Astro2020 Science White Paper

Protoplanetary Disk Science Enabled by Extremely Large Telescopes

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 processes that transform gas and dust in circumstellar disks into diverse exoplanets remain poorly understood. One key pathway is to study exoplanets as they form in their young (∼few Myr) natal disks. Extremely Large Telescopes (ELTs) such as GMT, TMT, or ELT, can be used to establish the initial chemical conditions, locations, and timescales of planet formation, via

(1) measuring the physical and chemical conditions in protoplanetary disks using infrared spectroscopy and (2) studying planet-disk interactions using imaging and spectro-astrometry. Our current knowledge is based on a limited sample of targets, representing the brightest, most extreme cases, and thus almost certainly represents an incomplete understanding. ELTs will play a transformational role in this arena, thanks to the high spatial and spectral resolution data they will deliver. We recommend a key science program to conduct a volume-limited survey of high-resolution spectroscopy and high-contrast imaging of the nearest protoplanetary disks that would result in an unbiased, holistic picture of planet formation as it occurs.

1 Introduction

The processes that transform gas and dust in circumstellar disks into diverse exoplanets are poorly understood. Existing theories of disk chemistry invoke different assumptions (about grain sizes, heating and cooling processes, molecular formation and destruction rates), and few models have been validated observationally to determine whether the assumptions are correct. Similarly, imaging observations of disks are not yet of high enough spatial resolution to provide good constraints to models of planet/disk interaction. A unified theory of planet formation requires information on conditions within the progenitor disks and studies of newly formed planets at the same scale (< 10AU) of current exoplanet surveys.

   To date, protoplanetary disks have only been probed in detail in their outer regions, whereas exoplanet discoveries are mostly inside those radii (Fig. 1). Transformational studies of planet formation will require studying protoplanetary disks at the very high spatial and spectral resolution provided by 20-m to 30-m telescopes such as the Giant Magellan Telescope (GMT), the Thirty Meter Telescope (TMT), and the European Extremely Large Telescope (ELT). These Extremely Large Telescopes (ELTs) have both the sensitivity (due to the large collecting area) and angular resolution to reveal new details about protoplanetary disks at unprecedented scales. Such work will establish the chemical initial conditions, locations, and timescales of planet formation. In this white paper, we focus specifically on the science cases to: (1) probe physical and chemical conditions in protoplanetary disks at the scale of planet formation using infrared spectroscopy, and (2) study planet-disk interactions through imaging and spectro-astrometry.

2 Physical and Chemical Conditions of Planet Formation

Whether a planet is wet or dry, icy or rocky, depends on how and how fast material is processed through a disk. The compositions of the feeding zone for planets that eventually populate the habitable zone of low-mass stars (<1 $M_\odot$) span scales of a few tenths to 10 AU. The temperatures
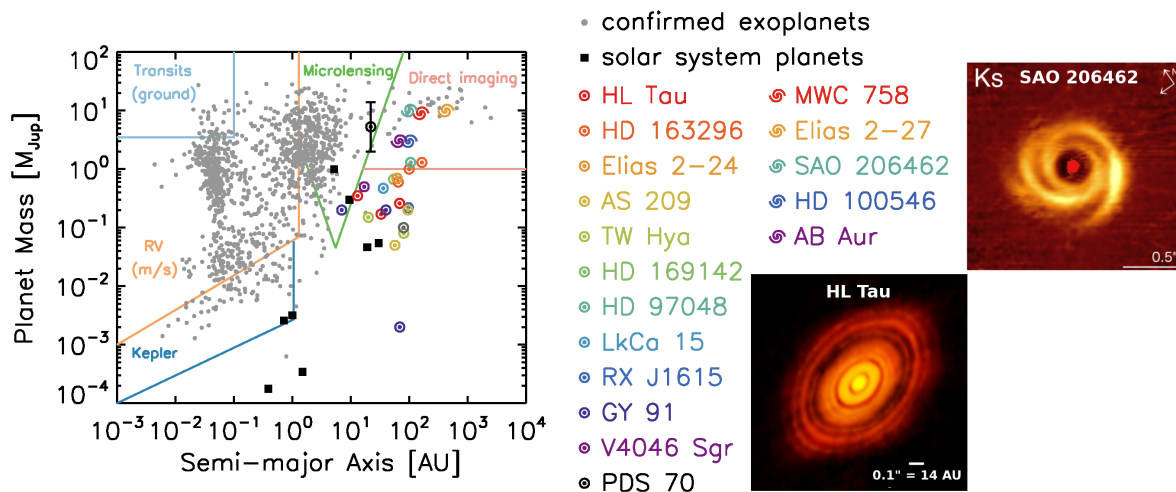

Figure 1: *Mass vs. orbital distance diagram of exoplanets and putative protoplanets in disks with gaps ($\odot$ symbols) or spiral arms (spiral symbols), adopted from Bae et al. (2018). The two inset images show example disks with gaps and spirals: HL Tau (ALMA Partnership et al., 2015) and SAO 206462 (Garufi et al., 2013). Putative protoplanets are located outside of the parameter space in which current exoplanet detection techniques are capable of finding exoplanets. With ELTs, we will be able to peer into the innermost regions of planet-forming disks.*
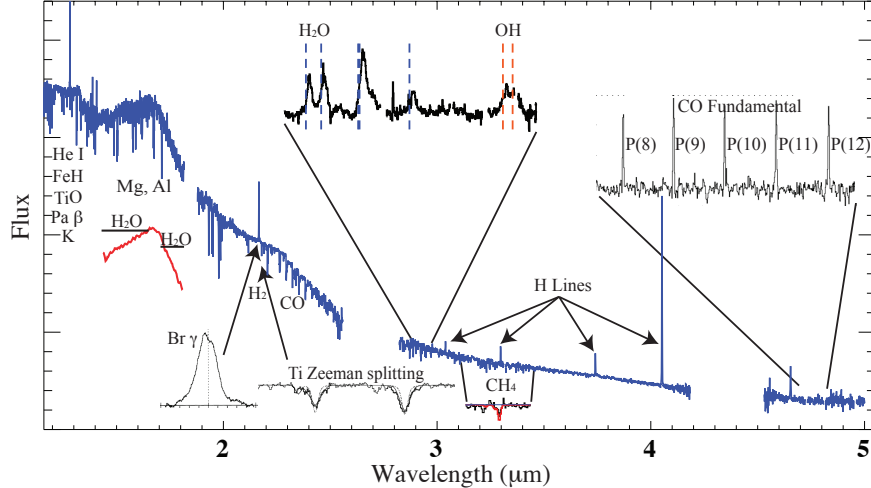
Figure 2: *Near-infrared spectra of TW Hydrae, the nearest classical T Tauri star. Here, a low resolution spectrum in blue (Vacca & Sandell, 2011) is overlayed with a subset of the interesting spectral features available for young stars, and circumstellar disks. Hydrogen emission line profiles and strengths probe disk accretion physics (Najita et al., 1996), spectral shape and atomic line widths indicate age (Allers & Liu, 2013), Zeeman splitting measures stellar magnetic fields (Yang et al., 2008), molecular emission lines reveal disk kinematics, abundances, and temperature structure (Banzatti et al., 2017; Gibb & Horne, 2013a; Salyk et al., 2007). Regions of strong telluric absorption are not plotted. The ELTs will enable the more typical young stars at ~140 pc to be studied with the same fidelity and also with spatial resolution. Credit: A. Weinberger.*

of interest will be $\lesssim$500 K, so that refractory solids are condensed throughout the region while volatile condensation fronts exist at the outer edges (low temperatures). Here, disks typically have high gas column densities and optical depths and only the upper disk atmosphere can be observed in the optical/near-IR (see Fig. 2). However, given short timescales for vertical mixing, this region should be closely linked to the larger molecule-rich disk interior. Line widths and velocities for kinematic measurements of circulation (turbulence) and accretion in the disk surface are necessary to make that connection quantitative. JWST will make strides on the warm molecular layer and optically thin holes, but lacks high spectral resolution for determining gas kinematics. ALMA is making outstanding progress on the cool, outer disk and disk midplane. The role of the ELTs will be to provide higher spatial and spectral resolution than JWST such that <10 AU scales are reachable for more than just the most extreme disks accessible with existing 8-m class facilities (see Fig. 3).

Carbon-bearing species and water are of particular interest. Measurements of the major carbon-carrying molecules (CO, C_2H_2, CH_4) and atomic carbon, simultaneously, will help us understand the carbon depletion of terrestrial planets (Gail & Trieloff, 2017), and predict the carbon abundance of terrestrial exoplanets. Spectroscopy of H_2O will allow us to understand the role of water ice in the formation of gas giants, and to measure the profile of C/O in the natal disk. Mid-IR spectra can provide the abundance of H_2O within the so-called "snow line", and, with sufficient coverage at long wavelengths, also provide the snow line location (e.g. Zhang et al., 2013; Blevins et al., 2016). Observations of OH can also provide insight into the chemical formation and destruction of water vapor in terrestrial planet forming regions, including measuring how much ultraviolet is penetrating the disk's upper layers to drive chemistry (e.g.
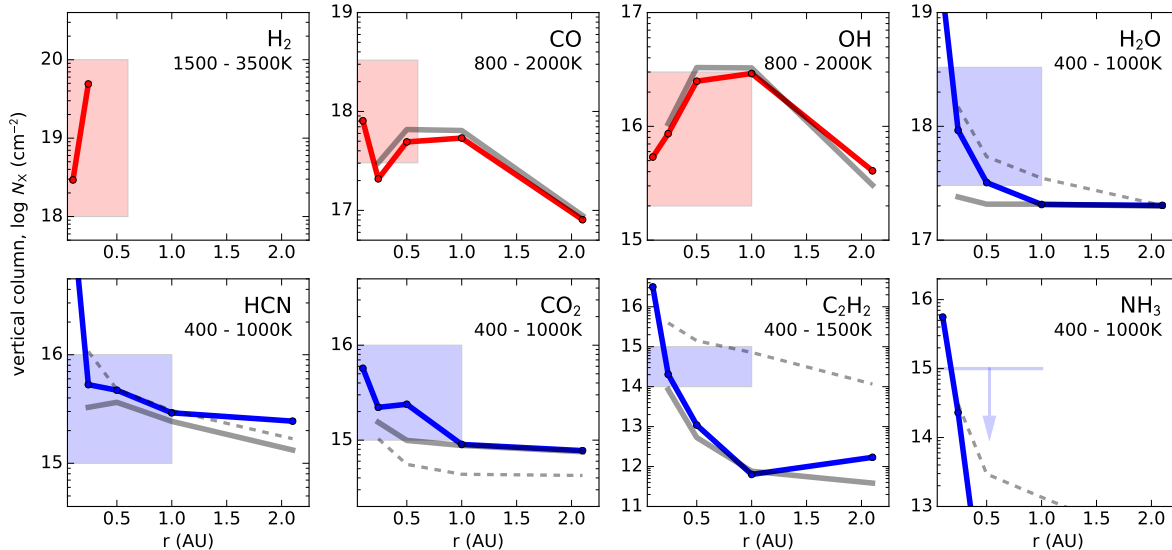
Figure 3: *Abundance of the primary molecular gas phase species in disks (Najita & Ádámkovics, 2017). The color lines plot the vertical column density of the species as a function of stellocentric radius. The gray solid line reflects the abundance in the absence of mechanical heating in the disk. The gray dashed line reflects the abundance in the absence of Ly-α emission in the disk. The shaded boxes indicate the measured abundance of each molecule. ELTs will provide more sensitive measures of the composition of the inner disk for an unbiased sample of sources.*

Najita et al., 2010). The increased sensitivity provided by ELTs will make it possible to study the detailed distribution of gas species with distance from the star for low-mass host stars in nearby (<200 pc) star-forming regions. The C/O ratio sets the oxidation state of a planet and may change drastically based on where a planet or its constituents form (e.g. Öberg et al., 2011). Derived temperatures and gas column densities will test models of disk thermal structure and chemistry, revealing the chemical and physical initial conditions for planet formation.

Few disks currently have direct measures of their turbulence, but this is a fundamental property of disks that influences the growth and settling of grains, the vertical thermal profiles and chemical mixing between the midplane and surface, and rate of accretion of grains and pebbles into the star. The relative opacities of closely spaced optically thick emission lines can reveal the "microscopic" turbulence of the gas. This method has been applied to infer the turbulence at the inner rim of disks (Hartmann et al., 2004; Carr et al., 2004). ALMA observations of *outer* disks have found surprisingly low levels of turbulence, and it has yet to be fully understood how these can be consistent with observed rates of stellar accretion (e.g. Hughes et al., 2011; Flaherty et al., 2017). With ELTs and very high spectral resolution, it may also be possible to use the abundant 3μm water lines in the L-band. The sensitivity and large spectral grasp of high resolution spectrographs on ELTs will enable the study of *inner* disk turbulence that will bridge the gap between what has been learned about the inner rim of disks and the outer disk.

3 Planet-disk Interactions

Substantial feedback occurs between forming planets and disks that affects disk structure the incorporation of disk material into planets. Planet-disk interactions may be very important for setting planetary compositions; for example, pressure bumps generated by young planets could cause a pile-up of volatile-rich grains from the outer disk that are then prevented from reaching
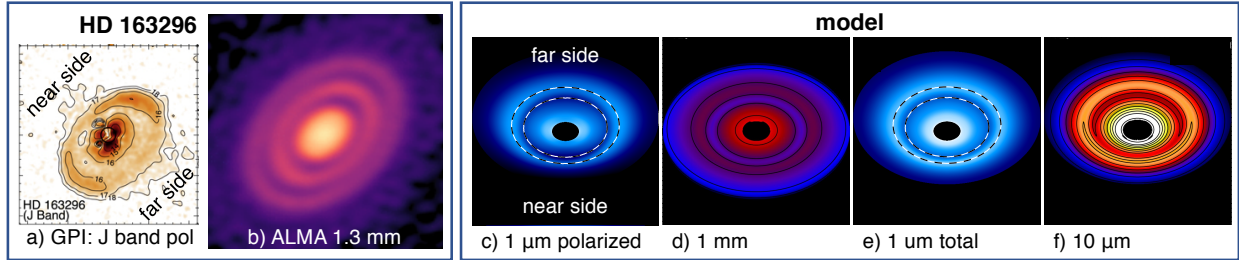
Figure 4: *Observed structure in HD 163296 compared with a disk model with a 70 Earth mass planet at 10 au inclined at 45°. The (a) polarized J-band image taken with GPI (Monnier et al. 2017) and the (b) ALMA image at 1.3 mm (Isella et al. 2016) can be compared to the model disk as viewed in (c) polarized intensity at 1 μm (Jang-Condell, 2017) and at (d) 1 mm (Jang-Condell & Turner, 2013), respectively. The images on the right show the disk model viewed at (e) 1 and (f) 10 micron total intensity (Jang-Condell & Turner, 2013). An ELT operating in the mid-infrared could probe thermal emission from the disk surface, as shown in the 10 micron image.*

inner rocky planets. While the outer regions of bright disks have been imaged in the optical to near-IR, ELTs will enable us to probe structures in fainter disks and structures much closer to the star where most planets appear to reside (Fig. 1). Direct observations of disk-planet interactions are needed to tease out the essential physics behind planet formation.

Resolved imaging of young, gas-dominated protoplanetary disks reveal structures such as gaps (e.g., HL Tau [Fig. 1], HD 163296 [Fig. 4]), spiral arms (e.g., SAO 206462 [Fig. 1]), warps (Loomis et al., 2017; Mayama et al., 2018; Benisty et al., 2018a), and inner holes (van der Marel et al., 2015). Hydrodynamic simulations predict that gaps and spiral arms can be caused by planets embedded in and interacting with the disk (Dong et al., 2015b,a). The appearance of gaps and spiral arms can also reveal planet properties (Debes et al., 2013; Dong et al., 2015a) or indicate gravitational instability (Dong et al., 2018). Other simulations have shown that a close-in stellar or planetary companion can break up the inner and outer disk and excite a misaligned inner disk, or warp (Facchini et al., 2013; Nealon et al., 2018). All these large scale disk structures are illuminated by the central star and may also cast shadows in disks: features that can be seen in resolved imaging with ELTs either in scattered light in optical to near-IR or in thermal emission at $10 - 20\ \mu$m (see Fig. 4). For example, shadows cast by warps could produce apparent spiral arms in the outer disk (Benisty et al., 2017, 2018b; Min et al., 2017).

Multiwavelength imaging can be particularly useful for interpreting disk structure. For example, a gap at 50 au has been imaged in HD 163296 in both polarized scattered light and 1.3 mm continuum emission (Fig. 4). By combining these datasets, the near side/far side degeneracy can resolved and the disk scale height estimated. As ALMA continues to reveal more gaps, rings, and spirals in disks (e.g. Andrews et al., 2018), synergy with imaging from ELTs at similar angular scales can give us greater insight into planets forming in them.

4 Survey Strategy

We recommend an unbiased imaging and spectroscopy survey of disk-bearing (Class II) stars in the nearby young (1–10 Myr) star-forming regions of Taurus, Ophiuchus, Lupus, and Scorpius-Centaurus. Likewise, the ability to combine both spectroscopic dissection of the physical and chemical properties of disks along with high-contrast imaging of the same disks and their protoplanets will provide an unbiased, holistic view of planet formation as it occurs.

Low spectral resolution Spitzer-IRS observations demonstrate that molecular detections will be nearly ubiquitous for young disks with sufficient S/N (Pontoppidan et al., 2010). The addition of high spectral and spatial resolution will be crucial for disentangling modeling degeneracies and determining inner disk chemical abundance structures. Most of these molecules have been detected at high spectral resolution in only a handful of the brightest disks (e.g. Mandell et al., 2012; Gibb & Horne, 2013b; Najita et al., 2018). ELTs will enable the observation of a more representative sample of disks, revealing the more "typical" conditions of planet formation.

The sensitivity required is a function of both the continuum brightness and the need to detect small line:continuum ratios. As an example, the median Taurus Class II star has J=9.5 mag and W1 (3.4 μm)=7.2 mag. We can scale this down to stars with M<0.5 M$_\odot$, which are the most interesting targets because because of their high fraction of low-mass planets, but the least explored by the current generation of telescopes at high spectral resolution (e.g., only two low-mass stars were studied in the sample of 55 stars in Banzatti et al. (2017)). The low mass stars in Taurus have J$\sim$14.8 mag. We can use J-[W1] to estimate the disk brightness, or, more realistically, the fact that disk mass is roughly proportional to stellar mass (Andrews et al., 2013), and assume the disks around low mass stars will be somewhat fainter, with W1 $\sim$ 13 mag. This sensitivity can be achieved with GMTNIRS and TMT-MODHIS at S/N$\sim$50 in 1 hr. This same sensitivity can detect a line:continuum ratio of 0.06, comparable to what is achieved presently on bright targets with current generation telescopes.

With these spectra we will be able to compare the chemistry of disks relative to system parameters such as stellar spectral type, stellar accretion rate, disk geometry, and x-ray luminosity. One of the principal outcomes of this survey will be the testing of thermochemical models of disks (Fig. 3). In addition to using the spectra to study the chemistry of disks, the line profiles will be analyzed spectro-astrometrically (or possibly with an IFU) to identify signatures of disk winds (e.g. Pontoppidan et al. 2011), planet-disk interactions, and possibly emission from a circumplanetary disk itself (e.g., Brittain et al. 2014). The indirect signatures of disks inferred from the spectra will then be validated by direct imagery of forming planets.

Disks with known well-resolved substructure from ALMA will naturally be higher priority targets for high-contrast imaging (e.g., Figure 4). While there are a few dozen such ALMA-resolved disks known now (e.g. ALMA Partnership et al., 2015; Andrews et al., 2016, 2018), we can anticipate many more by the time the ELTs are conducting science observations. The challenge for the ELTs will be to find structures, such as spirals, rings, and warps, in the inner regions of disks, where the strongest disk-planet interactions are expected and where they have the most impact on the composition and architectures of planetary systems. At the distance to the nearest clusters of on-going star formation, at $\sim$140 pc, the diffraction-limited resolution of 30 m class telescopes is essential to resolving the important scales: resolving 1 AU at 140 pc requires an angular resolution of 7 mas, which is the diffraction limit of a 30 m telescope at a wavelength of 1 μm. An inner working angle of 2-3 λ/D, provides a view from just inside to outside the putative water ice line. At visible and near-infrared wavelengths, photons are efficiently scattered off of dust in the disk surface and in imaging observations can reveal warps and spirals in the dust distribution. Using spectroastrometry, the gas motions in the vicinity of such structures can be measured and indicate whether a planet is truly modifying the trajectories of disk material. In one hour, the point source sensitivity for coronagraphic imaging is 15.6 magnitudes at L-band, or about 0.05 Jy/asec^2. As shown in Fig. 4, a planet at 10 au around a solar mass star can create structures that are as bright as $\sim$ 0.1 Jy/asec^2, which is easily seen with this sensitivity.

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