Astro2020 Science White Paper

Wide-Orbit Exoplanet Demographics

Thematic Areas: ☒ Planetary Systems   ☒ Star and Planet Formation
☐ Formation and Evolution of Compact Objects   ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution   ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract: The Kepler, K2 and TESS transit surveys are revolutionizing our understanding of planets orbiting close to their host stars and our understanding of exoplanet systems in general,

but there remains a gap in our understanding of wide-orbit planets. This gap in our understanding must be filled if we are to understand planet formation and how it affects exoplanet habitability. We summarize current and planned exoplanet detection programs using a variety of methods: microlensing (including WFIRST), radial velocities, Gaia astrometry, and direct imaging. Finally, we discuss the prospects for joint analyses using results from multiple methods and obstacles that could hinder such analyses.

We endorse the findings and recommendations published in the 2018 National Academy report on Exoplanet Science Strategy. This white paper extends and complements the material presented therein.

1 The Need for Exoplanet Demographics

When, where, and how frequently do habitable planets form in our galaxy and throughout the observable Universe? This question motivates a significant fraction of exoplanet, and indeed astronomical research today, in order to help us address whether or not we are alone in the Universe. In the past quarter century, we have made dramatic strides in our understanding of planetary systems, and we have made great progress in the development of instrumentation with the capability of detecting signs of life in planetary systems beyond our own. Nevertheless, we should keep in mind that our ignorance still greatly exceeds our knowledge of planet formation and especially planetary habitability. The conventional definition of the habitable zone is largely based on observations in our own solar system, and its position might vary for atmospheres very different from our own (e.g. Seager 2013). Furthermore, wide-orbit planets can influence the habitability of Earth-like planets in Earth-like orbits. The early formation of Jupiter's core could be one reason why the Earth does not have orders of magnitude more water (Morbidelli et al. 2016) in the context of pebble accretion scenarios. The small amount of water on the Earth could also result from the accretion of planetesimals formed interior to the snow line (e.g. Alibert et al. 2013). Also, the growth and migration of wide-orbit planets invariably scatters water-rich planetesimals across their planetary systems, which provide a sprinkling of water to rocky planets (Walsh et al 2011; Alibert et al. 2013; Raymond & Izidoro 2017).

Planet formation involves a multitude of complex processes that we do not have the ability to simulate in detail. As a result, observations have regularly discovered planetary systems with unexpected properties, such a hot Jupiters (Mayor & Queloz 1995) systems with numerous, low-density planets in very short period orbits (Lissauer et al. 2011). Thus, our understanding of planetary systems is driven by observations, with theory as a critical tool for interpreting the observations. We have made great progress in understanding planets in close orbits with radial velocities (e.g. Mayor et al. 2011) and especially the Kepler transit survey (Thompson et al. 2018), but our understanding of wide-orbit planets is lacking. In this white paper, we describe how a multitude of methods can be used to advance our understanding of wide-orbit exoplanet demographics.
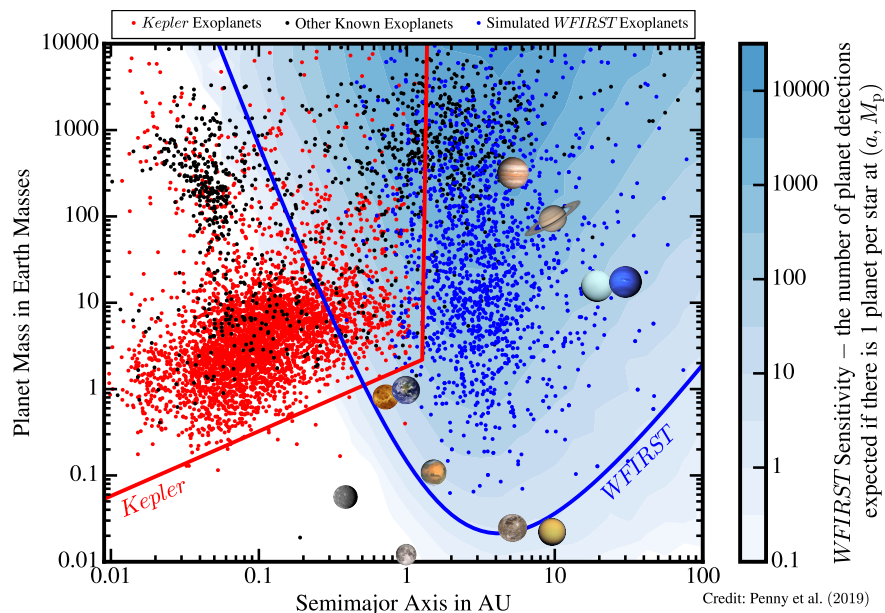

Figure 1: Comparison of planet mass and semimajor axis for planets candidates found by Kepler (red), planet discoveries by other current methods (black) and simulated planets from WFIRST (blue). The pictures show the locations of solar system planets and moons (as if they are planets).

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2 Microlensing with WFIRST and Ground-based Programs

The greatest planned investment in exoplanet demographics is the microlensing survey of the WFIRST mission. Fig. 1 compares the expected WFIRST exoplanet discoveries with Kepler's planet candidates and planets found by other methods (Penny et al. 2019). WFIRST's space-based microlensing survey was selected by the Astro2010 decadal survey because of the high sensitivity of space-based microlensing to low-mass planets in wide orbits, ranging from the habitable zone of FGK stars to infinity, i.e. unbound planets (Mróz et al. 2019). As Fig. 1 indicates, WFIRST is sensitive to analogs of all the planets in our Solar System, except for Mercury, and has sensitivity extending down to planets below the mass of Mars ($\lesssim 0.1 M_\oplus$). This is more than 2 orders of magnitude lower than the sensitivity of other methods.

While microlensing light curves themselves usually yield only the star-planet mass ratio, q, WFIRST's space-based imaging will yield host star and planet masses for the majority of planets discovered using a combination of microlensing light curve constraints and direct observations of the host star (Bennett et al. 2007; Bhattacharya et al. 2018). This also yields the lens systems' distance. Microlensing is also sensitive to planets in binary systems (Gould et al. 2013; Bennett et al. 2016), and WFIRST will be sensitive to exomoons in systems similar to the Earth-moon system (Bennett & Rhie 2002).
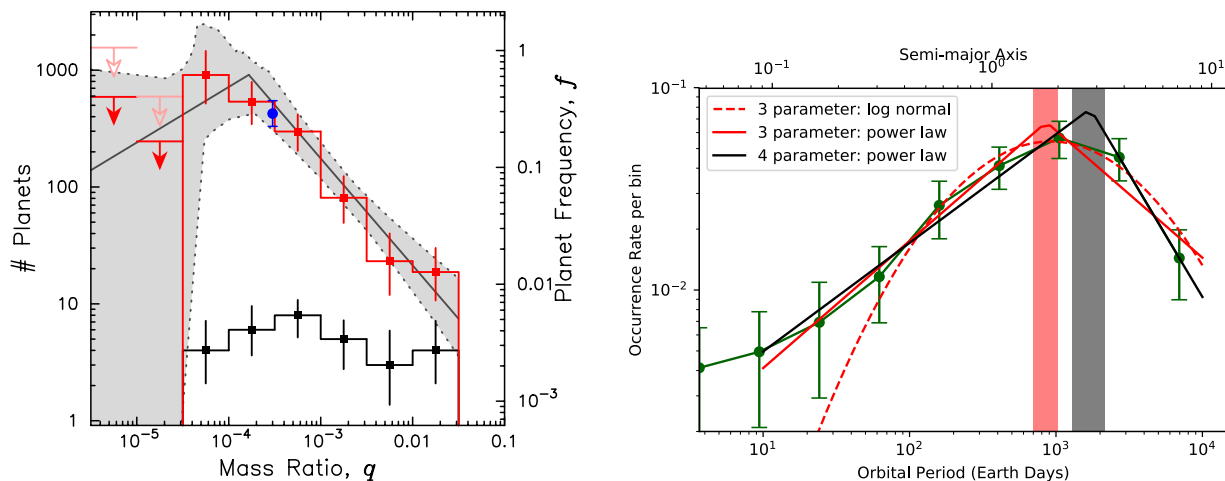

Figure 2: The left panel shows the raw microlens planet mass ratio distribution (Suzuki et al. 2016) in black, with the detection efficiency corrected distribution in red. The grey shading indicates the range of 1σ broken power law models. The peak at $q \approx 10^{-4}$ has been confirmed by Jung et al. (2019). The right panel shows the gas giant planet occurrence rate distribution for a large radial velocity sample (Fernandes et al. 2018) indicating a peak at periods 1000-2000 days.

Prior to WFIRST, ground-based microlensing surveys will provide the highest sensitivity to low mass planets in wide orbits around GKM stars. Recent results from the MOA group (see Fig. 2) show a smooth distribution of planets from mass ratio $q = 0.03$ down to $q \approx 6 \times 10^{-5}$ in seeming contradiction to a gap at 1-4 $\times 10^{-4}$ (or 20-80$M_\oplus$) predicted by the runaway accretion scenario of the core accretion model (Suzuki et al. 2018). The 3-telescope network of the KMTNet survey (Jung et al. 2019) is now detecting planets at a much higher rate than MOA, and should improve these statistics significantly prior to WFIRST. These ground-based microlensing demographic results can help to enable the planning of other near term programs, such as the search for sub-Saturn and Neptune mass exoplanets orbiting young M-dwarfs with JWST (Schlieder 2019).

3 Long-period Exoplanet Demographics with Radial Velocities

The radial velocity (RV) method has sensitivity to planets at a very large range of orbital periods ranging from ~ 1 day to > 20 years, which corresponds to a factor of ~ 400 in semi-major axes. In recent years, much of the RV effort has been focused on observations of transiting planets found by Kepler, K2, and now, TESS (e.g. Marcy et al. 2014; Petigura et al. 2017; Gandolfi et al.2018; Palle et al. 2019). Much of the effort in the near future will be focused on improving the precision of RV measurements for planets in the vicinity of the habitable zone (Fischer et al. 2016).

The amplitude of RV signal (K) caused by an orbiting planet is $K \propto M_P \, M_\star^{-1/2} a^{-1/2}$, where M_P is the mass of the planet, $M_\star$ is the mass of the host star, and a is semi-major axis, so the sensitivity degrades fairly gradually with semi-major axis. However, there are additional challenges for detecting long-period planets with the RV method. The planetary orbital periods of these planets can be similar to stellar magnetic cycles, so care must be taken to separate the RV and magnetic cycle effects. This requires some more observing time, but it can be done with RV data (Endl et al. 2016). Also, these periods are longer than healthy PhD timescales, and it can be a challenge to maintain records of observing decisions that might be needed for statistical analyses for planets with periods measured in decades. Statistical analyses of RV data can be compromised if observing plans are changed due to the detection of candidate planetary signals when a fraction of the data has been collected. Therefore, it would be useful to establish a repository of long duration data sets, including the details of any decisions to change observing plans to enable to RV studies of planets with multi-decade orbital periods.

Fortunately, several long duration surveys have been completed or are still ongoing (e.g., Mayor et al. 2011, Fischer et al. 2016, Howard et al. 2016) but with a plethora of new RV instruments coming online (Fischer et al. 2016) we need to conduct simultaneous surveys on both the old and new instruments in order to maximize the value of the legacy RV datasets and to maximize the observing baselines of new surveys with the latest generation of extremely-precise RV instruments.

The Mayor et al. (2011) sample of FGK stars has been analyzed by Fernandes et al. (2018) who found a peak in the orbital period distribution at periods of 1000-2000 days for planets of $> 50 M_\oplus$, as shown in the right panel of Fig. 2. This is consistent with the results of direct detection surveys, but it has not yet been compared in detail to the Suzuki et al. (2016) microlensing results.

4 Astrometry from Gaia

ESA's ongoing Gaia mission is expected to release a large catalog of planet discoveries in the final data release from its prime mission in 2022 or 2023 based on astrometric data from more than a million FGKM stars. The detection of $\sim 20,000$ planets of Jupiter mass or larger at orbital separations of 0.5 to 5 AU is expected (Perryman et al. 2014), and the 2-dimensional astrometric orbits will provide planetary mass measurements for the detected planets. The Gaia mission has already been extended to a 6.5 year duration, and based on Gaia's success to date, it seems likely that its mission will be extended to a full 10 years . This might triple the number of detected planets and detect as many as 3000 systems with two giant planets (Casertano et al. 2008). For $\sim$10% of these systems, sufficiently accurate orbital solutions would allow for precise mutual inclination angle determinations. Gaia's huge sample will allow a detailed investigation of the diversity of giant exoplanets in wide orbits.

The Gaia results will complement the RV studies quite well. Gaia will provide the inclinations and masses for previously discovered RV planets, while the RV data will provide information on

planets orbiting close to their host stars that are beyond Gaia's sensitivity. Gaia's fantastic statistics on giant planets orbiting stars in the Galactic neighborhood can be compared to the statistics of giant planets with measured distances from the WFIRST microlensing survey to determine how the population of wide-orbit giant planets depends on the Galactic environment.

5   Direct Imaging

Direct imaging is complementary to the indirect techniques discussed in this paper. Infrared imaging provides estimates of planet temperature and luminosity (and thus radius), as well as atmospheric composition, while optical imaging can provide information on rotation rate, dynamics, and climate. Such information provides fundamental constraints on possible habitability as well. Planets can be directly detected in reflected light, or in thermal emission, either from the residual heat of formation or in thermal equilibrium with the host star. It is easiest to image self-luminous planets farther from their host stars as observations are currently limited by the relative contrast achievable (typically 10^{-6} at 1").

Current surveys are capable of detecting young self-luminous gas giant planets at large orbital radii (e.g. $> 1 M_{\mathrm{Jup}}$ at $> 30 \mathrm{AU}$, where M_{Jup} is Jupiter's mass). Nearby young stars are rare, so host samples often use stars in nearby moving groups with ages of 30-300 Myr (providing better mass sensitivity) at distances of 20-200 pc, with the physical resolution depending on the distance. These surveys are conducted with 6-12 meter telescopes employing high contrast imaging systems utilizing high actuator density adaptive optics systems (e.g. GPI, SPHERE, MagAO, SCExAO). Recent work suggests that gas giant planets $1 - 10 M_{\mathrm{Jup}}$ are rare beyond 30 AU (Nielsen et al. submitted; Vigan et al. in preparation). Combined with data from other techniques, this implies a planet surface density distribution that rises to a peak between 1-10 AU, and then falls for both M dwarf and FGK star populations (Clanton & Gaudi 2016; Meyer et al. 2018; Fernandes et al. 2019). Sensitive gas giant planet searches also suggest a local minimum in the companion mass function between $10 - 40 M_{\mathrm{Jup}}$ (Reggiani et al. 2016). To date, the measured frequency of gas giant planets through direct imaging appears to depend on stellar mass in that higher mass stars have a higher giant planet occurrence rate (e.g. Bowler 2016), which is the opposite of the case for lower mass planets in short period orbits (Howard et al. 2012; Petigura et al. 2013; Mulders et al. 2015; Dressing et al. 2015).

Future work with the next generation extremely large telescopes (ELTs) will enable surveys to probe to smaller inner working angles ($< 3 \mathrm{AU}$) with greater sensitivity ($< 0.5 M_{\mathrm{Jupr}}$) around nearby young stars). The James Webb Space Telescope (JWST) will have extraordinary sensitivity from 1-28 microns compared to the ground when operating in the background limit (> 1"), but it will likely be inferior to ground-based AO in the contrast limit; (cf. Danielski et al. 2018; Delacroix et al. 2013). In the background limit ($> 20 \mathrm{AU}$ for typical targets), JWST should be able to detect planets as small as Uranus and Neptune if they are common. Both ground-based AO on current and future telescopes as well as HST and JWST characterization of wide-orbit companions will enable reliable assessment of planet atmospheric composition (e.g. volatiles such as C/O ratio) compared to the host star. Such studies provide fundamental tests of planet formation theory, both origin location and migration history.

A major breakthrough is expected with ELTs as they should be able to image small planets (1-$4 R_{\oplus}$) around the very nearest stars in both reflected light and thermal emission. Results from these surveys, when combined with those from other techniques, will enable us to assess: i) discontinu-

ities in planet mass functions and orbital surface density distributions and how they may depend on each other; ii) how diverse planet compositions depend on mass, radius, and orbital location; and iii) how all of the above depend on host star properties such as composition, multiplicity, and formation environment (e.g. field versus open cluster). Addressing these questions will enable us to put predictive planet formation models to the test, allowing us to take the next steps to assessing the frequency of planetary environments that may give rise to the biochemical origins of life.

6 Joint Analysis of Exoplanet Samples from Different Methods

This white paper grew out of discussions in the Science Interest Group (SIG) #2 of the Exoplanet Exploration Program Analysis Group (ExoPAG), which focuses on "Exoplanetary System Demographics," led by Jessie Christiansen and Michael Meyer. This group contains practitioners of all the exoplanet detection methods outlined in this paper, but in our discussions it became apparent many, if not most, SIG #2 members were unaware of the latest developments using other methods. However, it is also clear that our knowledge of exoplanet demographics can be advanced by combining the results from multiple methods (Clanton & Gaudi 2014a, 2014b; Pascucci et al. 2018), but this can become difficult if the practitioners of each method are unfamiliar with the details of the other methods. For example, the microlensing and radial velocity studies shown in Fig. 2 are not easily combined. The microlensing analysis was done for a sample of GKM stars using planet-star mass ratios because the host star masses are not always known, but the RV analysis was done using planet masses. While we know the masses of the RV planet host stars, we cannot convert the analysis to use mass ratios, because the detection efficiencies for the individual stars in the survey are not available. Fortunately, there is an ongoing program (Bhattacharya et al. 2018) to determine the masses of the host stars in the Suzuki et al. (2016) sample, so it will soon be possible to do a joint analysis using planet and host masses with the Mayor et al. (2011) sample.

We expect that this sort of problem will be very common when comparing demographic results from different studies. In fact, it can occur with studies using the same method. If the samples overlap, then some adjustment needs to be made to avoid over-counting the stars in the sample that overlap. This generally requires detection efficiencies for individual stars. Therefore, we recommend that a national exoplanet demographics database be established to collect detailed demographic data, like individual star exoplanet detection efficiencies, so that the results of published demographic studies can easily be incorporated into future studies.

References

Alibert, Y., Carron, F., Fortier, A., et al. 2013, A&A, 558, A109

Bennett, D. P., Anderson, J., & Gaudi, B. S. 2007, ApJ, 660, 781

Bennett, D. P., & Rhie, S. H. 2002, ApJ, 574, 985

Bennett, D. P., Rhie, S. H., Udalski, A., et al. 2016, AJ, 152, 125

Bhattacharya, A., Beaulieu, J.-P., Bennett, D. P., et al. 2018, AJ, 156, 289

Bowler, B. P. 2016, PASP, 128, 102001

Casertano, S., Lattanzi, M. G., Sozzetti, A., et al. 2008, A&A, 482, 699

Clanton, C., & Gaudi, B. S. 2014a, ApJ, 791, 90

Clanton, C., & Gaudi, B. S. 2014b, ApJ, 791, 91

Clanton, C., & Gaudi, B. S. 2016, ApJ, 819, 125

Dressing, C. D., & Charbonneau, D. 2015, ApJ, 807, 45

Endl, M., Brugamyer, E. J., Cochran, W. D., et al. 2016, ApJ, 818, 34

Fernandes, R. B., Mulders, G. D., Pascucci, I., Mordasini, C., & Emsenhuber, A. 2018, arXiv:1812.05569

Fischer, D. A., Anglada-Escude, G., Arriagada, P., et al. 2016, PASP, 128, 066001

Gandolfi, D., Barragán, O., Livingston, J. H., et al. 2018, A&A, 619, L10

Gould, A., Udalski, A., Shin, I.-G., et al. 2014, Science, 345, 46

Howard, A. W., Marcy, G. W., Bryson, S. T., et al. 2012, ApJS, 201, 15

Jung, Y. K., Gould, A., Zang, W., et al. 2019, AJ, 157, 72

Lissauer, J. J., Fabrycky, D. C., Ford, E. B., et al. 2011, Nature, 470, 53

Morbidelli, A., Bitsch, B., Crida, A., et al. 2016, Icarus, 267, 368

Marcy, G. W., Isaacson, H., Howard, A. W., et al. 2014, ApJS, 210, 20

Mayor, M., Marmier, M., Lovis, C., et al. 2011, arXiv:1109.2497

Mayor, M., & Queloz, D. 1995, Nature, 378, 355

Meyer, M. R., Amara, A., Reggiani, M., & Quanz, S. P. 2018, A&A, 612, L3

Mróz, P., Udalski, A., et al. 2019, A&A, 622, A201

Mulders, G. D., Pascucci, I., & Apai, D. 2015, ApJ, 814, 130

Palle, E., Nowak, G., Luque, R., et al. 2019, A&A, 623, A41

Pascucci, I., Mulders, G. D., Gould, A., & Fernandes, R. 2018, ApJL, 856, L28

Penny, M. T., Gaudi, B. S., Kerins, E., et al. 2019, ApJS, 241, 3

Perryman, M., Hartman, J., Bakos, G. Á., & Lindegren, L. 2014, ApJ, 797, 14

Petigura, E. A., Marcy, G. W., & Howard, A. W. 2013, ApJ, 770, 69

Petigura, E. A., Sinukoff, E., Lopez, E. D., et al. 2017, AJ, 153, 142

Raymond, S. N., & Izidoro, A. 2017, Icarus, 297, 134

Reggiani, M., Meyer, M. R., Chauvin, G., et al. 2016, A&A, 586, A147

Schlieder, J., 2019, JWST GTO Proposal 1184

Seager, S., 2013, Science, 340, 577

Sozzetti, A., & de Bruijne, J. 2018, Handbook of Exoplanets, 81

Suzuki, D., Bennett, D. P., Ida, S., et al. 2018, ApJL, 869, L34

Suzuki, D., Bennett, D. P., Sumi, T., et al. 2016, ApJ, 833, 135 (S16)

Thompson, S. E., Coughlin, J. L., Hoffman, K., et al. 2018, ApJS, 235, 38

Walsh, K.J., Morbidelli, A., Raymond, S.N., O'Brien, D.P., Mandell, A.M. 2011, Nature, 475, 206

Yee, J. C., et al. 2019, Astro2020 survey white paper