will enable measurements of molecular abundances, T-P profiles, cloud properties, spin rates, accretion, and weather. Finally I will present an overview of the Planetary Systems Imager, the TMT's multi-wavelength exoplanet imaging platform.

503.03 — The CHEOPS Mission: Launch Imminent for ESA's Next Exoplanet Mission

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The CHaracterising ExOPlanet Satellite (CHEOPS) is a mission jointly led by Switzerland and ESA which was selected in October 2012 as the first S-class mission in the ESA Science Programme. CHEOPS will be the first space observatory dedicated to search for transits of exoplanets by means of ultrahigh precision photometry on bright stars already known to host planets. It will have access to more than 2/3 of the sky and provide the unique capability of determining accurate radii for planets of known mass from ground-based spectroscopic surveys. This will allow a first order characterisation of the planets' internal structure by determination of their mean density, which provides direct insights into their composition. CHEOPS will also provide precise radii for new planets discovered by the next generation of ground- or space-based transits surveys.

To reach its goals, CHEOPS is designed to measure photometric signals with a precision of 20 ppm in 6 hours integration time on magnitude 9 stars, and 85 ppm in 3 hour integrations on magnitude 12 stars. The CHEOPS payload is a single telescope of 30 cm clear aperture, which has a single CCD focal plane detector. In Ritchey-Chrétien telescope optical configuration it provides a defocussed image of the target star. The main design drivers are related to the compactness of the optical system and to the capability to reject the stray light. The nominal CHEOPS operational orbit is a polar Sun-Synchronous Orbit (SSO) with an altitude of 700 km and a local time of the ascending node (LTAN) of 6 am; the orbit inclination is about 98° and the orbital period is 100 min. The nominal mission lifetime is 3.5 years, with a possible extension to 5 years. CHEOPS will launch as auxillary passenger on a Soyuz from Kourou. The launch is imminent with the launch window defined by Arianespace from 15 October to 14 November this year. This talk will review the CHEOPS mission, its scientific goals and mission design. We will discuss the expected performances and also present latest analysis of the ground calibration campaign. An overview of the GTO programme will be presented.

503.04 — ARIEL: ESA's Mission to Study the Nature of Exoplanets

Göran Pilbratt[1]
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The ~4000 exoplanets currently known display a great diversity of physical parameters, and orbit stars with different properties and planetary system architectures. For most of them we know only either mass or size, or both. However, planetary modelling based on sizes and masses alone suffer from important degeneracies. To independently measure chemical composition is the next challenge. It would enable improved modelling, which will enhance our understanding of what planets are made of, how planets and planetary systems form, and how planets and their atmospheres evolve to what we observe today.

The Atmospheric Remote-Sensing Infrared Exoplanet Large-survey (ARIEL) mission has been selected by ESA as M4 in the Cosmic Vision programme for a 2028 launch. ARIEL is dedicated to performing measurements of the chemical composition and dynamics of exoplanet atmospheres for a large population (many hundreds) of known diverse preferentially warm and hot transiting planets, enabling the understanding of the physics and chemistry of these far away worlds.

The observations will probe atmospheric chemistry and dynamics, by means of infrared spectroscopy in three bands (covering 1.1-7.8 um) and visible/NIR photometry in three bands (covering 0.5-1.1 um). All six bands are observed simultaneously with an off-axis Cassegrain telescope having a ~1.1 × 0.7 m aperture. Both transit and eclipse/occultation spectroscopy will be employed to obtain transmission and emission spectra. The photometry provides thermal and scattering properties and monitors stellar activity.

ARIEL will conduct its observations from a large halo orbit around the Sun-Earth L2 point. ARIEL wants to embrace the general community, by offering open involvement in target selection, and by providing timely public releases of high quality data products at various processing levels throughout the mission.

In this presentation I will provide an overview of all aspects of the mission, describe the current ongoing activities in ESA, the ARIEL Consortium, and industry, and the overall schedule.

503.05 — How to Determine Whether M-Dwarf Terrestrial Planets Possess Atmospheres

Eliza Kempton[1]; Daniel D. B. Koll[2]; Megan Mansfield[3]; Matej Malik[1]; Edwin Kite[3]; Jacob L. Bean[3]; Dorian Abbot[3]; Renyu Hu[4]

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In the era of TESS, we expect to detect legions of planets for which atmospheric characterization will be possible with JWST. Perhaps the most exciting among these planets are the rocky ones, which up until now have not been accessible to atmospheric studies. Yet small rocky planets will still be challenging targets for JWST, so the question arises of how best to use JWST to make tangible progress toward understanding the atmospheres of terrestrial bodies. We posit that JWST is best suited to distinguish between rocky planets that do and do not possess atmospheres by photometrically observing their secondary eclipses. The argument is as follows. The dayside temperature of a tidally locked planet will be reduced by the presence of an atmosphere, either because the atmosphere transports heat to the night side of the planet or because atmospheric scatterers such as clouds will increase the planet's Bond albedo. There is therefore a maximal secondary eclipse depth that is representative of a hot dayside hemisphere with no atmosphere present. We focus on planets orbiting M stars because they are being discovered in large numbers by current facilities, they are within the observational grasp of JWST, and there is considerable skepticism as to whether these planets can retain atmospheres at all given the high-energy irradiation from their host stars.

I will present the results from a multi-institution collaboration investigating the promise and the limits of secondary eclipse photometry as a test for candidate atmospheres on rocky M-dwarf planets. We have developed a suite of general circulation models and radiative-convective atmospheric structure models, and have developed our understanding of rocky planet surface geochemistry, in order to address this topic. We have focused our efforts on three warm transiting super-Earths that will be ideal targets for secondary eclipse investigations with JWST. We find that JWST can distinguish between planets with and without atmospheres in as little as a one eclipse — a time investment that significantly outperforms phase curves and the more traditional transit spectroscopy techniques.

503.06 — Cold exoplanets with WFIRST: demographics with the microlensing survey, and characterization with the coronagraph instrument

Matthew Penny[1]

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As outlined by the 2010 Decadal Survey, NASA's next flagship mission WFIRST will conduct wide-field infrared surveys and demonstrate space-based coronagraphy techniques necessary to directly image exoplanets in reflected visible light. We will give an update on the status of the WFIRST mission, focusing on its two major exoplanet goals. Using its wide field instrument (WFI), WFIRST will carry out a large exoplanet microlensing survey toward the Galactic bulge. This survey is designed to statistically explore exoplanet demographics over a wide range of orbital separations (from <~1 AU to infinity [i.e., free-floating planets]), and five orders of magnitude in mass (super-Jupiters down to a few lunar masses). These broad statistics will provide vital, and otherwise unobtainable, observational constraints on the end products of the planet formation process, and on the occurrence rates of low-mass planets in wider orbits than can be probed by radial velocity and transit techniques. Focusing on recent and upcoming results from the WFIRST Microlensing Science Investigation Team, we will describe new estimates of WFIRST's capabilities to detect bound and free-floating planets, the development of techniques required to measure microlensing planet masses, and the results of a data challenge designed to test planet detection and modelling techniques on WFIRST-like simulated data. For the coronagraph instrument (CGI) we present a few key highlights of CGI's predicted capabilities

for characterizing nearby planetary systems via its technology demonstration of extreme contrast coronagraphic imaging and spectroscopy in visible light. CGI will demonstrate five main areas that aid future direct imaging missions such as LUVOIR and HabEX: exquisite wavefront control through a pair of deformable mirrors, suppression of an on-axis star's diffraction pattern through occulting masks or shaped pupils, the use of photon counting visible detectors, and post-processing techniques at high contrast in space, and high contrast spectroscopy.

503.07 — Radial Velocity Science in the 2020s: The Future of Ground-based EPRV Surveys

Jennifer Burt[1]
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The radial velocity community has delivered a variety of new and exciting instruments around the globe over the past two years. While many of these facilities began operations during the end of the 2010s, their true science impact will not be felt until the 2020s. Extreme precision radial velocity instruments such as ESPRESSO, EXPRES, and Neid will allow for detailed monitoring of our closest stellar neighbors on a scale that has never been seen before. They will obtain mass measurements for many of the smallest transiting planets from missions like TESS, in addition to surveying nearby stars in search of the short period, terrestrial planets that we expect based on the Kepler planet occurrence rates. Meanwhile, near-infrared spectrographs like HPF, SPIRou, and IRD will facilitate searches for planets around the coolest nearby stars, targeting a variety of stellar host that has not previously been surveyed by Doppler facilities. I will discuss the upcoming advancements within these branches of radial velocity science and how they are expected to expand the current boundaries of exoplanet discovery space.