Astro2020 Science White Paper

Protostellar Disks: The Missing Link Between Cores and Planets

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 (optional):
Over the past decade, ALMA has been revolutionizing our view of protoplanetary disks. However, it has also become increasingly clear that protoplanetary disks are not the sites where formation begins, but rather that they likely host young forming planets or planetesimals within. If this is the case, then in order to understand the initial conditions from which planet formation will proceed, it is necessary to study protostellar disks, the younger counterparts to protoplanetary disks that are still embedded in their natal envelope of collapsing cloud material. Protostellar disks, as the ultimate product of cloud collapse, also serve as the link between planets and large scale molecular clouds, and their structures encode information about how cloud collapse proceeded. ALMA has already begun to push major improvements in our understanding of the structures of protostellar disks, and will continue to do so, but their high masses and small sizes result in high optical depths at most ALMA bands. Looking to the future, a higher resolution and higher sensitivity upgrade to the VLA will be an critical step forward in our ability to continue to understand the structures of protostellar disks. As the tools used to study protostellar disks continue to evolve, improve, and become more computationally intensive, there will continue to be a need for access to powerful supercomputing resources like NSF XSEDE.

Introduction

Disks are the natural consequence of the conservation of angular momentum as clouds of gas and dust collapse to form stars. So called "protoplanetary disks" are thought to be the birthplaces of planets, and so they have been studied in great detail. This is particularly true since the advent of ALMA, as the significant improvements in angular resolution and sensitivity at millimeter wavelengths has led to numerous studies of the structures of protoplanetary disks. This includes measurements of the distribution of protoplanetary disk masses and radii (e.g. Ansdell et al. 2016, Tazzari et al. 2017, Eisner et al. 2018), as well as studies of dust grain growth (and spatially resolved dust grain growth; e.g. Ricci et al. 2010, Perez et al. 2012, Tazzari et al. 2016) and disk chemistry (e.g. Qi et al. 2013; Oberg et al. 2015, van 't Hoff et al. 2017). Perhaps most exciting, has been the discovery that nearly every protoplanetary disk seems to host to substructures such as gaps, cavities, azimuthal asymmetries, and spiral arms (e.g. ALMA Partnership 2015, Andrews et al. 2018, Long et al. 2018). These substructures are tantalizing evidence that planets may already be formed and hiding in protoplanetary disks.

If that is the case, then to understand the initial conditions in disks, which are crucial inputs into our understanding of the planet formation process (e.g. Mordasini 2018), we must turn to ``protostellar disks," where the disk is still forming and embedded within its natal envelope of infalling material. It is these early disks, with ages <1 Myr (e.g. Evans et al. 2009), where the initial conditions for planet formation, such as how much mass is present and how it is distributed in the disk, are likely to be found. Moreover, the radius and mass of the forming disk can be regulated by the angular momentum of the infalling material, and magnetic fields can remove angular momentum efficiently in the absence of dissipative processes (e.g., Li et al. 2014). As such, the structure of these protostellar disks is expected to be connected to their formation conditions. If gravitational instability in disks is a viable mechanism for angular momentum transport, the formation of multiple star systems, and possibly giant planet formation, the disks in the protostellar phase are those most likely to have the requisite conditions (Kratter et al. 2010; Tobin et al. 2016). Finally, protostellar disks are mediators of mass accretion and control the rate at which stellar mass is built up during the phase while young stars are still experiencing most of their growth. The density structure of disks may carry hints as to how accretion from disk to star will proceed in the protostellar phase, whether it will happen smoothly or in stochastic bursts (see WP by Fischer, Green, and Hunter).

Studies of protostellar disks have long been hindered by the presence of their surrounding envelopes. The emission from the dense, infalling envelopes is blended with that of the protostellar disks and therefore necessitates high resolution observations at wavelengths where the envelopes are optically thin, and/or radiative transfer modeling to separate disk and envelope (e.g. Sheehan & Eisner 2017). The presence of a disk throughout the protostellar phase is only now becoming well-established (e.g., Yen et al. 2017), and the structure of these disks is poorly understood, despite their important role in establishing the initial conditions for disk evolution and planet formation. The VLA and ALMA Nascent Disk and Multiplicity (VANDAM) Survey (PI: Tobin) has been pioneering the study of large samples of protostellar disks, targeting ~200 protostellar disks in Perseus and Orion with the VLA at 0.07" (~21-30 AU; Tobin et al. 2016) and another ~330 protostellar disks in Orion with ALMA at ~0.1" resolution (~40 AU; see Figure 1). Though the VANDAM survey has been crucial in improving our understanding of the structure of these early disks, there remain limitations in how much can be learned with current facilities.

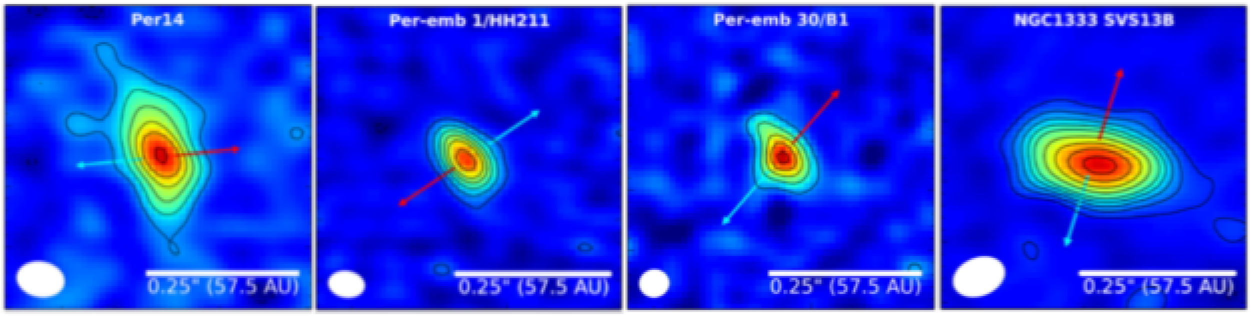

Figure 1 - Images of some well-resolved disks from the VANDAM: Perseus survey at 8 mm, from Segura-Cox et al. (2016). The contours in each panel are [-6, -3, 3, 6, 9, 12, 15, 20, 25, 30, 35, 40, 50] × σ, where σ = 11 μJy at 8 mm.

Protostellar Disk Structure: The Initial Conditions for Planet Formation

Among the discoveries from recent surveys of protostellar disks has been the revelation that they are on-average more massive than protoplanetary disks (e.g. Sheehan & Eisner 2017, Tychoniec et al. 2018). Although it is good news that protostellar disks have a large reservoir of material available for planet formation, it also complicates their study due to their potentially large optical depths, particularly at wavelengths where ALMA operates. Figure 2 shows the surface density profiles of disks of varying sizes and masses, as well as where they become optically thick, and demonstrates that typical protostellar disks, with $M_{disk} \geq 0.01\ M_{sun}$, are optically thick at 1.3 mm out to $R \geq 10$ au (Tobin et al. 2018). Thus, it is highly uncertain as to how much mass protostellar disks are harboring at radii near the protostar, potentially available for rapid accretion. Wavelengths of 3 mm and longer are essential for characterizing disk structure, as protostellar disks are substantially more optically thin at those wavelengths.

The VLA currently provides access to these longer wavelengths, observing at ~7 mm and longer, but observing dust at long wavelengths requires higher sensitivity. Dust emission scales as $\lambda^{-(2+\beta)}$, with $0 < \beta < 2$, so protostellar disks are also substantially fainter at VLA wavelengths. The VANDAM Survey had 3σ mass sensitivities[1] at 9 mm of 0.009 M_{sun} at 300 pc in Perseus and 0.015 M_{sun} at 400 pc in Orion, severely limiting the ability to detect protostellar disks. Making matters worse, these are point source sensitivities, but many disks are/would be resolved by the VLA and therefore have significantly less emissivity per beam, making them difficult to detect. Moreover, the VANDAM surveys collectively took 600 hours of time on the VLA, indicating that substantially improving upon this survey with the current VLA is infeasible. As such, significant improvements to the sensitivity of the VLA at similar wavelengths are needed to detect protostellar disks and study their structure.

Another issue is that protostellar disks are, on average, smaller than 50 AU at (sub)millimeter wavelengths. The VANDAM Survey has found that protostellar disks are quite compact, with radii typically less than 30 AU at 9 mm (Segura-Cox et al. 2018). Although this may, to some degree, be a surface brightness limitation, the ALMA 870 micron observations of protostellar disks in Orion also find the median disk radius to be ~30 AU (Tobin et al., in prep.). This is problematic for studying the structure of protostellar disks, as the current best VLA resolution is only about 0.07" (~30 au at 400 pc, distance to Orion); ALMA at 3 mm has about ~0.05" maximum resolution. In order to determine the density profile of disks smaller than ~30

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[1] Mass sensitivities are estimated assuming the millimeter flux traces optically thin emission with a 3σ sensitivity of $F_{3\sigma}$ such that the mass can be estimated from $M_{3\sigma} = F_{3\sigma}B_\nu(T)\ /(\kappa_\nu d)$, where κ_ν is the opacity, d is the distance, and $B_\nu(T)$ is the blackbody function. Here we assume an isothermal temperature of 30 K and $\kappa_\nu = 0.89\ \mathrm{cm}^2/\mathrm{g}$ (Ossenkopf & Henning 1994).

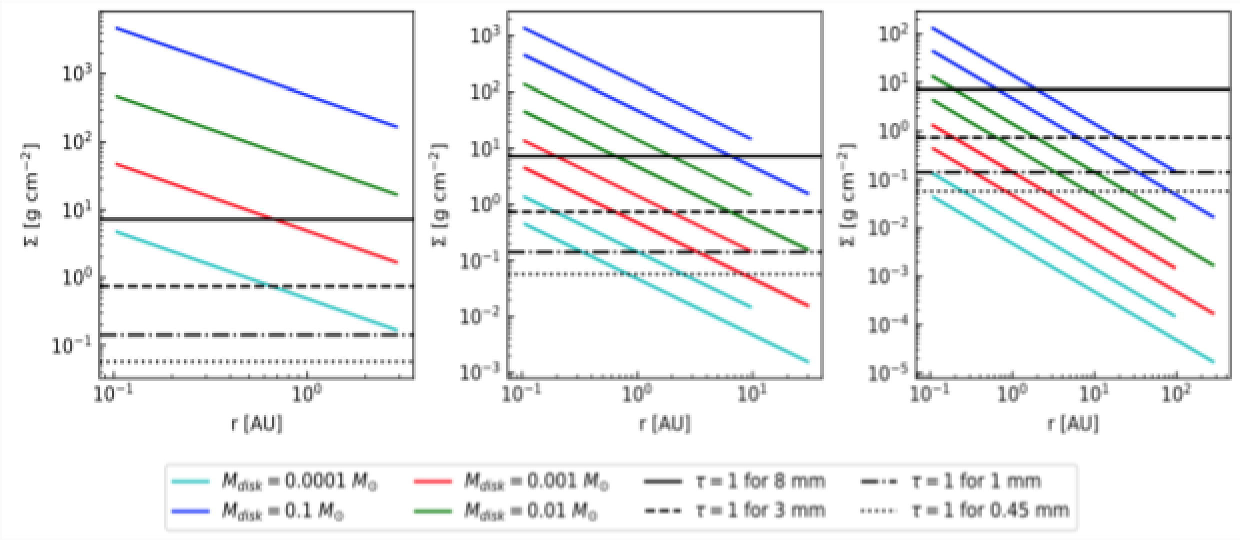

Figure 2 - Surface density of disks versus radius. Note that range of radius plotted increases from left to right; the 3 AU disks are plotted in the left panel, the 10 AU and 30 AU disks are plotted in the middle panel, and the 100 AU and 300 AU disks are plotted in the right panel. Horizontal lines are plotted that denote the surface density corresponding to τ = 1 at 7.5 mm (solid), 3 mm (dashed), 1 mm (dash-dot), and 0.45 mm (dotted). The dust mass opacities calculated are 0.15, 1.35, 7.03, 17.43 cm^2/g at wavelengths of 7.5, 3, 1, and 0.45 mm, respectively.

AU and their size distribution, higher resolution is required. Understanding how matter is distributed in these early disks is crucial for understanding where and how planet formation will proceed. Thus, a new millimeter/centimeter-wave facility that can resolve the inner protostellar disk with ~10x higher angular resolution and ~10x higher sensitivity is needed to enable protostellar disk characterization. Furthermore, such a facility will enable detection of protostellar disk emission from the inner disk to outer disk, which is essential for understanding the evolution from protostellar disks to protoplanetary disks. The high spatial resolution of such a facility would also enable the study of protostellar disk structure in more distant, massive star forming regions with similar spatial resolution that is currently available toward nearby star forming regions. Nearby star forming regions have at most ~300 protostellar disks (Orion; 400 pc), with most having fewer than 30. Cygnus-X, at 1.5 kpc, hosts an additional ~1000 protostellar disks that could be studied, but is currently too distant for current instruments to detect, let alone resolve protostellar disks. With such a facility and large samples, Science Ready Data Products will be essential. A detailed examination of the capabilities required to observe protostellar disks at long wavelengths of different sizes and masses, as well as at different distances is presented in Tobin et al. (2018).

The Role of Magnetic Fields in Regulating Protostellar Disk Formation and Evolution

Magnetic fields outside of the disk can play a significant role in the creation of disks. While protostellar disks often are seen at the Class 0 stage, a significant fraction of these disks are very low-mass and are undetected (e.g., Tychoniec et al. 2018; Maury 2019; Andersen et al. 2019). By using polarimetric observations to trace magnetic fields at 100 au scales for 10 protostars, Cox et al. (2018) found that the presence of a disk may depend on the alignment between the magnetic field and the protostar's rotation axis. Such polarimetric studies need to be expanded to many more protostars, where the presence of the disk is known.

Magnetic fields within the disk also play a significant role in angular momentum transport via disk winds (e.g., Konigl & Pudritz 2000) and magnetorotational instability (e.g., Balbus & Hawley

1998). Measuring fields with disk polarization at these scale may be challenging, as disks are conducive to polarization due to self-scattering, and fields may not align large grains. Nevertheless, it is possible for the youngest disks, where grains have not grown substantially, polarization at millimeter or centimeter wavelengths can trace the magnetic field morphology in disks. Moreover, circular polarization of spectral lines, such as those that can be observed by ALMA, may enable the magnetic field strength to be measured using the Zeeman effect.

The Seeds of Planet Formation at Early Times

The early stages of planet formation are thought to begin as micron-sized dust grains collide and grow to centimeter or larger sizes. These centimeter sized bodies are therefore the early seeds of planet formation, that will succumb to mechanisms such as streaming instabilities to form planetesimals (e.g. Youdin & Goodman 2005). Still, the question remains how early such centimeter sized bodies are present in disks, and the answer has implications for when and how planets will ultimately form (e.g. Drazkowska & Dullemond 2018). Dust grain sizes are typically estimated by measuring millimeter fluxes at two separate wavelengths, as $F_\lambda \sim \lambda^{-(2+\beta)}$, where β is related to the size of dust grains present. If dust grains are larger than the wavelengths of the observations, then $\beta \sim 0$, otherwise $\beta \sim 2$. Observations at millimeter wavelengths are therefore crucial for determining the sizes of dust grains present in disks. Moreover, long wavelengths where dust is optically thin are crucial for making such measurements, as optically thick dust emission has $F_\lambda \sim \lambda^{-2}$ and can be mistaken for dust grain growth. Furthermore, polarimetric observations of disks at (sub)millimeter wavelengths (e.g., Stephens et al. 2014; 2017, Kataoka et al. 2016; 2018) show evidence of self-scattering of dust grains (e.g., Kataoka et al. 2015; Yang et al. 2016). Since the fraction of polarized light depends on the grain size, these observations can also constrain grain growth in disks. The optimal grain size for producing polarization through scattering at wavelength λ is $\sim\lambda/2\pi$, so centimeter wavelength observations are crucial for probing millimeter-sized dust grains.

The presence of large, millimeter or centimeter sized dust grains has been suggested in protoplanetary disks through measurements of β (e.g. Ricci et al. 2010, Ansdell et al. 2016). Moreover, in several well studied cases, radially varying maximum dust grain sizes have been inferred for protoplanetary disks (e.g. Perez et al. 2012, 2015, Tazzari et al. 2016), perhaps indicating the work of radial drift in protoplanetary disks. If planets or planetesimals are to have formed already in protoplanetary disks, however, it seems likely that large dust aggregates must form sometime during the protostellar disk phase. If so, it is essential to understand the substructure of disks down to small radii in order to assess the presence of large dust prior to the protoplanetary disk phase. This is particularly important because radial drift is more rapid for larger grains and could cause the large grains to drift inward and be accreted on to the protostar, removing them from the planet formation process. Though there are a few tantalizing hints at the presence of large dust grains in protostellar disks (e.g. Harsono et al. 2018), little is known in general about the sizes of dust aggregates at early times. Improvements to long wavelength radio interferometer facilities are once again crucial to understanding the formation of planets at early times. With high resolution, such a facility would open the door to also studying grain size as a function of radius within the disk.

Substructure in Protostellar Disks

Substructures in protoplanetary disks have been the source of a significant amount of theoretical and observational work, particularly since the discovery of numerous concentric rings in the disk of HL Tau (ALMA Partnership 2015). Some effort has gone into searching for substructure in protostellar disks (e.g. Tobin et al. 2016, Sheehan & Eisner 2018); however there remains much we do not know. If gravitational instability is a viable mechanism for planet formation, it can only feasibly occur in the protostellar phase when the disks are massive enough and may leave signatures in the protostellar disk density structure such as clumps and spirals. Core accretion acting at early times may generate rings and gaps, although the infall of envelope material may also create such features (e.g. Bae et al. 2014). Resolved images of the inner regions of disks may help to inform the accretion history (and future) of the protostar. If the inner regions are smooth it may indicate that accretion proceeds steadily, while density enhancements (such as a dead zone) may be links to potential episodic accretion (e.g., Zhu et al. 2008, 2009; Bae et al. 2013). Longer wavelengths will help to characterize disk substructures, particularly smaller surface density perturbations and structures at small radii, both of which can be substantially optically thick at submillimeter wavelengths. Similarly, near-infrared variability from accretion bursts may help to inform the presence of substructures at small radii (see WP by Fischer, Green, and Hunter).

Tools for Studying Protostellar Disk Structure

Disk structure has historically been measured through relatively simple estimations. To first order, disk radii can be estimated by fitting two dimensional Gaussians to resolved imaging of disks, or by measuring the radius including 90% of the flux (e.g. Ansdell et al. 2018, Eisner et al. 2018). Disk mass can similarly be estimated using a measurement of the total flux and assuming the emission is optically thin and isothermal, as well as assuming a dust opacity (e.g. Hildebrand 1983). To move beyond simple estimators, models that include variations in how material is distributed throughout the disk, i.e. measure the density profile of the disk, are needed. A disk's surface brightness profile is a convolution of the three dimensional density, the radial and vertical temperature, and dust optical properties. As such, truly understanding disk structure requires radiative transfer modeling. Such techniques have long a staple of studying disks (e.g. Eisner et al. 2005, Andrews et al. 2010), but the advances in Markov Chain Monte Carlo fitting algorithms in recent years (e.g. Foreman-Mackey et al. 2013) have spurred efforts to increase the rigor with which such modeling is applied (e.g. Czekala et al. 2015, Tazzari et al. 2017, Sheehan & Eisner 2018). As radiative transfer modeling is computationally expensive, moving towards applying such methods to large samples of protostellar disks will require a significant amount of computing time. To meet this need, continued access to supercomputing facilities at the national level, such as those currently offered by NSF XSEDE, are instrumental to pushing forward our understanding of protostellar (and protoplanetary) disks.

Summary

The structure of protostellar disks remains a relatively unexplored frontier that is ripe with potential for filling in gaps in our understanding of the early stages of star and planet formation. In order to take the next step towards these goals, however, improvements to our millimeter facilities, in particular a millimeter/centimeter facility with 10x the spatial resolution and 10x the sensitivity of the VLA, the improved availability of Science Ready Data Products, as well as continued improvements to our polarization capabilities, are crucial. With such improvements, we will be able to put together a comprehensive view of the initial conditions in protostellar disks.

References

ALMA Partnership, Brogan, C. L., Pérez, L. M., et al. 2015, ApJ, 808, L3

Andersen, B. C., Stephens, I. W., Dunham, M. M., et al. 2019, arXiv:1902.05956

Andrews, S. M., Wilner, D. J., Hughes, A. M., Qi, C., & Dullemond, C. P. 2010, ApJ, 723, 1241

Andrews, S. M., Rosenfeld, K. A., Kraus, A. L., & Wilner, D. J. 2013, ApJ, 771, 129

Andrews, S. M., Wilner, D. J., Zhu, Z., et al. 2016, ApJ, 820, L40

Andrews, Sean M., Huang, J., Pérez, L. M., et al. 2018, ApJL, 869, 41

Ansdell, M., Williams, J. P., van der Marel, N., et al. 2016, ApJ, 828, 46

Ansdell, M., Williams, J. P., Trapman, L., et al. 2018, ApJ, 859, 21

Bae, J., Hartmann, L., Zhu, Z., & Gammie, C. 2013, ApJ, 774, 57

Bae, J., Hartmann, L., Zhu, Z., & Nelson, R. P. 2014, ApJ, 795, 61

Balbus, S. A., & Hawley, J. F. 1998, Reviews of Modern Physics, 70, 1

Cox, E. G., Harris, R. J., Looney, L. W., et al. 2018, ApJ, 855, 92

Czekala, I., Andrews, S. M., Jensen, E. L. N., et al. 2015, ApJ, 806, 154

Drazkowska, J., & Dullemond, C. P. 2018, A&A, 614, A62

Eisner, J. A., Hillenbrand, L. A., Carpenter, J. M., & Wolf, S. 2005, ApJ, 635, 396

Eisner, J. A., Arce, H. G., Ballering, N. P., et al. 2018, ApJ, 860, 77

Evans, II, N. J., Dunham, M. M., Jørgensen, J. K., et al. 2009, ApJS, 181, 321

Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, PASP, 125, 306

Harsono, D., Bjerkeli, P., van der Wiel, M. H. D., et al. 2018, Nature Astronomy, 2, 646

Hildebrand, R. H. 1983, QJRAS, 24, 267

Kataoka, A., Muto, T., Momose, M., et al. 2015, ApJ, 809, 78

Kataoka, A., Muto, T., Momose, M., Tsukagoshi, T., & Dullemond, C. P. 2016, ApJ, 820, 54

Kataoka, A., Tsukagoshi, T., Pohl, A., et al. 2017, ApJL, 844, L5

Konigl, A., & Pudritz, R. E. 2000, Protostars and Planets IV, 759

Kratter, K. M., Matzner, C. D., Krumholz, M. R., & Klein, R. I. 2010, ApJ, 708, 1585 Kryukova, E., Megeath, S. T., Hora, J. L., et al. 2014, AJ, 148, 11

Li, Z.-Y., Banerjee, R., Pudritz, R. E., et al. 2014, Protostars and Planets VI, 173 Manara, C. F., Rosotti, G., Testi, L., et al. 2016, A&A, 591, L3

Long, F., Pinilla, P., Herczeg, G. J., et al. 2018, ApJ, 869, 17

Maury, A. J., Andre, P., Testi, L., et al. 2019, A&A, 621, A76

Mordasini, C. 2018, Handbook of Exoplanets, 143

Oberg, K. I., Guzman, V. V., Furuya, K., et al. 2015, Nature, 520, 198

Ossenkopf, V., & Henning, T. 1994, A&A, 291, 943

Pérez, L. M., Carpenter, J. M., Chandler, C. J., et al. 2012, ApJ, 760, L17

Pérez, L. M., Chandler, C. J., Isella, A., et al. 2015, ApJ, 813, 41

Qi, C., Oberg, K. I., Wilner, D. J., et al. 2013, Science, 341, 630

Ricci, L., Testi, L., Natta, A., et al. 2010, A&A, 512, A15

Segura-Cox, D. M., Harris, R. J., Tobin, J. J., et al. 2016, ApJ, 817, L14

Segura-Cox, D. M., Looney, L. W., Tobin, J. J., et al. 2018, ApJ, 866, 161

Sheehan, P. D., & Eisner, J. A. 2017, ApJ, 851, 45

Sheehan, P. D., & Eisner, J. A. 2018, ApJ, 857, 18

Stephens, I. W., Looney, L. W., Kwon, W., et al. 2014, Nature, 514, 597

Stephens, I. W., Yang, H., Li, Z.-Y., et al. 2017, ApJ, 851, 55

Tazzari, M., Testi, L., Ercolano, B., et al. 2016, A&A, 588, A53

Tazzari, M., Testi, L., Natta, A., et al. 2017, A&A, 606, A88

Tobin, J. J., Hartmann, L., Chiang, H.-F., et al. 2012, Nat, 492, 83

Tobin, J. J., Dunham, M. M., Looney, L. W., et al. 2015, ApJ, 798, 61

Tobin, J. J., Looney, L. W., Li, Z.-Y., et al. 2016, ApJ, 818, 73

Tobin, J. J., Kratter, K. M., Persson, M. V., et al. 2016, Nat, 538, 483

Tobin, J. J., Sheehan, P., Johnstone, D., & Sharma, R. 2018, Science with a Next Generation Very Large Array , 517, 345

Tychoniec, L., Tobin, J. J., Karska, A., et al. 2018, ApJS, 238, 19

van 't Hoff, M. L. R., Walsh, C., Kama, M., Facchini, S., & van Dishoeck, E. F. 2017, A&A, 599, A101

Yen, H.-W., Koch, P. M., Takakuwa, S., et al. 2017, ApJ, 834, 178

Yang, H., Li, Z.-Y., Looney, L. W., et al. 2016, MNRAS, 460, 4109

Youdin, A. N., & Goodman, J. 2005, ApJ, 620, 459

Zhu, Z., Hartmann, L., Calvet, N., et al. 2008, ApJ, 684, 1281

Zhu, Z., Hartmann, L., Gammie, C., & McKinney, J. C. 2009, ApJ, 701, 620