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Astro2020 Science White Paper

Observing Planetary Systems in the Making

Thematic Areas: Star and Planet Formation

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Abstract:

The unprecedented imaging capabilities provided by ALMA and modern near-infrared high-contrast cameras have served as the foundation of a new and rapidly expanding field of research posed to unveil the origin of planetary systems. The outstanding discoveries obtained in the current decade have demonstrated that the outer regions of protoplanetary disks (>10 au) are much more interesting than expected. The direct imaging of newborn wide separation planets and the myriad of structures discovered in the dust and gas emission expose the complexity of the planet formation process. These unexpected findings **urge for the construction of telescopes capable of imaging the terrestrial planet formation region (<10 au), where the vast majority of planets are expected to form.** We argue that achieving sub-au imaging capabilities at wavelength between 1 mm and 1 cm should be a top priority for astronomy in the next decade. At these wavelengths the dust emission is optically thin, enabling us to peer through the densest disk regions and image planetary systems in formation. At the same time, we urge to intensify efforts aimed at developing sub-au resolution high-contrast planet detection techniques in the thermal infrared with the ELTs and infrared long-baseline interferometry. These capabilities are required to directly image newborn planets and measure their physical properties.

Introduction and Motivations

The discovery of thousands of exoplanets over the last couple of decades has shown that the birth of planets is a very efficient process in nature [1]. Theories invoke a multitude of mechanisms to describe the assembly of planets in the disks around pre-main sequence stars, a.k.a. *protoplanetary disks* (PPD), but observational constraints have been sparse on the account of insufficient sensitivity and spatial resolution. Investigating how planets form and interact with their gas rich primordial disk is crucial to understanding the morphology of our own Solar system and to unravel the diverse demographics of exo-planetary systems.

Two key issues hamper our understanding of planet formation. The first is that the discovery of *hot Jupiters* has indicated that the orbits of planets likely vary after their formation. In particular, newborn planets can migrate either inward or outward through exchange of angular momentum with the circumstellar material [2]. Knowing where planets form in the disk is crucial to constrain the dynamical and chemical history of planetary systems. Secondly, our current understanding of planet formation posits that planets form through the agglomeration of small dust particles into much larger *planetesimals*, which are massive enough to gravitationally attract other solids and gas in the disk [3]. Yet, the formation of planetesimals is a challenging problem for theories of planet formation. In the simplest assumption of a gas-rich disk with density and temperature decreasing with the distance from the star, small solids are quickly lost into the central star as a consequence of aerodynamic drag by the circumstellar gas [4].

Only in recent years telescopes have achieved the angular resolution sufficient to resolve nearby PPDs (< 200 pc) on spatial scales between 10-50 au, and provide the first direct constraints on planet formation theories. High angular resolution images of PPDs have been obtained using high-contrast cameras at near-infrared wavelengths (NIR) and long-baseline interferometers at (sub-)mm and cm wavelengths. At short wavelengths, the disk emission is optically thick and dominated by the stellar light scattered by sub- μm dust grains present in the disk atmosphere [5, 6]. These observations constrain the vertical structure of PPDs and could directly detect the thermal emission of newborn planets [7, 8]. Conversely, the disk emission at long wavelengths can be optically thin and is dominated by thermal radiation from dust, pebbles, and cold molecular gas. For these reasons, (sub-)mm/cm images of PPDs are an exquisite tool to investigate the dust evolution, the disk chemistry, and the interaction between forming planets and the parent disk [9, 10].

Telescopes like the JVLA, ALMA, Keck, Gemini, Subaru, and the VLT have opened an observational window on planet formation. Yet, they do not provide the angular resolution, contrast, and inner working angle required to image the innermost disk regions. Here, we argue that **imaging PPDs at sub-au spatial resolution is key to investigate planet formation in the terrestrial region**, defined as the innermost 10 au of PPDs. This is a necessary condition to unveil the origin of planetary systems, including our own Solar system. Achieving this goal is difficult but not impossible. High fidelity imaging at sub-au resolution is within the reach of a suite of next generation ground based telescopes, including the *next generation Very Large Array* (ngVLA, [11]), the *Planet Formation Imager* (PFI, [12]) optical/near-IR *Extremely Large telescopes* (ELTs), as well as a possible expansion of ALMA [13]. Additionally, concept studies for the 2020 decadal survey have also explored large apertures in space that could map the terrestrial planet forming region (Figure 1).

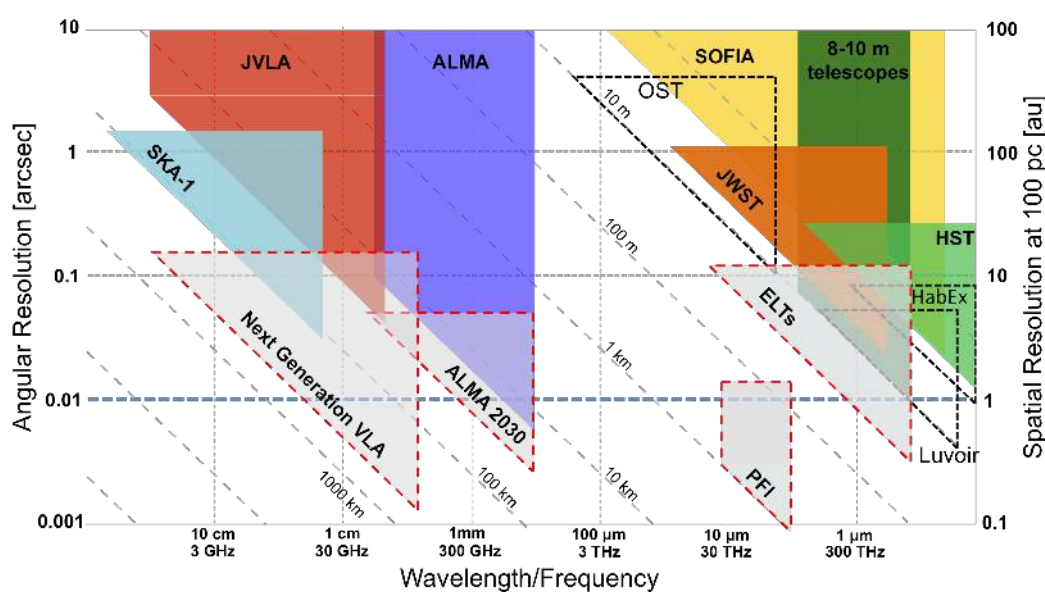


Figure 1: Current and future facilities capable of imaging PPDs at both high sensitivity and high angular resolution. Triangles with red dashed borders indicate the angular resolution and wavelength coverage of the

next generation Very Large Array (ngVLA), the *Planet Formation Imager* (PFI), the *Extremely Large Telescopes* (GMT, TMT, and the european ELT), and a possible expansion of ALMA to include maximum baselines up to 30 km (ALMA-2030). See references in the text. All these new telescopes provide sub-au resolution imaging capabilities, but observations at wavelengths between 1 mm and 1 cm are necessary to peer into dense dusty disks and reveal the formation of low mass planets and planetesimals. For sake of completeness, triangles with black dashed contours indicate three of the proposed future NASA space telescopes, namely, the *Origin Space Telescope*, the *Habitable Planet Observatory* (HabEx), and the *Large UV/Optical/IR Surveyor* (LUVOIR). The horizontal blue dashed line indicates a spatial resolution of 1 au at a distance of 100 pc.

Measuring the birth orbital radius of planets

Depending on the formation process, gas giant planets in PPDs are expected to have effective temperatures between 500-2000 K [14] and should therefore shine in the NIR. Furthermore, such planets should be accreting gas from a circumplanetary disk, and therefore emit in the $H\alpha$ line. However, the facts that they are embedded in a dusty disk that scatters stellar light and the proximity to their parent stars make their direct imaging challenging. For these reasons, only a handful of planets in PPDs have been directly imaged so far [15, 16, 17]. These planets are very massive ($> 5M_J$) and have large orbital radii (> 20 au), and are likely not representative of the bulk planet population. Alternatively, the presence of planets in PPDs can be inferred by observing the gravitational perturbations that they exert on the circumstellar material. A robust prediction of planet-disk interaction models is that planets with masses above 5-10 Earth masses (M_E) should carve circular gaps in the circumstellar material at their orbital radius [18, 19]. ALMA observations of nearby PPDs have found a multitude of such gaps with radii between 10 and 200 au [20, 21, 22] (Figure 2). The comparison with theoretical models indicate that these structures might have been created by yet unseen planets with masses between 0.2-1 M_J [23, 24]. The link between planets and gaps is nicely demonstrated by the direct detection of PDS 70 b, a planet with a mass $> 5 M_J$ orbiting at 22 au around a 5 Myr-old T Tauri star [16, 25]. The planet is located at the center of the dust depleted gap, whose structure is in agreement with the planet mass

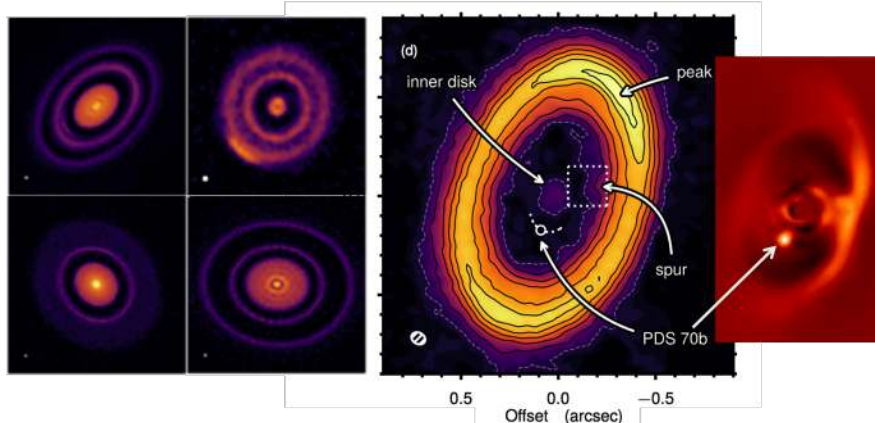


Figure 2: Left: 1.3 mm continuum ALMA images of four PPDs characterized by multiple dust gaps [21]. Right: 0.87 mm continuum ALMA image of the PDS 70 disk recorded at an angular resolution of $0.07''$ (8 au at the distance of the source) [16]. The inset on right shows the H-band discovery

image of PDS 70 b obtained with SPHERE/VLT [25]. The planet is located at the center of a dust depleted gap as predicted by planet-disk interaction models.

estimated from NIR observations (Figure 2). The direct detection of planets in PPDs is key for testing planet-disk interaction theories, which are the backbone of planet migration models, and to measure the planet temperature, which constrains planet formation models [14].

Currently, the limited capability of NIR facilities to deliver high contrast images enables the direct detection of planets only more massive than several M_J at orbital radii larger than ~ 20 au at distances between 100-200 pc. Future ELTs capable of high contrast imaging at their diffraction limit, large aperture space telescopes, and long-baseline interferometers operating between 1-10 μm , would allow us to detect lower mass and closer in planets, like those responsible for the gaps observed with ALMA. At longer wavelengths, the capability to probe the presence of planets is limited by two factors. First, the angular resolution of ALMA allows to image dust gaps with radii larger than $\sim 7 - 10$ au. Second, as observations have shown, the dust continuum emission arising within 10-30 au from the star is often optically thick, preventing us from observing partially depleted gaps created by planets with masses below 10-30 M_E [26].

A natural solution to these two problems consists in imaging PPDs at sub-au spatial resolution at wavelength longer than 1mm, where the dust continuum emission from the innermost disk regions is optically thin. This goal could be achieved with a long-baseline interferometer such as the ngVLA, whose large collecting area and sensitivity would allow the imaging of nearby PPDs at an angular resolution of about 3 milli-arcseconds, and by substantially increasing the angular resolution and sensitivity of ALMA. Recent estimates [27] found that the ngVLA would be capable of detecting gaps produced by planets with masses as low as 10 M_E and orbital radii between at 1-10 au. As shown in Figure 3, the ngVLA would drastically expand the space of discovery for young planets during their formation.

Unveiling the formation of planetesimals

Reconciling the long time scale necessary to form planetary embryos (> 1 Myr) with the short depletion time scale of planetesimals caused by the gas drag ($< 10^3$ yr for a boulder of 10 m in diameter at 1 au [29]) has been a long standing problem for theories of planet

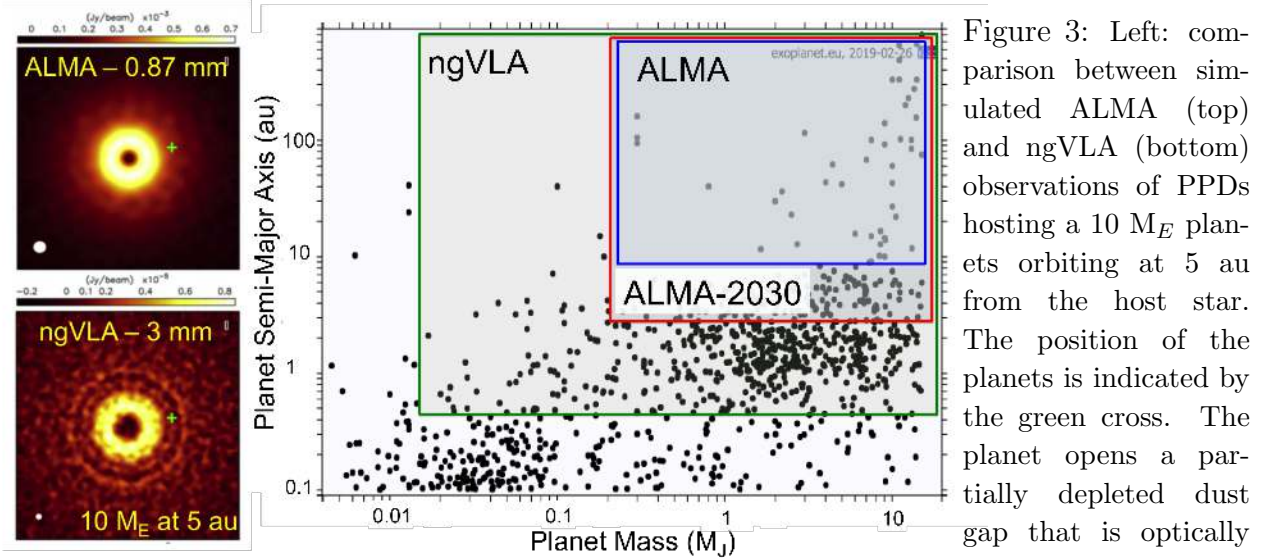


Figure 3: Left: comparison between simulated ALMA (top) and ngVLA (bottom) observations of PPDs hosting a $10 M_E$ planets orbiting at 5 au from the host star. The position of the planets is indicated by the green cross. The planet opens a partially depleted dust gap that is optically

thick at 0.87 mm, but becomes optically thin at 3 mm [28]. Right: current ALMA observations probe the presence of planets with masses as low as $0.1\text{-}0.3 M_J$ and orbital radii $a > 10$ au (blue rectangle). Expanding ALMA baselines up to 30 km would allow the direct imaging of planets with orbital radii as small as ~ 3 au (red rectangle). ngVLA observations at 3 mm and 1 cm would probe planet masses as low as $5 M_E$ (green rectangle). The black dots show the distribution of known exoplanets. Noticeable, ngVLA observations would probe a region of the parameter space ($M < 0.1 M_J$, $a > 10$ au) that is outside the reach of current exoplanet detection techniques.

formation. One mechanism proposed to slow down, and even stop, the inward migration of solids is to assume the existence of local long-lived gas over-densities, which, by reversing the radial gas pressure gradient, might be capable of trapping solid particles [30]. In such regions, the local dust-to-gas mass ratio might increase up to the point at which the dusty disk become unstable and fragment into clumps capable of forming planetesimals [31, 32].

The dust trapping process depends on the dust Stokes number $St \propto a/\Sigma$, where a is the radius of the particle and Σ is the gas surface density [29]. If $St \ll 1$, particles are well coupled to the gas and follow the gas distribution. Conversely, particles characterized by $St \gg 1$ do not experience any drag from the gas. Between these two extremes, particles with $St \sim 1$ are the most affected by the gas drag and are the one most efficiently trapped in local gas over-densities. At the typical densities of PPDs, $St \sim 1$ corresponds to solids with sizes between 0.1-1 cm, which should therefore be more concentrated toward the center of gas over-densities than smaller or larger grains.

In the last decade, ALMA, and to minor extent JVLA, observations of PPDs have discovered local accumulation of dust particles at distances $> 20\text{-}50$ au from their host star [33], and have measured a local increase of the dust-to-gas mass ratio in those regions [34]. Some of the observed dust traps are located at the outer edge of the gaps likely produced by the planet-disk interactions discussed above, suggesting that giant planets might play a fundamental and unexpected role in the formation of planetesimals (a solution of the evident chicken-egg problem might perhaps contemplate that giant planets form in a different way, e.g., as the result of gravitational instabilities in very young PPDs). In other cases, dust traps have the shape of dust crescents [35, 36], which might result from instabilities related

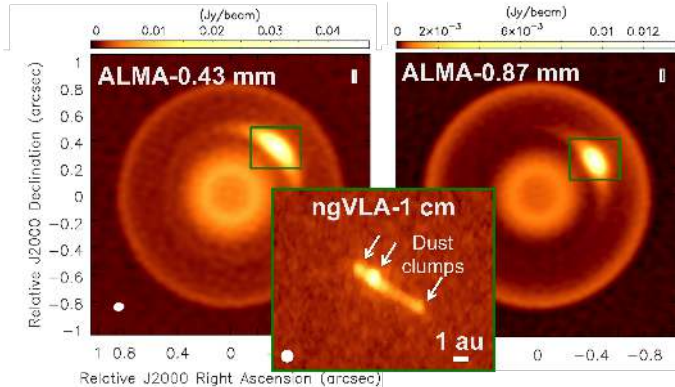


Figure 4: Simulated images of a PPD characterized by an azimuthal dust trap generated by an anticyclonic vortex (green rectangle) located at 60 au away from the host star. Similar features have been observed in a number of PPDs imaged by ALMA [39, 40]. The left and right panels show ALMA observations of the continuum emission at 0.43 mm and 0.87 mm, which probe dust grains of ~ 70 and ~ 140 μm in size,

respectively. The inset shows ngVLA observations of the dust trap at 1 cm, which probe the distribution of ~ 2 mm size grains. These larger particles are trapped in the center of the vortex where they cluster in a chain of clumps. Simulations suggest that the dust-to-gas ratio in these clumps could reach unity and trigger the streaming instability and the subsequent formation of planetesimals [32]. The angular resolution of ALMA and ngVLA observations is $0.05''$ and $0.007''$, respectively.

to step radial variations of the disk surface density [37].

Because solids with sizes between 0.1-1 cm are the most affected by dust traps, multi-wavelength observations in the wavelength range covered by ALMA and the JVLA are the best suited to study this important process. Currently, the main observational limitation comes from the fact that the VLA lacks the angular resolution and sensitivity required to image the distribution of large particles inside dust traps [38]. Conversely, the unprecedented imaging capabilities provided by a telescope like the ngVLA would allow the study of particle concentration in great details. In particular, sub-au observations of dust traps could reveal dust clumps resulting from the predicted fragmentation of the dusty disk in regions where the dust-to-gas ratio exceed unity (Figure 4). Furthermore, the combination of sub-au resolution observations obtained with the ngVLA, ALMA, and the ELTs will allow to trace dust particles varying by 6 orders of magnitude in size greatly improving our understanding of the dust dynamics in gaseous rich PPDs.

Conclusions and Recommendations

The unprecedented imaging capabilities provided by ALMA and modern NIR high-contrast cameras have served as the foundation of a new and rapidly expanding field of research posed to unveil the origin of planetary systems. The outstanding discoveries obtained in this field in the current decade, a few of which were discussed in this paper, urge for the construction of telescopes capable of imaging the terrestrial planet formation region (0.1-10 au) in nearby PPDs. We argue that achieving milli-arcsecond imaging capabilities at wavelength between 1 mm and 1 cm should be a top priority for astronomy in the next decade. At the same time we urge to intensify efforts aimed at developing milliarcsecond-resolution high-contrast planet detection techniques in the thermal infrared with the ELTs and infrared long-baseline interferometry.

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