Astro2020 Science White Paper

Detecting Protoplanets and Tracing the Composition and Evolution of Planet-forming Material with Large UV/Optical Observatories

Thematic Areas: ☒ Planetary Systems ☒ Star and Planet Formation

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Abstract:
With approximately 4,000 confirmed extrasolar planets, a key challenge for the next decade is characterizing the environments in which planets assemble and grow their nascent atmospheres. Understanding the characteristics of planet-forming disks is critical to our larger search for habitable worlds in two primary ways. First, by determining the timescale and composition of nebular volatiles, we constrain which nearby planetary systems are most likely to host habitable atmospheres. Second, by constraining planet properties that are not directly observable (e.g. bulk composition), we provide important context for spectra of potential Earth-like planets. This white paper describes how future, large (primary apertures larger than ~12m) UV/optical observatories can detect accreting protoplanets, quantify the evolution of material at planet-forming radii, and provide new constraints on the dispersal of material through disk winds.

Recent high-resolution images of circumstellar disks around young (1–10 Myr) stars revealed complex structures (e.g. ALMA Partnership 2015; Wagner et al. 2015; Andrews et al. 2016; Perez et al. 2016; Pohl et al. 2017; Hendler et al. 2018), some of which point to advanced planet formation. A few candidate giant planets have been recently detected around Myr-old stars (e.g. Sallum et al. 2015, Keppler et al. 2018) and short timescales to assemble asteroid-size objects and giant planets are well in line with the evolution and dispersal of gas and dust in the solar nebula (Pascucci & Tachibana 2010). Thus, 1–10 Myr-old circumstellar disks provide an opportunity to study planet formation in action.

At the distances of nearby star-forming regions (e.g. Taurus-Auriga, Lupus, or Chamaeleon I), 1 AU corresponds to an angular scale of ~10 mas and gas probing ~1 AU radii will have emission line FWHMs of ~30 km/s. Therefore, high angular and spectral resolution is required for mapping the inner disks where terrestrial planet formation occurs (Figure 1). Such high-resolution observations will directly link birth environments to the final architecture of the exoplanetary systems. We argue that high-sensitivity, multi-object, high-resolution UV/optical observations of young stars will allow us to detect and characterize protoplanets (Section I), trace the composition, evolution, and dispersal of planet-forming material (Section II), and map protoplanetary material dispersed via disk winds (Section III).

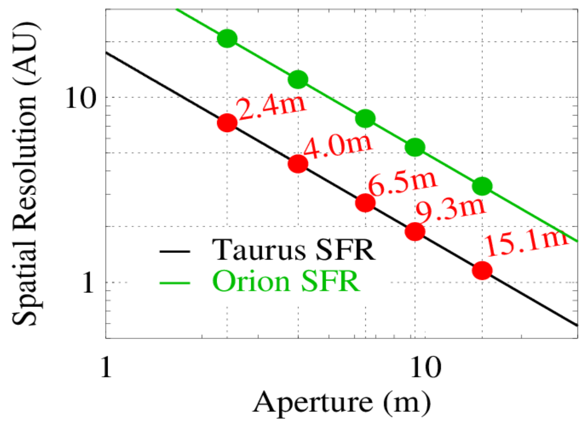

Figure 1: Terrestrial planet-forming radii resolved at 500 nm as a function of telescope aperture for nearby star-forming regions (SFRs) with a range of massive star content. A 15m telescope resolves ~1 AU at the distance of the Taurus-Auriga SFR.

I. Detect and characterize protoplanets

As protoplanets are likely accreting gas through a circumplanetary disk, multi-wavelength observations are necessary to separate disk emission from that produced in an accretion shock and thereby constrain the properties of forming planets. Accreting giant planets will glow in U- and B-band as well as UV and Balmer emission lines (e.g. Hα at 656.3 nm; Figure 2), while the circumstellar disk will start to dominate at ~1000 nm (e.g. Zhu 2015). 30m-class ground-based telescopes with extreme AO systems will be diffraction limited at near-infrared and visible wavelengths over small field of view (~few square arcseconds) and will mostly probe re-processed emission, one circumplanetary disk at a time.

Jovian mass planets at > 5 AU separations will carve gaps in their natal disks that can be readily resolved in coronagraphic scattered light images in the visible. UV/visible imaging in narrow-band filters sensitive to accretion diagnostics will enable the direct detection of protoplanets and their circumplanetary disks within these gaps. To estimate the potential science return from future observatories, we used the Large Ultraviolet Optical Infrared Surveyor' (LUVOIR) on-line signal-to-noise tools (https://asd.gsfc.nasa.gov/luvoir/tools/) to carry out representative data simulations in this white paper. The LUVOIR concept is simply representative of a large space observatory with instruments that advance the state-of-the-art relative to HST. Figure 2 shows an example of a simulated face-on disk + actively accreting protoplanet, at the distance of the Taurus star-forming region. The simulation is shown in units of the signal-to-noise per resolution element, using LUVOIR/HDI's narrow-band Hα filter. The emission is assumed to originate near the accretion flows onto the protoplanet; the circumplanetary disk is predicted to be a negligible source of Hα emission for 1 M_J protoplanets (Szulágyi & Mordasini 2017). The simulation illustrates that accreting gas giant planets should be detectable in all nearby star-forming regions. A 12 - 15m space telescope simultaneously offers the angular resolution and imaging sensitivity to confidently image these protoplanets in Hα. These wide orbital separation accreting planets can be detected without coronagraphy in narrow-band Hα imagery. They can be efficiently surveyed with space instruments that combine high resolution and wide field of view, enabling a statistical study of protoplanets in both mass and semi-major axis. Furthermore, an accreting protoplanet survey will identify the brightest targets for follow-up FUV and NUV spectroscopy with space-based observatories – enabling us to characterize both the protoplanets and the circumplanetary accretion environment in detail.

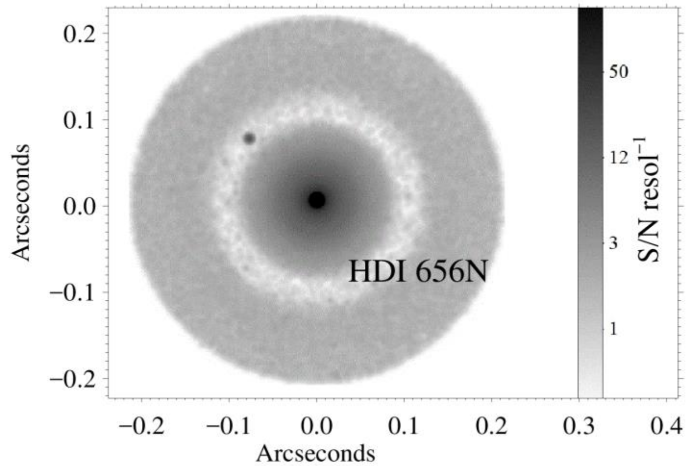

Figure 2: Simulated scattered light image of a protoplanetary disk (α = 10^{-3}; h/r = 0.04) and accreting protoplanet (located in the dust gap at the upper left) at the distance of the Taurus star-forming region. The 1 Jupiter-mass protoplanet is located 30 AU from the host proto-K star, and is accreting with 1/100th the Hα luminosity of more massive, large-separation protoplanets (Zhou et al. 2014), conservatively below the theoretical predictions of Szulagyi & Mordasini (2017). In a 9000 sec exposure with a 15m space telescope and the LUVOIR/HDI narrow-band Hα filter, the protoplanet is detected at S/N~20, the outer disk is detected at SNR between 1–2 per resolution element (easily binned to increase SNR), and the inner disk is detected at SNR between 2–12. Disk simulation courtesy of R. Dong (Steward Observatory/University of Arizona), based on work published in Dong & Fung (2017).

Neptune-mass planets may be too faint to be directly detected but can dynamically carve partially clear narrow (~1–10AU) gaps in circumstellar disks (e.g., Crida et al. 2006; Duffell 2015). High-resolution scattered light images probe the population of small (sub-micron) grains that are coupled to the gas and, as such, can trace dynamical perturbations induced by planets. The narrow gap at ~80 AU in the nearby disk of TW Hya imaged with HST and SPHERE (Debes et al. 2013; van Boekel et al. 2017) is likely opened by a 0.1 Jovian mass planet (Dong & Fung 2017). JWST will detect similar gaps at large radial distances (> 30 AU), but a space-based observational capability is required for the study of planet forming regions inside ~10 AU while still capturing structures at large distances thanks to its field of view.

While star-light suppression techniques (e.g. coronagraph, angular differential imaging) will be necessary for all instruments to detect exoplanets at ~1 AU, only a space observatory can extend these studies into the UV, fully probe the accretion component, and help determine the properties of forming planets at solar system scales. By comparing where exoplanets form in disks and their properties at birth with the location and properties of exoplanets around Gyr-old stars, we will be able to assess which processes shape planetary architectures and constrain the luminosity evolution of giant planets.

II. Trace the composition, evolution, and dispersal of planet-forming material

UV spectroscopy is a unique tool for observing the molecular gas in the inner disk; the strongest electronic band systems of H_2 and CO reside in the 100–170 nm wavelength range (e.g., Herczeg et al. 2002; France et al. 2011). UV fluorescent H_2 spectra are sensitive to gas surface densities lower than 10^{-6} g cm^{-2}, making them an extremely useful probe of remnant gas at r < 10 AU. In cases where mid-IR CO spectra or traditional accretion diagnostics (e.g. Hα equivalent widths) suggest that the inner gas disk has dissipated, far-UV H_2 observations can offer unambiguous evidence for the presence of a remnant molecular disk (Ingleby et al. 2011; France et al. 2012; Arulanantham et al. 2018; Alcala et al. 2019).

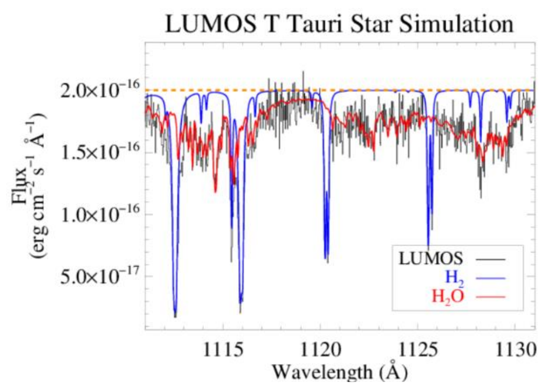

Figure 3: Spectral simulation the 1111–1132 Å spectrum of an edge-on protoplanetary disk , a spectral region containing strong lines of H_2 and H_2O (France et al. 2017). This spectrum is obtained in a 1 hour integration. Multi-object spectroscopy enables simultaneous detection of up to 30 young stars simultaneously in a region like the Orion Nebula Cluster. In dense regions, a multiplexed instrument on a 12-15m space observatory would eclipse the total UV disk archive of HST in 2 - 4 pointings. A space observatory with a combination of broad spectral coverage, large collecting area, and multiplexing capability is essential for surveying the composition of planet-forming environments around young stars.*
*https://asd.gsfc.nasa.gov/luvoir/tools/

A space observatory with a multi-object, high-resolution capability (R > 40,000, ≥ 4 square arcminutes per field) and peak effective area ≥ 10^5 cm^2 enables truly transformative emission-line surveys and absorption-line studies of high-inclination (i > 60°) disks. Absorption line spectroscopy through high-inclination disks, currently limited to a small number of bright stars (e.g., Roberge et al. 2000, 2001; France et al. 2014), are especially important because coverage from FUV to NIR provides access to important molecular species such as H_2, CO, OH, H_2O, CO_2, and CH_4. UV absorption line spectroscopy is the only direct observational technique to characterize co-spatial populations of these molecules with H_2, offering unique access to absolute abundance and temperature measurements without having to rely on molecular conversion factors or geometry-dependent model results as with emission-line spectroscopy.

Uniform spectral surveys of local star-forming regions are required for a systematic determination of disk abundances and gas disk lifetimes. For star-forming regions beyond Taurus-Auriga, the efficiency of these surveys goes up dramatically with the introduction of multi-object spectroscopy, greatly reducing the total observing time and increasing the survey efficiency in a census of star-forming regions at distances less than 1 kpc. To achieve the angular resolution and sensitivity required to carry out large surveys, a telescope diameter in the 12 - 15m class is required. With such a capability, hundreds of systems currently inaccessible to the Hubble Space Telescope due to dust reddening are reached and entire star-forming regions at the distance of Orion and beyond could be spectrally mapped with key projects requiring ~100 hours of observing time. In the course of a 5 year prime mission, a UV spectroscopic disk archive with 20 times the number of targets accessible to HST (and observed with imaging spectroscopy, higher resolution, and broader bandpass) could be obtained.

III. Map protoplanetary material dispersed via disk winds

Recent theoretical work suggests that disk evolution and dispersal are driven by a combination of thermal and MHD disk winds (e.g., Alexander et al. 2014; Gorti et al. 2016; Ercolano & Pascucci 2017). Disk winds can affect all stages of planet formation. During planetesimal formation, winds reduce the disk gas-to-dust mass ratio (e.g., Carrera et al. 2017). Winds may control the final masses of giant planets by starving gas accretion onto late-forming planet cores (e.g., Shu et al. 1993). Winds influence planetary orbits by dispersing gas from preferential radial distances and halting planet migration (e.g., Alexander & Pascucci 2012; Ercolano & Rosotti 2015). However, computational challenges and poorly constrained input parameters make it difficult to predict how basic disk properties evolve and to ascertain the role of different winds.

On the observational side, high-resolution (R>30,000) optical and infrared spectroscopy yields growing evidence of slow (<40 km/s) disk winds around Myr-old stars (e.g., Pascucci & Sterzik 2009; Sacco et al. 2012; Rigliaco et al. 2013; Simon et al. 2016; Fang et al. 2018; Banzatti et al. 2019). Modeling of the line profiles and line flux ratios suggests that emission arises at disk radii between 0.1 and 10 AU. On similar spatial scales, jets (ejected material moving at ~100 km/s) are also expected to be accelerated and collimated (e.g., Ray et al. 2007). Many of the brightest jet diagnostics are accessible to high-resolution imaging spectroscopy at UV and optical wavelengths (see e.g., Frank et al. 2014 for a recent review). High spatial resolution and UV through near-IR wavelength coverage are therefore needed to understand the origin of disk winds, the relative roles and interplay of MHD and photoevaporative winds, as well as to clarify the physical mechanism by which jets are launched and collimated. In addition to high-resolution spectroscopy, slitless spectroscopy and narrow-band images in UV and optical forbidden lines will map for the first time the launching region of jets and disk winds, and reveal their interaction.

In summary, we argue that a large space observatory with UV/optical imaging and spectroscopic capabilities would be transformative for studying the early phases of an exoplanet's lifecycle. The three essential components for these studies are 1) a large (~15 m) collecting area to achieve high angular resolution (1 AU at Taurus) and high sensitivity (peak FUV and NUV effective areas > 10^5 cm^2), 2) a high-resolution, multi-object spectrograph operating from 100 – 700 nm, and 3) a high-resolution imager operating from the NUV to the NIR.

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