



Observing Planetary Systems in the Making

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Astro2020 Science White Paper

Observing Planetary Systems in the Making

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Principal Author:

Name: Andrea Isella

Institution: Rice University, Houston, Texas, USA

Email: isella@rice.edu

Phone: +1 713-348-5491

Co-authors: (names and institutions)

Luca Ricci	<i>California State University Northridge, USA</i>
Sean M. Andrews	<i>Harvard-Smithsonian Center for Astrophysics, USA</i>
Clement Baruteau	<i>University of Toulouse, France</i>
Jean-Philippe Berger	<i>Université Grenoble Alpe, France</i>
Edwin Bergin	<i>University of Michigan, USA</i>
Tilman Birnstiel	<i>Universitäts-Sternwarte Munich, Germany</i>
Brendan Bowler	<i>University of Texas Austin, USA</i>
Crystal Brogan	<i>National Radio Astronomy Observatory, USA</i>
Carlos Carrasco Gonzalez	<i>Universidad Nacional Autónoma de México, Mexico</i>
Claire Chandler	<i>National Radio Astronomy Observatory, USA</i>
Thayne Currie	<i>National Astronomical Observatory of Japan, Japan</i>
Jeffrey N. Cuzzi	<i>NASA Ames Research Center, USA</i>
Gennaro D'Angelo	<i>Los Alamos National Laboratory, USA</i>
Ruobing Dong	<i>University of Victoria, Canada</i>
Gaspard Duchene	<i>University of California Berkeley, USA</i>
Anne Dutrey	<i>Laboratoire d'Astrophysique de Bordeaux, France</i>
Barbara Ercolano	<i>Universitäts-Sternwarte Munich, Germany</i>
Catherine Espaillat	<i>Boston University, USA</i>
Paul R. Estrada	<i>SETI Institute, USA</i>
Mario Flock	<i>Max Planck Institute for Astronomy, Germany</i>
Andras Gaspar	<i>University of Arizona, USA</i>
Thomas P. Greene	<i>NASA Ames Research Center, USA</i>
Jane Huang	<i>Harvard-Smithsonian Center for Astrophysics, USA</i>
Hannah Jang-Condell	<i>University of Wyoming, USA</i>
Christopher Johns-Krull	<i>Rice University, USA</i>
Grant Kennedy	<i>University of Warwick, UK</i>
Serena Kim	<i>University of Arizona, USA</i>
Florian Kirchschlager	<i>University College London, UK</i>
Stefan Kraus	<i>University of Exeter, UK</i>

Sebastiaan Krijt	<i>University of Arizona, USA</i>
Hui Li	<i>Los Alamos National Laboratory, USA</i>
Wladimir Lyra	<i>California State University Northridge, USA</i>
Bruce Macintosh	<i>Stanford University, USA</i>
John Monnier	<i>University of Michigan, USA</i>
Karin Öberg	<i>Harvard-Smithsonian Center for Astrophysics, USA</i>
Ilaria Pascucci	<i>University of Arizona, USA</i>
Laura Perez	<i>Universidad de Chile, Chile</i>
Romain Petrov	<i>University of Nice, France</i>
Paola Pinilla	<i>University of Arizona, USA</i>
Stephen Ridgway	<i>National Optical Astronomy Observatory, USA</i>
Keivan Stassun	<i>Vanderbilt University, USA</i>
Theo ten Brummelaar	<i>Georgia State University, USA</i>
Leonardo Testi	<i>European Southern Observatory, Germany</i>
Neal Turner	<i>Jet Propulsion Laboratory, USA</i>
Gerard Van Belle	<i>Lowell Observatory, USA</i>
Nienke van der Marel	<i>Herzberg Astronomy and Astrophysics, Canada</i>
Alycia Weinberger	<i>Carnegie Institution of Washington, USA</i>
Jacob White	<i>Konkoly Observatory, Hungary</i>
Jonathan Williams	<i>University of Hawaii, USA</i>
David Wilner	<i>Harvard-Smithsonian Center for Astrophysics, USA</i>
Alwyn Wootten	<i>National Radio Astronomy Observatory, USA</i>
Ya-Lin Wu	<i>University of Texas, Austin, USA</i>
Andrew N. Youdin	<i>University of Arizona, USA</i>
Ke Zhang	<i>University of Michigan, USA</i>
Zhaohuan Zhu	<i>University of Nevada, Las Vegas, USA</i>

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).

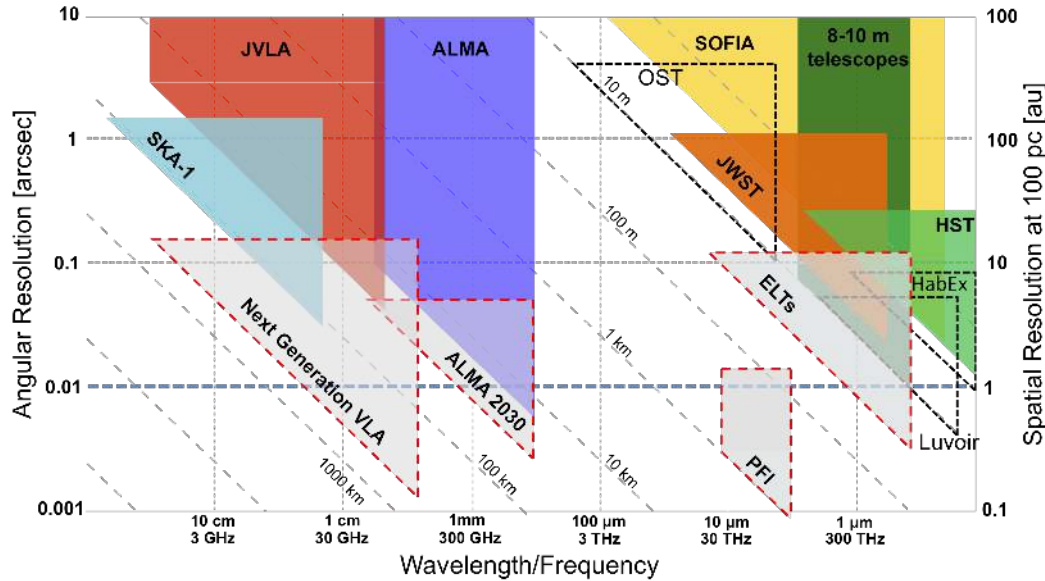


Figure 1: Current and future facilities capable of imaging PPDs at both high sensitivity and high angular resolution. Triangles with red dashed borders indicate the angular resolution and wavelength coverage of the

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

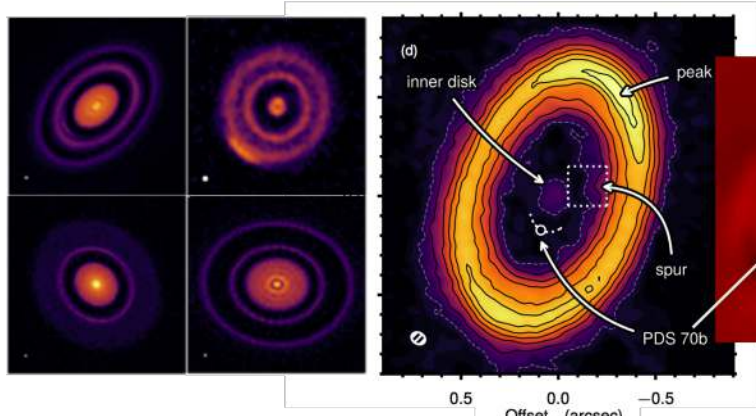


Figure 2: Left: 1.3 mm continuum ALMA images of four PPDs characterized by multiple dust gaps [21]. Right: 0.87 mm continuum ALMA image of the PDS 70 disk recorded at an angular resolution of $0.07''$ (8 au at the distance of the source) [16]. The inset on right shows the H-band discovery

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

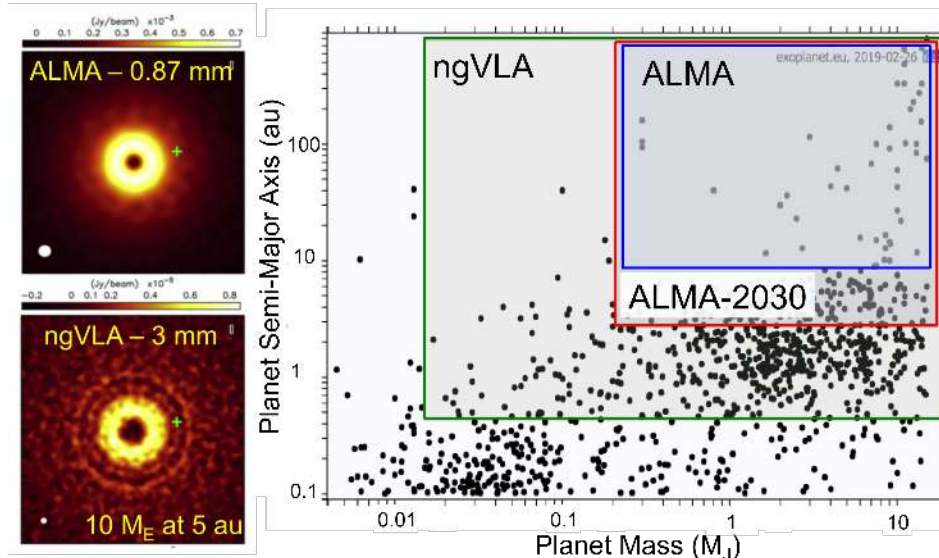


Figure 3: Left: comparison between simulated ALMA (top) and ngVLA (bottom) observations of PPDs hosting a $10 M_E$ planets orbiting at 5 au from the host star. The position of the planets is indicated by the green cross. The planet opens a partially depleted dust gap that is optically

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

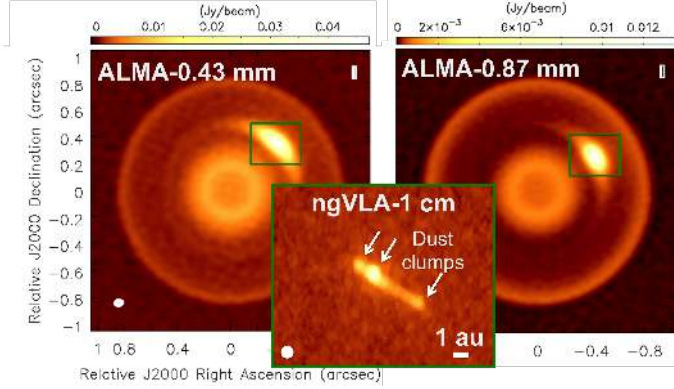


Figure 4: Simulated images of a PPD characterized by an azimuthal dust trap generated by an anticyclonic vortex (green rectangle) located at 60 au away from the host star. Similar features have been observed in a number of PPDs imaged by ALMA [39, 40]. The left and right panels show ALMA observations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

References

- [1] C. J. Burke, J. L. Christiansen, F. Mullally, S. Seader, D. Huber, J. F. Rowe, J. L. Coughlin, S. E. Thompson, J. Catanzarite, B. D. Clarke, T. D. Morton, D. A. Caldwell, S. T. Bryson, M. R. Haas, N. M. Batalha, J. M. Jenkins, P. Tenenbaum, J. D. Twicken, J. Li, E. Quintana, T. Barclay, C. E. Henze, W. J. Borucki, S. B. Howell, and M. Still, “Terrestrial Planet Occurrence Rates for the Kepler GK Dwarf Sample,” *ApJ*, vol. 809, p. 8, Aug. 2015.
- [2] P. J. Armitage, “Massive Planet Migration: Theoretical Predictions and Comparison with Observations,” *The Astrophysical Journal*, vol. 665, pp. 1381–1390, Aug. 2007.
- [3] A. Johansen, J. Blum, H. Tanaka, C. Ormel, M. Bizzarro, and H. Rickman, “The Multifaceted Planetesimal Formation Process,” *Protostars and Planets VI*, pp. 547–570, 2014.
- [4] S. J. Weidenschilling, “Aerodynamics of solid bodies in the solar nebula,” *MNRAS*, vol. 180, pp. 57–70, July 1977.
- [5] A. Garufi, S. P. Quanz, H. Avenhaus, E. Buenzli, C. Dominik, F. Meru, M. R. Meyer, P. Pinilla, H. M. Schmid, and S. Wolf, “Small vs. large dust grains in transitional disks: do different cavity sizes indicate a planet?. SAO 206462 (HD 135344B) in polarized light with VLT/NACO,” *Astronomy & Astrophysics*, vol. 560, p. A105, Dec. 2013.
- [6] M. Benisty, A. Juhasz, A. Boccaletti, H. Avenhaus, J. Milli, C. Thalmann, C. Dominik, P. Pinilla, E. Buenzli, A. Pohl, J.-L. Beuzit, T. Birnstiel, J. de Boer, M. Bonnefoy, G. Chauvin, V. Christiaens, A. Garufi, C. Grady, T. Henning, N. Huelamo, A. Isella, M. Langlois, F. Ménard, D. Mouillet, J. Olofsson, E. Pantin, C. Pinte, and L. Pueyo, “Asymmetric features in the protoplanetary disk MWC 758,” *Astronomy & Astrophysics*, vol. 578, p. L6, June 2015.
- [7] M. Reggiani, S. P. Quanz, M. R. Meyer, L. Pueyo, O. Absil, A. Amara, G. Anglada, H. Avenhaus, J. H. Girard, C. Carrasco Gonzalez, J. Graham, D. Mawet, F. Meru, J. Milli, M. Osorio, S. Wolff, and J.-M. Torrelles, “Discovery of a Companion Candidate in the HD 169142 Transition Disk and the Possibility of Multiple Planet Formation,” *The Astrophysical Journal Letters*, vol. 792, p. L23, Sept. 2014.
- [8] M. Keppler, M. Benisty, A. Müller, T. Henning, R. van Boekel, F. Cantalloube, C. Ginski, R. G. van Holstein, A.-L. Maire, A. Pohl, M. Samland, H. Avenhaus, J.-L. Baudino, A. Boccaletti, J. de Boer, M. Bonnefoy, G. Chauvin, S. Desidera, M. Langlois, C. Lazzoni, G. Marleau, C. Mordasini, N. Pawellek, T. Stolker, A. Vigan, A. Zurlo, T. Birnstiel, W. Brandner, M. Feldt, M. Flock, J. Girard, R. Gratton, J. Hagelberg, A. Isella, M. Janson, A. Juhasz, J. Kemmer, Q. Kral, A.-M. Lagrange, R. Launhardt, A. Matter, F. Ménard, J. Milli, P. Mollière, J. Olofsson, L. Perez, P. Pinilla, C. Pinte, S. P. Quanz, T. Schmidt, S. Udry, Z. Wahhaj, J. P. Williams, E. Buenzli, M. Cudel, C. Dominik, R. Galicher, M. Kasper, J. Lannier, D. Mesa, D. Mouillet, S. Peretti, C. Perrot, G. Salter, E. Sissa, F. Wildi, L. Abe, J. Antichi, J.-C. Augereau, A. Baruffolo, P. Baudoz, A. Bazzon, J.-L. Beuzit, P. Blanchard, S. S. Brems, T. Buey, V. De Caprio, M. Carillet, M. Carle, E. Cascone, A. Cheetham, R. Claudi, A. Costille, A. Delboulbé, K. Dohlen, D. Fantinel, P. Feautrier, T. Fusco, E. Giro, D. Gisler, L. Gluck, C. Gry, N. Hubin, E. Hugot, M. Jaquet, D. Le Mignant, M. Llored, F. Madec, Y. Magnard, P. Martinez, D. Maurel, M. Meyer, O. Moeller-Nilsson, T. Moulin, L. Mugnier, A. Origne, A. Pavlov, D. Perret, C. Petit, J. Pragt, P. Puget, P. Rabou, J. Ramos, F. Rigal, S. Rochat, R. Roelfsema, G. Rousset, A. Roux, B. Salasnich, J.-F. Sauvage, A. Sevin, C. Soenke, E. Stadler, M. Suarez,

- M. Turatto, and L. Weber, “Discovery of a planetary-mass companion within the gap of the transition disk around PDS 70,” *ArXiv e-prints*, June 2018.
- [9] C. Qi, K. I. Öberg, D. J. Wilner, and K. A. Rosenfeld, “First detection of $c\text{-C}_3\text{H}_2$ in a circumstellar disk,” *The Astrophysical Journal*, vol. 765, pp. L14–5, Feb. 2013.
 - [10] M. K. McClure, C. Espaillat, N. Calvet, E. Bergin, P. D’Alessio, D. M. Watson, P. Manoj, B. Sargent, and L. I. Cleeves, “DETECTIONS OF TRANS-NEPTUNIAN ICE IN PROTOPLANETARY DISKS,” *The Astrophysical Journal*, vol. 799, pp. 162–13, Feb. 2015.
 - [11] E. J. Murphy, A. Bolatto, S. Chatterjee, C. M. Casey, L. Chomiuk, D. Dale, I. de Pater, M. Dickinson, J. D. Francesco, G. Hallinan, A. Isella, K. Kohno, S. R. Kulkarni, C. Lang, T. J. W. Lazio, A. K. Leroy, L. Loinard, T. J. Maccarone, B. C. Matthews, R. A. Osten, M. J. Reid, D. Riechers, N. Sakai, F. Walter, and D. Wilner, “The ngVLA Science Case and Associated Science Requirements,” in *Science with a Next Generation Very Large Array* (E. Murphy, ed.), vol. 517 of *Astronomical Society of the Pacific Conference Series*, p. 3, Dec. 2018.
 - [12] J. D. Monnier, S. Kraus, M. J. Ireland, F. Baron, A. Bayo, J.-P. Berger, M. Creech-Eakman, R. Dong, G. Duchêne, C. Espaillat, C. Haniff, S. Hönig, A. Isella, A. Juhasz, L. Labadie, S. Lacour, S. Leifer, A. Merand, E. Michael, S. Minardi, C. Mordasini, D. Mozurkewich, J. Olofsson, C. Paladini, R. Petrov, J.-U. Pott, S. Ridgway, S. Rinehart, K. Stassun, J. Surdej, T. t. Brummelaar, N. Turner, P. Tuthill, K. Vahala, G. van Belle, G. Vasisht, E. Wishnow, J. Young, and Z. Zhu, “The planet formation imager,” *Experimental Astronomy*, vol. 46, pp. 517–529, Dec. 2018.
 - [13] J. Carpenter, D. Iono, L. Testi, N. Whyborn, A. Wootten, and N. Evans, “The ALMA Development Roadmap,” *arXiv e-prints*, Feb. 2019.
 - [14] D. S. Spiegel and A. Burrows, “Spectral and Photometric Diagnostics of Giant Planet Formation Scenarios,” *The Astrophysical Journal*, vol. 745, p. 174, Feb. 2012.
 - [15] S. Sallum, K. B. Follette, J. A. Eisner, L. M. Close, P. Hinz, K. Kratter, J. Males, A. Skemer, B. Macintosh, P. Tuthill, V. Bailey, D. Defrère, K. Morzinski, T. Rodigas, E. Spalding, A. Vaz, and A. J. Weinberger, “Accreting protoplanets in the LkCa 15 transition disk,” *Nature*, vol. 527, pp. 342–344, Nov. 2015.
 - [16] M. Keppler, M. Benisty, A. Müller, T. Henning, R. van Boekel, F. Cantalloube, C. Ginski, R. G. van Holstein, A.-L. Maire, A. Pohl, M. Samland, H. Avenhaus, J.-L. Baudino, A. Boccaletti, J. de Boer, M. Bonnefoy, G. Chauvin, S. Desidera, M. Langlois, C. Lazzoni, G.-D. Marleau, C. Mordasini, N. Pawellek, T. Stolker, A. Vigan, A. Zurlo, T. Birnstiel, W. Brandner, M. Feldt, M. Flock, J. Girard, R. Gratton, J. Hagelberg, A. Isella, M. Janson, A. Juhasz, J. Kemmer, Q. Kral, A.-M. Lagrange, R. Launhardt, A. Matter, F. Ménard, J. Milli, P. Mollière, J. Olofsson, L. Pérez, P. Pinilla, C. Pinte, S. P. Quanz, T. Schmidt, S. Udry, Z. Wahhaj, J. P. Williams, E. Buenzli, M. Cudel, C. Dominik, R. Galicher, M. Kasper, J. Lannier, D. Mesa, D. Mouillet, S. Peretti, C. Perrot, G. Salter, E. Sissa, F. Wildi, L. Abe, J. Antichi, J.-C. Augereau, A. Baruffolo, P. Baudoz, A. Bazzon, J.-L. Beuzit, P. Blanchard, S. S. Brems, T. Buey, V. De Caprio, M. Carillet, M. Carle, E. Cascone, A. Cheetham, R. Claudi, A. Costille, A. Delboulbé, K. Dohlen, D. Fantinel, P. Feautrier, T. Fusco, E. Giro, L. Gluck, C. Gry, N. Hubin, E. Hugot, M. Jaquet, D. Le Mignant, M. Llored, F. Madec,

- Y. Magnard, P. Martinez, D. Maurel, M. Meyer, O. Möller-Nilsson, T. Moulin, L. Mugnier, A. Origné, A. Pavlov, D. Perret, C. Petit, J. Pragt, P. Puget, P. Rabou, J. Ramos, F. Rigal, S. Rochat, R. Roelfsema, G. Rousset, A. Roux, B. Salasnich, J.-F. Sauvage, A. Sevin, C. Soenke, E. Stadler, M. Suarez, M. Turatto, and L. Weber, “Discovery of a planetary-mass companion within the gap of the transition disk around PDS 70,” *Astronomy & Astrophysics*, vol. 617, p. A44, Sept. 2018.
- [17] M. Reggiani, V. Christiaens, O. Absil, D. Mawet, E. Huby, E. Choquet, C. A. Gomez Gonzalez, G. Ruane, B. Femenia, E. Serabyn, K. Matthews, M. Barraza, B. Carlomagno, D. Defrère, C. Delacroix, S. Habraken, A. Jolivet, M. Karlsson, G. Orban de Xivry, P. Piron, J. Surdej, E. Vargas Catalan, and O. Wertz, “Discovery of a point-like source and a third spiral arm in the transition disk around the Herbig Ae star MWC 758,” *Astronomy & Astrophysics*, vol. 611, p. A74, Mar. 2018.
- [18] G. Bryden, X. Chen, D. N. C. Lin, R. P. Nelson, and J. C. B. Papaloizou, “Tidally Induced Gap Formation in Protostellar Disks: Gap Clearing and Suppression of Protoplanetary Growth,” *The Astrophysical Journal*, vol. 514, pp. 344–367, Mar. 1999.
- [19] Z. Zhu and J. M. Stone, “Dust Trapping by Vortices in Transitional Disks: Evidence for Non-ideal Magnetohydrodynamic Effects in Protoplanetary Disks,” *The Astrophysical Journal*, vol. 795, p. 53, Nov. 2014.
- [20] A. Partnership, C. L. Brogan, L. M. Pérez, T. R. Hunter, W. R. F. Dent, A. S. Hales, R. E. Hills, S. Corder, E. B. Fomalont, C. Vlahakis, Y. Asaki, D. Barkats, A. Hirota, J. A. Hodge, C. M. V. Impellizzeri, R. Kneissl, E. Liuzzo, R. Lucas, N. Marcelino, S. Matsushita, K. Nakanishi, N. Phillips, A. M. S. Richards, I. Toledo, R. Aladro, D. Brogiere, J. R. Cortes, P. C. Cortes, D. Espada, F. Galarza, D. Garcia-Appadoo, L. Guzman-Ramirez, E. M. Humphreys, T. Jung, S. Kamenno, R. A. Laing, S. Leon, G. Marconi, A. Mignano, B. Nikolic, L.-A. Nyman, M. Radiszcz, A. Remijan, J. A. Rodón, T. Sawada, S. Takahashi, R. P. J. Tilanus, B. Vila Vilaro, L. C. Watson, T. Wiklind, E. Akiyama, E. Chapillon, I. de Gregorio-Monsalvo, J. Di Francesco, F. Gueth, A. Kawamura, C. F. Lee, Q. Nguyen Luong, J. Mangum, V. Piétu, P. Sanhueza, K. Saigo, S. Takakuwa, C. Ubach, T. van Kempen, A. Wootten, A. Castro-Carrizo, H. Francke, J. Gallardo, J. Garcia, S. Gonzalez, T. Hill, T. Kamiński, Y. Kurono, H. Y. Liu, C. Lopez, F. Morales, K. Plarre, G. Schieven, L. Testi, L. Videla, E. Villard, P. Andreani, J. E. Hibbard, and K. Tatematsu, “The 2014 ALMA Long Baseline Campaign: First Results from High Angular Resolution Observations toward the HL Tau Region,” *The Astrophysical Journal Letters*, vol. 808, p. L3, July 2015.
- [21] S. M. Andrews, J. Huang, L. M. Pérez, A. Isella, C. P. Dullemond, N. T. Kurtovic, V. V. Guzmán, J. M. Carpenter, D. J. Wilner, S. Zhang, Z. Zhu, T. Birnstiel, X.-N. Bai, M. Benisty, A. M. Hughes, K. I. Öberg, and L. Ricci, “The Disk Substructures at High Angular Resolution Project (DSHARP). I. Motivation, Sample, Calibration, and Overview,” *The Astrophysical Journal Letters*, vol. 869, p. L41, Dec. 2018.
- [22] F. Long, P. Pinilla, G. J. Herczeg, D. Harsono, G. Dipierro, I. Pascucci, N. Hendler, M. Tazzari, E. Ragusa, C. Salyk, S. Edwards, G. Lodato, G. van de Plas, D. Johnstone, Y. Liu, Y. Boehler, S. Cabrit, C. F. Manara, F. Menard, G. D. Mulders, B. Nisini, W. J. Fischer, E. Rigliaco, A. Banzatti, H. Avenhaus, and M. Gully-Santiago, “Gaps and Rings in an ALMA Survey of Disks in the Taurus Star-forming Region,” *The Astrophysical Journal*, vol. 869, p. 17, Dec. 2018.

- [23] A. Isella, G. Guidi, L. Testi, S. Liu, H. Li, S. Li, E. Weaver, Y. Boehler, J. M. Carperter, I. De Gregorio-Monsalvo, C. F. Manara, A. Natta, L. M. Pérez, L. Ricci, A. Sargent, M. Tazzari, and N. Turner, “Ringed Structures of the HD 163296 Protoplanetary Disk Revealed by ALMA,” *PRL*, vol. 117, p. 251101, Dec. 2016.
- [24] S.-F. Liu, S. Jin, S. Li, A. Isella, and H. Li, “New Constraints on Turbulence and Embedded Planet Mass in the HD 163296 Disk from Planet-Disk Hydrodynamic Simulations,” *The Astrophysical Journal*, vol. 857, p. 87, Apr. 2018.
- [25] A. Müller, M. Keppler, T. Henning, M. Samland, G. Chauvin, H. Beust, A.-L. Maire, K. Molaverdikhani, R. van Boekel, M. Benisty, A. Boccaletti, M. Bonnefoy, F. Cantalloube, B. Charnay, J.-L. Baudino, M. Gennaro, Z. C. Long, A. Cheetham, S. Desidera, M. Feldt, T. Fusco, J. Girard, R. Gratton, J. Hagelberg, M. Janson, A.-M. Lagrange, M. Langlois, C. Lazzoni, R. Ligi, F. Ménard, D. Mesa, M. Meyer, P. Mollière, C. Mordasini, T. Moulin, A. Pavlov, N. Pawellek, S. P. Quanz, J. Ramos, D. Rouan, E. Sissa, E. Stadler, A. Vigan, Z. Wahhaj, L. Weber, and A. Zurlo, “Orbital and atmospheric characterization of the planet within the gap of the PDS 70 transition disk,” *Astronomy & Astrophysics*, vol. 617, p. L2, Sept. 2018.
- [26] S. Zhang, Z. Zhu, J. Huang, V. V. Guzmán, S. M. Andrews, T. Birnstiel, C. P. Dullemond, J. M. Carpenter, A. Isella, L. M. Pérez, M. Benisty, D. J. Wilner, C. Baruteau, X.-N. Bai, and L. Ricci, “The Disk Substructures at High Angular Resolution Project (DSHARP). VII. The Planet-Disk Interactions Interpretation,” *The Astrophysical Journal Letters*, vol. 869, p. L47, Dec. 2018.
- [27] L. Ricci, S.-F. Liu, A. Isella, and H. Li, “Investigating the Early Evolution of Planetary Systems with ALMA and the Next Generation Very Large Array,” *The Astrophysical Journal*, vol. 853, p. 110, Feb. 2018.
- [28] L. Ricci, S.-F. Liu, A. Isella, and H. Li, “Investigating the Early Evolution of Planetary Systems with ALMA and the Next Generation Very Large Array,” *ApJ*, vol. 853, p. 110, Feb. 2018.
- [29] L. Testi, T. Birnstiel, L. Ricci, S. Andrews, J. Blum, J. Carpenter, C. Dominik, A. Isella, A. Natta, J. P. Williams, and D. J. Wilner, “Dust Evolution in Protoplanetary Disks,” *Protostars and Planets VI*, pp. 339–361, 2014.
- [30] P. Pinilla, T. Birnstiel, L. Ricci, C. P. Dullemond, A. L. Uribe, L. Testi, and A. Natta, “Trapping dust particles in the outer regions of protoplanetary disks,” *Astronomy & Astrophysics*, vol. 538, p. A114, Feb. 2012.
- [31] A. N. Youdin and F. H. Shu, “Planetesimal Formation by Gravitational Instability,” *The Astrophysical Journal*, vol. 580, pp. 494–505, Nov. 2002.
- [32] A. N. Youdin and J. Goodman, “Streaming Instabilities in Protoplanetary Disks,” *The Astrophysical Journal*, vol. 620, pp. 459–469, Feb. 2005.
- [33] C. P. Dullemond, T. Birnstiel, J. Huang, N. T. Kurtovic, S. M. Andrews, V. V. Guzmán, L. M. Pérez, A. Isella, Z. Zhu, M. Benisty, D. J. Wilner, X.-N. Bai, J. M. Carpenter, S. Zhang, and L. Ricci, “The Disk Substructures at High Angular Resolution Project (DSHARP). VI. Dust Trapping in Thin-ringed Protoplanetary Disks,” *The Astrophysical Journal Letters*, vol. 869, p. L46, Dec. 2018.

- [34] A. Isella, G. Guidi, L. Testi, S. Liu, H. Li, S. Li, E. Weaver, Y. Boehler, J. M. Carperter, I. De Gregorio-Monsalvo, C. F. Manara, A. Natta, L. M. Pérez, L. Ricci, A. Sargent, M. Tazzari, and N. Turner, “Ringed Structures of the HD 163296 Protoplanetary Disk Revealed by ALMA,” *Physical Review Letters*, vol. 117, p. 251101, Dec. 2016.
- [35] Y. Boehler, E. Weaver, A. Isella, L. Ricci, C. Grady, J. Carpenter, and L. Perez, “A Close-up View of the Young Circumbinary Disk HD 142527,” *The Astrophysical Journal*, vol. 840, p. 60, May 2017.
- [36] N. van der Marel, P. Pinilla, J. Tobin, T. van Kempen, S. Andrews, L. Ricci, and T. Birnstiel, “A Concentration of Centimeter-sized Grains in the Ophiuchus IRS 48 Dust Trap,” *The Astrophysical Journal Letters*, vol. 810, p. L7, Sept. 2015.
- [37] H. Li, S. Li, J. Koller, B. B. Wendroff, R. Liska, C. M. Orban, E. P. T. Liang, and D. N. C. Lin, “Potential Vorticity Evolution of a Protoplanetary Disk with an Embedded Protoplanet,” *The Astrophysical Journal*, vol. 624, pp. 1003–1009, May 2005.
- [38] C. Carrasco-González, T. Henning, C. J. Chandler, H. Linz, L. Pérez, L. F. Rodríguez, R. Galván-Madrid, G. Anglada, T. Birnstiel, R. van Boekel, M. Flock, H. Klahr, E. Macias, K. Menten, M. Osorio, L. Testi, J. M. Torrelles, and Z. Zhu, “The VLA View of the HL Tau Disk: Disk Mass, Grain Evolution, and Early Planet Formation,” *The Astrophysical Journal Letters*, vol. 821, p. L16, Apr. 2016.
- [39] N. van der Marel, E. F. van Dishoeck, S. Bruderer, T. Birnstiel, P. Pinilla, C. P. Dullemond, T. A. van Kempen, M. Schmalzl, J. M. Brown, G. J. Herczeg, G. S. Mathews, and V. Geers, “A Major Asymmetric Dust Trap in a Transition Disk,” *Science*, vol. 340, pp. 1199–1202, June 2013.
- [40] Y. Boehler, L. Ricci, E. Weaver, A. Isella, M. Benisty, J. Carpenter, C. Grady, B.-T. Shen, Y.-W. Tang, and L. Perez, “The Complex Morphology of the Young Disk MWC 758: Spirals and Dust Clumps around a Large Cavity,” *The Astrophysical Journal*, vol. 853, p. 162, Feb. 2018.