A DWARF TRANSITIONAL PROTOPLANETARY DISK AROUND XZ TAU B

Mayra Osorio1, Enrique Macías1, Guilem Anglada1, Carlos Carrasco-González2, Roberto Galván-Madrid2, Luis Zapata2, Nuria Calvet3, José F. Gómez3, Erick Nagel4, Luis F. Rodríguez5, José M. Torrelles5,6, and Zhaohuan Zhu6

1 Instituto de Astrofísica de Andalucía (CSIC), Glorieta de la Astronomía s/n, E-18008 Granada, Spain; osorio@iaa.es
2 Instituto de Radioastronomía y Astrofísica UNAM, Apartado Postal 3-72 (Xangari), 58089 Morelia, Michoacán, Mexico
3 Department of Astronomy, University of Michigan, 825 Dennison Building, 500 Church Street, Ann Arbor, MI 48109, USA
4 Departamento de Astronomía, Universidad de Guanajuato, Guanajuato, Gto 36240, Mexico
5 Institut de Ciències del Espai (CSIC)-Institut de Ciencies del Cosmos (UB)/IEEC, Martí i Franquès 1, E-08028 Barcelona, Spain
6 Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA

Received 2016 April 16; revised 2016 June 4; accepted 2016 June 8; published 2016 June 27

ABSTRACT

We report the discovery of a dwarf protoplanetary disk around the star XZ Tau B that shows all the features of a classical transitional disk but on a much smaller scale. The disk has been imaged with the Atacama Large Millimeter/submillimeter Array (ALMA), revealing that its dust emission has a quite small radius of ~1.3 au and presents a central cavity of ~1.3 au in radius that we attribute to clearing by a compact system of orbiting (proto)planets. Given the very small radii involved, evolution is expected to be much faster in this disk (observable changes in a few months) than in classical disks (observable changes requiring decades) and easy to monitor with observations in the near future. From our modeling we estimate that the mass of the disk is large enough to form a compact planetary system.

Key words: planet–disk interactions – protoplanetary disks – stars: formation – stars: individual (XZ Tau B) – stars: pre-main sequence

1. INTRODUCTION

Planetary systems originate from the evolution of accretion disks of gas and dust that develop around young stars as part of the star formation process itself (Blum & Wurm 2008). However, the details of how planets form are far from well understood. Some accretion disks, known as “transitional disks” (Calvet et al. 2005), present central cavities and annular gaps in their dust emission that have been attributed to the effects of tidal interactions of orbiting planetary or protoplanetary bodies (Papaloizou et al. 2007; Andrews et al. 2011; Zhu et al. 2011; Osorio et al. 2014) and are considered signposts of the planet formation process. Typical transitional disks imaged so far have radii of 50–100 au and masses of 10–100 $M_J$, with central cavities of 15–70 au in radius (Andrews et al. 2011; Espaillat et al. 2014; Andrews 2015). Nevertheless, some results, based on the spectral energy distribution (SED) modeling, suggest that significantly smaller disks should exist (McClere et al. 2008; Pádu et al. 2014), but direct imaging has not been possible yet.

XZ Tau B is a young M2 dwarf star (see stellar properties in Table 1) in the L1551 molecular cloud. It belongs to a triple system composed of the close pair XZ Tau A/C (separation ~0″09) and XZ Tau B (currently located ~0″3 to the NW; Carrasco-González et al. 2009). A sequence of expanding bubbles imaged by the Hubble Space Telescope (Krist et al. 2008) has been attributed to XZ Tau A/C (Carrasco-González et al. 2009; Zapata et al. 2015), while high-velocity jets have been associated with both XZ Tau A/C and XZ Tau B (Krist et al. 2008).

During the Long Baseline Campaign of the ALMA Science Verification process, a field centered on HL Tau was observed at 2.9 and 1.3 mm (ALMA Partnership et al. 2015a, 2015b; hereafter AP2015a, AP2015b). XZ Tau B was reported only as an unresolved continuum source at 2.9 mm. Here, we present a detailed analysis of the 1.3 mm continuum observations that angularly resolve the source.

2. OBSERVATIONS

The observations were carried out between 2014 October 14 and November 14 using 42 antennas of ALMA, with baselines from 12 to 15,240 m. The phase center was at the position of HL Tau, $\alpha$(J2000) = $4^h3^m38^s.4263$, $\delta$(J2000) = 18°13′ 57″047. The 1.3 mm data were obtained from 2014 October 24–31 with the ALMA correlator configured in 4 spectral windows of 2000 MHz and 128 channels each. The 2.9 mm data were obtained using wide spectral windows for the continuum and narrow spectral windows centered on the $\mathrm{HCO}^+$ (1–0), $\mathrm{HCN}(1–0)$, $\mathrm{CO}(1–0)$, and $\mathrm{CN}(1–0)$ lines. A description of the observational setup and the calibration process is given in AP2015a; AP2015b.

The continuum emission at 2.9 mm was imaged by AP2015a (beam = 0″085 $\times$ 0″061, $PA = -179°$, rms = 24 $\mu$Jy beam$^{-1}$). We obtained cleaned, continuum-subtracted, channel maps (channel width = 0.25 km s$^{-1}$; beam = 0″10 $\times$ 0″06, $PA = 12°$) for the observed line transitions. No line emission was detected toward XZ Tau.

Images at 1.3 mm were obtained with the task clean of CASA (version 4.2.2). XZ Tau falls ~24″ away from the phase center, where the response of the primary beam ($\mathrm{FWHM} \approx 27″$ at 1.3 mm) is only 1/19. However, the extraordinary sensitivity of ALMA allows a good signal-to-noise imaging. To avoid HL Tau sidelobes in the XZ Tau field, we first cleaned the HL Tau emission and subtracted it from the $uv$ data. We tried several self-calibration strategies. Although self-calibration slightly improves the images of HL Tau, it blurs the XZ Tau images. We attribute these unfavorable effects on XZ Tau.
to the lack of a strong compact source in the field and to the large separation of XZ Tau from the phase center. Since we are interested in XZ Tau, we did not apply self-calibration in our final images. Given the narrow channel width and small integration time per visibility, the expected bandwidth and time smearing are negligible at the position of XZ Tau (0′′0016 and 0′′0035, respectively).

Figure 1(a) shows our primary-beam corrected 1.3 mm image of XZ Tau B. The source is angularly resolved, with a size of ~0′′05 and a flux density of 7 ± 2 mJy. At 2.9 mm it was reported as angularly unresolved (size <0′′054) with a flux density of 1.83 ± 0.12 mJy (AP2015a; Zapata et al. 2015). Uncertainties in flux densities have been calculated as in AP2015a, but adding quadratically the absolute flux density calibration uncertainty (5%) and the primary beam response uncertainty due to pointing errors (~0′′6), using the Dzib et al. (2014) prescription.

Since the 2.9 mm observations are less affected by the primary beam attenuation, they are much more sensitive. The fact that the source size upper limit set by these observations is similar to the observed size at 1.3 mm (~0′′05 ≈ 7 au) indicates that the sensitivity of the 1.3 mm image is high enough to reveal the full structure of the source and not just the brightest part. Thus, we interpret the observed emission as tracing the dust of a very small (~3.5 au in radius) circumstellar disk.

Interestingly, the 1.3 mm ALMA image reveals substructure in the disk (Figure 1(a)). Emission decreases toward the center, indicating a hole or cavity. Otherwise, the emission would peak toward the central position. We have plotted the real component of the visibility profile (Figure 1(b)), which shows the characteristic null and negative region that confirm the presence of a central hole in the disk (e.g., Andrews et al. 2009). The null falls around 5–8 Mλ, corresponding to

---

**Table 1**

Parameters of the XZ Tau B Star and Disk

| Parameter                      | Value       | Notes        | References |
|--------------------------------|-------------|--------------|------------|
| Star                           |             |              |            |
| Distance (pc)                  | 140         | Adopted      | 1          |
| Visual Extinction (mag)        | 1.4         | Adopted      | 2          |
| Spectral Type                  | M2          | Adopted      | 2          |
| Age (Myr)                      | 4.6         | Adopted      | 2          |
| Effective Temperature (K)      | 3550        | Adopted      | 2          |
| Radius ($R_\odot$)             | 1.24        | Calculated   |            |
| Mass ($M_\odot$)               | 0.37        | Adopted      | 2          |
| Mass Accretion Rate ($M_\odot$ yr$^{-1}$) | $1.4 \times 10^{-8}$ | Calculated   |            |
| Disk                           |             |              |            |
| Inclination (deg)              | 35 ± 10     | Adopted/Refined | 3          |
| Position Angle of Major Axis (deg) | 140 ± 10  | Adopted/Refined | 4          |
| Inner Radius (au)              | 1.30 ± 0.05 | Fitted       |            |
| Outer Radius (au)              | 3.4 ± 0.1   | Fitted       |            |
| Viscosity Parameter            | 0.001       | Adopted      |            |
| Mass Accretion Rate ($M_\odot$ yr$^{-1}$) | $7.0 \times 10^{-8}$ | Fitted | |
| Degree of Settling             | 0.10        | Fitted       |            |
| 1.3 mm Optical Depth at 1 au   | 18          | Calculated   |            |
| 1.3 mm Optical Depth at 3.4 au | 14          | Calculated   |            |
| Mass Evacuated in Cavity ($M_j$)| 3           | Calculated   |            |
| Total Mass ($M_j$)             | 9           | Calculated   |            |
| Dust Mass ($M_j$)              | 25          | Calculated   |            |
| Cavity Wall                    |             |              |            |
| Radius (au)                    | 1.30 ± 0.05 | = Disk Inner Radius |          |
| Temperature (K)                | 420         | Calculated   |            |
| Height (au)                    | 0.09        | = Disk Hydrostatic |          |
|                               |             | = Scale Height |            |

**References.** (1) Torres et al. (2009), (2) Hartigan & Kenyon (2003), (3) C. Carrasco-González et al. (2016, in preparation), (4) Krist et al. (2008).
hole radii of 0.6–0.9 au to 1.4–2.2 au for the extreme cases of an infinite disk and a thin ring, respectively (Hughes et al. 2007). Since our small disk should be something intermediate, we estimate a radius of the hole ~1 au, consistent with the value obtained from our modeling of the SED and image (Section 3). Thus, XZ Tau B appears to be a “transitional disk” (Calvet et al. 2005) with a small central cavity probably due to the tidal forces created by an orbiting substellar object or protoplanet (Andrews et al. 2011). In order to substantiate this interpretation, we carried out a detailed modeling.

3. MODELING

The disk parameters are determined by modeling and fitting the observed SED and the normalized radial intensity profile of the 1.3 mm image. To construct the observed SED, we compiled photometric and spectroscopic data from the Spitzer, WISE, Akari, and IRAS databases; from the literature (White & Ghez 2001; Hartigan & Kenyon 2003; Carrasco-González et al. 2009; AP2015a; Forgan et al. 2014); and from this paper. Measurements that do not separate the A and B components have been taken as upper limits.

Our model includes the contributions from both the central star and the disk. Since the XZ Tau B star is known to be optically variable, we reanalyzed the results of Hartigan & Kenyon (2003) but using the photometry of XZ Tau A from Coffey et al. (2004) to estimate the aperture correction. The stellar and accretion (veiling) luminosities of XZ Tau B were obtained following Pecaut & Mamajek (2013), Kenyon & Hartmann (1995), and Calvet & Gullbring (1998) assuming an M2 star and an 8000 K blackbody as the veiling source. Finally, using the Siess et al. (2000) tracks, the stellar parameters were derived (Table 1). The contribution of the central star to the SED (Figure 3(a)) is calculated by using the reanalyzed fluxes and extrapolating to other wavelengths following Kenyon & Hartmann (1995) and Pecaut & Mamajek (2013).

The disk is modeled using an updated version of the irradiated α-accretion disk models with dust settling developed by D'Alessio et al. (2006). A dust grain population similar to the interstellar medium is used in the upper layers of the disk, while in the midplane a population of larger dust grains, with radii up to 1 mm, is assumed. The grain mixture composition is the same as in Osorio et al. (2014), but incorporating water ice with the abundance given by McClure et al. (2015), resulting in a dust-to-gas ratio of 0.0085. A central cavity is included in the model by emptying the innermost regions of the disk. The edge of this region, or wall, is directly irradiated by the star and the accretion shock and, thus, heated to a higher temperature (D'Alessio et al. 2005).

The high H, K, and L band fluxes (White & Ghez 2001; Hioki et al. 2009) indicate that hot dust, which may correspond to a residual inner disk, is present inside the cavity, suggesting that XZ Tau B is at an earlier pre-transitional stage (Espaillat et al. 2008). However, because of the variability of the star and the limited data in this wavelength range, we cannot determine the properties of this inner component, and thus we did not include it in our model.

The disk inclination (angle between the rotation axis and the line of sight) and PA were fitted by exploring different values, assuming as an initial guess that the disk lies in the B and A/C orbital plane (i = 47°C. Carrasco-González et al. 2016, in preparation) and is perpendicular to the direction of the observed collimated jet (Krist et al. 2008).

Hence, the main free parameters are the viscosity parameter, α, the mass accretion rate in the disk, $\dot{M}_{\text{disk}}$, and the degree of settling, $\epsilon$. Planet-forming disks are expected to have dust populations highly settled onto the midplane (i.e., a low value of $\epsilon$, defined as the dust-to-gas ratio in the atmosphere relative to the total of the disk), so that planetesimals can grow through the aggregation of large grains. Thus, we explored low values of $\epsilon$, $0.001 \leq \epsilon \leq 0.1$.

To analyze how the viscosity affects the gas and dust evolution, we have carried out gas-dust two-fluid hydrodynamical simulations as in Zhu et al. (2012). With a large viscosity (e.g., $\alpha = 10^{-2}$), such a small disk evolves very fast. As shown in the right panel of Figure 2, the disk gas surface density decreases by four orders of magnitude within 0.1 Myr, and all the dust drifts to the central star. With a smaller viscosity (e.g., $\alpha = 10^{-3}$ as shown in the left panel of Figure 2), ~0.1 $M_J$ mass planets are sufficient to produce a cavity that is almost two orders of magnitude deep. Thus, multiple planets could account for the observed cavity in XZ Tau B as long as the viscosity is small enough ($\alpha \lesssim 10^{-3}$).

Simulations also show that accretion onto the planet creating the gap can account for up to 90% of $M_{\text{disk}}$ (Zhu et al. 2011) and would reduce the mass accretion rate onto the star, $\dot{M}_s$. Therefore, we explored values of $M_{\text{disk}}$ in the range $M_s < M_{\text{disk}} < 10 M_s$, where $M_s$ is given in Table 1.

We have run a grid of 40 models with parameters in the above-mentioned ranges. Since we are interested in studying the capability of the disk to form planets, we have selected the model that fits the data with the highest allowed value for the viscosity parameter, which gives the lowest disk mass ($9 M_J$). As we show in Section 4, even this low-mass disk is capable of forming a planetary system. The parameters of this disk are given in Table 1.

The resulting SED, showing the separate contributions of the main components, is plotted in Figure 3(a). The free–free contribution from the ionized jet has also been taken into account in the fit, showing that it is negligible in the millimeter range. A comparison of the observed and model intensity profiles along the major axis of the disk is shown in Figure 3(b). Figure 3(c) shows the surface density and temperature model profiles. Figure 3(d) shows a CASA simulated image of the model emission at 1.3 mm as it would be observed with the same ALMA configuration as Figure 1. These figures show that the model reproduces the observations reasonably well. Thus, our results support the interpretation that XZ Tau B is associated with a dwarf transitional disk.

4. DISCUSSION

Modeling shows that the outer radius of the disk is 3.4 au and the radius of the central cavity is 1.3 au (Table 1). These radii are well constrained by the intensity profile and are much smaller than those of other transitional disks (typically ~50–100 au for the disk and ~15–70 au for the cavity; Andrews et al. 2011; Espaillat et al. 2014; Andrews 2015). Tidal interactions in a close binary are expected to truncate circumstellar disks to an outer radius ~1/3 of the binary
separation (Papaloizou & Pringle 1977).  This has been observed in the L1551-IRS5 binary system of disks, each 10 au in radius (Rodríguez et al. 1998).  Interestingly, the radius of the XZ Tau B disk is significantly smaller than the value of \( \sim 14 \) au expected from tidal truncation, given the separation of \( \sim 42 \) au between XZ Tau B and the A/C pair.  A highly eccentric orbit could truncate the disk at a smaller radius, but the analysis of the relative positions of the stars over >20 years favors a nearly circular orbit (Carrasco-González et al. 2009, C. Carrasco-González et al. 2016, in preparation).

The reason for the small size of the XZ Tau B disk is uncertain. It is feasible that the disk was originally small; that simple tidal truncation models (Papaloizou & Pringle 1977) may not apply for the particular geometry of this disk and truncation occurs at a smaller scale; that the disk is outwardly truncated by a forming planet in an outer orbit (Osorio et al. 2014); or that the outer parts of the disk have been removed by other mechanisms (e.g., swept out by the sequence of expanding bubbles from the A/C stars; Krist et al. 2008). It is possible that the gas component of the XZ Tau B disk is more extended than the dust, as it occurs in standard disks (e.g., HD 163296; de Gregorio-Monsalvo et al. 2013). Unfortunately, the sensitivity of our line observations is insufficient to set a tight constraint to the gas disk size. Anyhow, the disk of dust in XZ Tau B is much smaller than any other angularly resolved disk of dust imaged so far.

The observed image (Figure 1(a)) is marginally asymmetric, with the flux density in the southeast region \( \sim 30\% \) higher than in the northwest one. Such an asymmetry could not result from opacity effects due to the disk inclination since our modeled image (Figures 3(b), (d)) is symmetric. Instead, this asymmetry is suggestive of a dust trap, where the largest dust grains accumulate (e.g., Birnstiel et al. 2013; van der Marel et al. 2013). However, this needs to be confirmed with higher sensitivity data.

These results suggest that XZ Tau B shows the features that characterize transitional disks, but on a much smaller scale (e.g., compare Figure 1(a) with Figure 1(b) in Osorio et al. 2014). Since the evolution of these features is determined by their orbital motions around the central star, a dwarf disk like XZ Tau B is expected to evolve \( \sim 50-500 \) times faster than their bigger counterparts. Unfortunately, the current 1.3 mm ALMA observations, spanning just one week, are insufficient to search for disk evolution, but significant changes can occur in observations separated by only a few months. Thus, we anticipate that the disk in XZ Tau B, and possibly other similar dwarf disks, may serve in the near future as valuable small-scale models for a fast and efficient study of the evolution of transitional disks.

The diversity of planetary systems observed in the exoplanet surveys suggests that an equivalent diversity should be found in their progenitors, the protoplanetary disks. In particular, the Kepler mission has identified a number of “low-mass compact multiple-planet systems,” orbiting within <1 au from the star and with planetary masses ranging from a fraction to a few times the Earth’s mass (Lissauer et al. 2011, 2014; Jontof-Hutter et al. 2015). Dwarf disks similar to that found in XZ Tau B appear as the natural precursors of these systems.

To fit both the relatively high mm flux density of the disk and its small size, a high mass accretion rate was needed in our model. This, combined with the low viscosity of the disk, resulted in very high disk surface densities (Figure 3(c)). These values are higher than those expected at the inner regions of larger disks around this type of stars (Williams & Cieza 2011; Andrews 2015), but they are still one order of magnitude smaller than the values of the “minimum mass protoplanetary nebula” estimated by Swift et al. (2013) to form “in situ” the Kepler-32 planetary system.

It is also interesting to compare with the compact system of five sub-Earth radius planets around the K0 star Kepler-444A, in a hierarchical triple stellar system. Dupuy et al. (2016) estimated a small radius of \( \sim 2 \) au and a relatively large mass \( \geq 70 M_{\oplus} \) for the primordial protoplanetary disk around Kepler-444A. These authors propose that the outer regions of such a massive disk would have been unstable, leading to the formation of the triple star system through gravitational fragmentation. XZ Tau B could be similar to Kepler-444A. However, the disk of XZ Tau B presents a central gap, while the planets around Kepler-444A have masses well below the gap-opening mass (Dupuy et al. 2016). This implies that the planets recently formed in XZ Tau B are probably more massive than the planets around Kepler-444A. The reason of this could be the difference in the position of the snowline. Whereas the whole disk of Kepler-444A would have fallen

**Figure 2.** Hydrodynamical simulations of the surface density (solid line—gas; dotted line—1 mm dust) at different times for viscous disks (\( \alpha = 0.001 \), left; \( \alpha = 0.01 \), right) with three accreting 0.12 \( M_{\odot} \) planets, at radii 0.4, 0.63, and 1 au.
within its snowline, our model of XZ Tau B shows that (for points slightly above the disk midplane, where the minimum temperature is reached) it could be located inside the cavity, at a radius of \( \sim 0.5 \) au, where \( T_{\text{min}} \approx 180 \) K (Figure 3(c)). Therefore, giant planets, which form much more easily beyond the snowline (e.g., Ros & Johansen 2013), could be forming in the XZ Tau B disk cavity.

Some theoretical studies already pointed to the possible existence of a relatively large population of very small disks (McClure et al. 2008; Piétu et al. 2014; Kraus et al. 2015; Furlan et al. 2016). However, none of these putative dwarf disks has been angularly resolved. In XZ Tau B we have been able not only to angularly resolve the disk and determine its size, but also to observe and model its substructure at au-scales. The Kepler mission raised a number of puzzling questions regarding the observed planetary systems at distances < 1 au from the star, such as the debate of migration versus “in situ” planetary formation (Ogihara et al. 2015), or the abundance of super-Earths very close to the star (Lee et al. 2014). XZ Tau B opens a new window to investigate with ALMA observations the disk evolution and first stages of planet formation on timescales and at radii that so far remained unexplored.

This paper is dedicated to the memory of Paola D’Alessio who passed away in November of 2013. Support from MINECO-FEDER AYA2014-57369-C3 grant, CONACyT, and DGAPA-UNAM is acknowledged. This paper makes use of the following ALMA data: ADS/JAO.ALMA #2011.0.00015.SV. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), NSC and
ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Facility: ALMA.

REFERENCES

ALMA Partnership, Brogan, C. L., Pérez, L. M., et al. 2015a, ApJL, 808, L3 (AP2015a)
ALMA Partnership, Fomalont, E. B., Vlahakis, C., et al. 2015b, ApJL, 808, L1 (AP2015b)
Andrews, S. M. 2015, PASP, 127, 961
Andrews, S. M., Wilner, D. J., Hughes, A. M., Qi, C., & Dullemond, C. P. 2009, ApJ, 700, 1502
Birnstiel, T., Dullemond, C. P., & Pinilla, P. 2013, A&A, 550, L8
Blum, J., & Wurm, G. 2008, ARA&A, 46, 21
Calvet, N., D’Alessio, P., Watson, D. M., et al. 2005, ApJL, 630, L185
Calvet, N., & Gallimore, E. 1998, ApJ, 509, 802
Carrasco-González, C., Rodríguez, L. F., Anglada, G., & Curiel, S. 2009, ApJL, 693, L86
Coffey, D., Downes, T. P., & Ray, T. P. 2004, A&A, 419, 593
D’Alessio, P., Calvet, N., Hartmann, L., Franco-Hernández, R., & Servín, H. 2006, ApJ, 658, 314
D’Alessio, P., Hartmann, L., Calvet, N., et al. 2005, ApJ, 621, 461
de Gregorio-Monsalvo, I., Ménard, F., Dent, W., et al. 2013, A&A, 557, A133
Dupuy, T. J., Kratter, K. M., Kraus, A. L., et al. 2016, ApJ, 817, 80
Dzib, S. A., Loinard, L., Rodríguez, L. F., & Galli, P. 2014, ApJ, 788, 162
Espaillat, C., Calvet, N., Luhan, K. L., Muzerolle, J., & D’Alessio, P. 2008, ApJL, 682, L125
Espaillat, C., Muzerolle, J., Najita, J., et al. 2014, in Protostars and Planets VI, ed. H. Beuther et al. (Tucson, AZ: Univ. Arizona Press), 497
Forgan, D., Ivison, R. J., Sibthorpe, B., Greaves, J. S., & Ibar, E. 2014, MNRAS, 439, 4057
Furlan, E., Fischer, W. J., Ali, B., et al. 2016, ApJS, 224, 5
Hartigan, P., & Kenyon, S. J. 2003, ApJ, 583, 334
Hioki, T., Ishii, Y., Oasa, Y., et al. 2009, PASJ, 61, 1271
Hughes, A. M., Wilner, D. J., Calvet, N., et al. 2007, ApJ, 664, 536
Jontof-Hutter, D., Rowe, J. F., Lissauer, J. J., Fabrycky, D. C., & Ford, E. B. 2015, Nat, 522, 321
Kenyon, S. J., & Hartmann, L. 1995, ApJS, 101, 117
Kraus, A. L., Andrews, S. M., Bowler, B. P., et al. 2015, ApJL, 798, L23
Krist, J. E., Stapelfeldt, K. R., Hester, J. J., et al. 2008, AJ, 136, 1980
Lee, E. J., Chiang, E., & Ormel, C. W. 2014, ApJ, 797, 95
Lissauer, J. J., Dawson, R. I., & Tremaine, S. 2014, Nat, 513, 336
Lissauer, J. J., Fabrycky, D. C., Ford, E. B., et al. 2011, Nat, 470, 53
McClure, M. K., Espaillat, C., Calvet, N., et al. 2015, ApJ, 799, 162
McClure, M. K., Forrest, W. J., Sargent, B. A., et al. 2008, ApJL, 683, L187
Ogihara, M., Morbidelli, A., & Guillot, T. 2015, A&A, 578, A36
Osorio, M., Anglada, G., Carrasco-González, C., et al. 2014, ApJL, 791, L36
Papaloizou, J., & Pringle, J. E. 1977, MNRAS, 181, 441
Papaloizou, J. C. B., Nelson, R. P., Kley, W., Masset, F. S., & Artymowicz, P. 2007, in Protostars and Planets V, ed. B. Reipurth, D. Jewitt, & K. Keil (Tucson, AZ: Univ. Arizona Press), 655
Pecaut, M. J., & Mamajek, E. E. 2013, ApJS, 208, 9
Pień, V., Guilloteau, S., Di Folco, E., Dutrey, A., & Boehler, Y. 2014, A&A, 564, A95
Rodríguez, L. F., D’Alessio, P., Wilner, D. J., et al. 1998, Nat, 395, 355
Ros, K., & Johansen, A. 2013, A&A, 552, A137
Siess, L., Dufour, E., & Forestini, M. 2000, A&A, 358, 593
Swift, J. J., Johnson, J. A., Morton, T. D., et al. 2013, ApJ, 764, 105
Torres, R. M., Loinard, L., Mioduszewski, A. J., & Rodríguez, L. F. 2009, ApJ, 698, 242
van der Marel, N., van Dishoeck, E. F., Bruderer, S., et al. 2013, Sci, 340, 1199
White, R. J., & Ghez, A. M. 2001, ApJ, 556, 265
Williams, J. P., & Cieza, L. A. 2011, ARA&A, 49, 67
Zapata, L. A., Galván-Madrid, R., Carrasco-González, C., et al. 2015, ApJL, 811, L4
Zhu, Z., Nelson, R. P., Dong, R., Espaillat, C., & Hartmann, L. 2012, ApJ, 755, 6
Zhu, Z., Nelson, R. P., Hartmann, L., Espaillat, C., & Calvet, N. 2011, ApJ, 729, 47

Osorio et al.