THE MATRYOSHKA DISK: KECK/NIRC2 DISCOVERY OF A SOLAR-SYSTEM-SCALE, RADIIALLY SEGREGATED RESIDUAL PROTOPLANETARY DISK AROUND HD 141569A

THAYNE CURRIE1, CAROL A. GRADY2, RYAN CLOUTIER3, MIHOKO KONISHI4, KEIVAN STASSUN5, JOHN DEBES6, NIENKE VAN DER MAREL7, TAKAYUKI MUT08, RAY JAYAWARDHANA9, AND THORSTEN RATZKA10

1 National Astronomical Observatory of Japan, Subaru Telescope, Hilo, HI, USA
2 Exoplanets and Stellar Astrophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA
3 Department of Astronomy and Astrophysics, University of Toronto, Toronto, Ontario, Canada
4 Department of Earth and Space Sciences, Graduate School of Science, Osaka University, Osaka, Japan
5 Department of Physics and Astronomy, Vanderbilt University, Nashville, TN, USA
6 Space Telescope Science Institute, Baltimore, MD, USA
7 Institute for Astronomy, University of Hawaii-Manoa, Honolulu, HI, USA
8 Kogakuin University, Tokyo, Japan
9 Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
10 Institute for Physics/IGAM, NAWI Graz, University of Graz, Graz, Austria

Received 2016 January 13; accepted 2016 February 2; published 2016 March 7

ABSTRACT

Using Keck/NIRC2 L′ (3.78 μm) data, we report the direct imaging discovery of a scattered-light-resolved, solar-system-scale residual protoplanetary disk around the young A-type star HD 141569A, interior to and concentric with the two ring-like structures at wider separations. The disk is resolved down to ~0.25″ and appears as an arc-like rim with attached hook-like features. It is located at an angular separation intermediate between that of warm CO gas identified from spatially resolved mid-infrared spectroscopy and diffuse dust emission recently discovered with the Hubble Space Telescope. The inner disk has a radius of ~3.9.au, a position angle consistent with north up, and an inclination of i ~ 56° and has a center offset from the star. Forward modeling of the disk favors a thick torus-like emission sharply truncated at separations beyond the torus’s photocenter and heavily depleted at smaller separations. In particular, the best-fit density power law for the dust suggests that the inner disk dust and gas (as probed by CO) are radially segregated, a feature consistent with the dust trapping mechanism inferred from observations of “canonical” transitional disks. However, the inner disk component may instead be explained by radiation pressure-induced migration in optically thin conditions, in contrast to the two stellar companion/planet-influenced ring-like structures at wider separations. HD 141569A’s circumstellar environment—with three nested, gapped, concentric dust populations—is an excellent laboratory for understanding the relationship between planet formation and the evolution of both dust grains and disk architecture.

Key words: planetary systems – stars: early-type – stars: individual (HD 141569A)

1. INTRODUCTION

Gas-rich, optically thick and luminous protoplanetary disks surrounding young stars typically dissipate in 5–10 Myr by a combination of viscous draining, photoevaporative clearing, and/or giant-planet formation (Williams & Cieza 2011). At older ages, optically thin gas-poor debris disks whose dust is sustained by planetesimal collisions comprise most of the disk population (Kenyon & Bromley 2008; Wyatt 2008). Directly imaging systems covering the protoplanetary-to-debris disk transition reveals a diverse set of disks architectures, probes disk dispersal mechanisms, and identifies evidence for infant Jovian planets (e.g., Kraus & Ireland 2012; Grady et al. 2013; Currie et al. 2015a).

The circumstellar environment around the nearby (d = 116 pc; van Leeuwen 2007) A-type star HD 141569A is a particularly good laboratory for studying the last moments of this transition phase. The system’s nominal age (5 ± 3 Myr; Weinberger et al. 2000; Aarnio et al. 2008) is comparable to the characteristic protoplanetary disk evolution timescale (Cloutier et al. 2014). While HD 141569A retains a significant reservoir of gas (~0.2–0.5 MJ; Zuckerman et al. 1995; Thi et al. 2014), its infrared dust emission is optically thin and its fractional luminosity is not much higher than that of luminous debris disk-bearing stars like HR 4796A. Near-infrared (IR) to optical scattered-light imaging reveals two nested, bright rings of dust at r ~ 250 and 400 au exhibiting pericenter offsets, and spiral structures driven by the primary’s M dwarf companions and perhaps unseen newly formed planets (Weinberger et al. 1999; Mouillet et al. 2001; Clampin et al. 2003; Wyatt 2005; Janson et al. 2013; Biller et al. 2015; Mazoyer et al. 2016; Konishi et al. 2016).

Additionally, HD 141569A includes warm circumstellar material: CO gas emission cleared out to 11 au and marginally resolved warm thermal dust emission (10–20 μm) potentially depleted interior to 30 au (Fisher et al. 2000; Marsh et al. 2002; Goto et al. 2006). Recently, Konishi et al. (2016) discovered an additional diffuse optical scattered-light component at 40–100 au. Deeper high-contrast scattered-light imaging may clarify how HD 141569A’s circumstellar environment is being cleared of residual protoplanetary material at smaller, solar-system-like scales.

In this Letter, we present the discovery of a bright, solar-system-scale residual protoplanetary disk around HD 141569A using Keck/NIRC2 L′ high-contrast imaging.11 The scattered-light-detected dust disk lies interior to the diffuse emission recently discovered by Konishi et al. (2016) but is peaked at radii exterior to the CO gas resolved by Goto et al. (2006). The

11 We note an independent detection of this inner disk from D. Mawet (et al. 2016, in preparation).
dust disk is likely heavily evacuated at the CO gas’s inner radius, revealing evidence for dust/gas segregation.

2. OBSERVATIONS AND DATA REDUCTION

We imaged HD 141569A on 2015 June 8 with the NIRC2 camera on the Keck II telescope on Maunakea in the $L'$ filter ($\lambda_c = 3.778$ $\mu$m) using the narrow camera (9,952 mas pixel$^{-1}$; Yelda et al. 2010) and the “large hex” pupil plane mask in the angular differential imaging mode (Marois et al. 2006) and in a three-point dither pattern (Program N134.N2). Our science frames consisted of seventy-four 50 s exposures ($t_{\text{int}} = 0.25$ s, 200 coadds) for a total integration time of 3700 s, covering a field rotation of 45°79. Conditions were photometric with slightly above-average quality seeing (0''4–0''5 in the optical). We obtained shorter, unsaturated images bracketing our science data by realigning each coadd within the cube, removing off-axis signal with only weak algorithm self-subtraction—i.e., a large rotation gap equal to the PSF core width ($\delta = 1$), a high SVD cutoff ($\text{SVDlim} = 10^{-3}$), and a large optimization area from which we determine the LOCI coefficients ($N_A = 1000$ PSF footprints).

3. DETECTION OF THE HD 141569A RESIDUAL INNER DISK

Figure 1 shows the reduced, combined Keck/NIRC2 image with a nominal image stretch (top left), a higher dynamic range (top right), and box-car smoothed to better reveal low-intensity extended emission (lower left) along with the VLT/NaCo image (lower right). The Keck image identifies a bright torus-shaped emission, largely on the west side, between 0''25 and 0''55: a feature recovered by the NaCo data. Our data do not recover the nested debris-like rings nor the extended halo (Konishi et al. 2016). However, the newly identified inner disk appears to have a similar north–south orientation and inclination.

The data reveal a bright peak at a separation of $r \approx 0''28$ (32 au) on the south side (top right panel) that appears point-source-like with a brightness (subtracted from the surrounding disk) comparable to that expected for a 5 Myr old, 5–6 $M_J$ planet (Baraffe et al. 2003). However, dust scattering properties may also explain this peak (see Section 4). “Hook”-like features extend from both disk ansae and are especially visible on the south side in the smoothed image, somewhat similar to the thermal IR-bright arm in HD 100546’s disk (Currie et al. 2014c).

To conservatively define the signal-to-noise ratio per resolution element (SNRE), we replace each pixel with the sum of values enclosed by an FWHM-wide aperture, estimate the radial noise profile of this summed image, and divide the summed image by the noise profile. This procedure yields SNRE $\sim$4–6 along the visible trace of the disk in the NIRC2 image between $r \sim 0''27$ and 0''55 and slightly lower SNRE at these separations in the NaCo image.

From inspection, the disk signal and its self-subtraction footprints, not residual speckles, dominate the pixels at $r \sim 0''27$–0''55, thereby biasing the estimate of the noise profile and yielding an underestimated disk SNRE (see also Thalmann et al. 2014; Currie et al. 2015a). Masking a rectangular “evaluation region” with dimensions 0''54 by 1''08 centered on the star and defining the radial noise profile from pixels outside this region, we derive a disk SNRE in the Keck image to $\sim$8–10 at most separations. The “hook”-like (spiral?) features are likewise statistically significant (SNRE $\sim$3–5). We nominally adopt the former (hereafter “conservative” SNRE) estimate in our disk geometry analysis (Section 4.1) and use the latter (hereafter “optimistic” SNRE) as our starting point for our disk scattered-light forward modeling (Section 4.2), although these choices do not consequentially affect our results.

4. ANALYSIS

To derive the HD 141569A inner disk geometry, we follow the same approach used for analyzing HD 115600’s disk (Currie et al. 2015b). First, we derive the disk’s basic geometry from ellipse fitting. Second, we use forward modeling to fine-tune these properties and calculate second-order properties of the disk (e.g., scattering function), assuming that we are seeing optically thin, scattered-light emission. We focus our analysis on the higher-quality Keck/NIRC2 data.

4.1. Geometry

From the IDL mpfitellipse package, we first define a trace of the disk, where the pixels are weighted by their conservative SNRE. Second, we constructed a grid of ellipse parameters around the best-fit set determined by mpfitellipse, calculating a value using the “maximum merit” procedure (Thalmann et al. 2011). We repeat this step using different ranges in radii and different cutoffs in SNRE for the disk trace (e.g., SNR > 3, and followed steps outlined in Currie et al. 2014b). As in Currie et al. (2011), we registered each image to a common center using a cross-correlation approach.

We performed PSF subtraction using the A-LOCI pipeline (Currie et al. 2014c), an extension and modification of the original locally optimized combination of images algorithm (Laflènire et al. 2007). We use a moving pixel mask (Currie et al. 2012) to reduce and normalize throughput, as well as a singular value decomposition (SVD) cutoff (Marois et al. 2010; Currie et al. 2014c), and speckle filtering/frame selection to reduce errors propagating through the matrix inversion and prevent the solutions from being overdetermined. We adopted conservative settings proven successful for detecting a bright off-axis signal with only weak algorithm self-subtraction (Currie et al. 2015a, 2015b)—i.e., a large rotation gap equal to the PSF core width ($\delta = 1$), a high SVD cutoff ($\text{SVDlim} = 10^{-3}$), and a large optimization area from which we determine the LOCI coefficients ($N_A = 1000$ PSF footprints).

$^{12}$ The high $L'$ sky background likely precludes detecting the low surface brightness outer two rings. We do not detect the inner disk in existing conventional AO near-IR data because of their low Strehl ratios.
5; \(r = 0''25-0''5, 0''25-0''55\) to define best-estimated values and associated uncertainties.

The disk geometry generally agrees well with the most precise estimates for the outer disks’ geometry (Konishi et al. 2016; Mazoyer et al. 2016). We derive a best-fit position angle of \(\text{PA} = -1.2 \pm 2.4\). While we derive an inclination of \(i = 56^\circ \pm 4^\circ\) considering the mean value of all estimates, a large subset of solutions center around 60°. The disk semimajor/minor axes are \(r_\text{osc} = 25, 36.9, 39.1, 41.3\) and \(r_\text{osc} = 0''189 \pm 0''010 (21.9 \pm 0.2\) au), respectively. The projected disk center is offset from the star is \(\Delta x, \Delta y = -0''044 \pm 0''016 (6.1 \pm 1.3\) au), \(0''014 \pm 0''010 (1.6 \pm 1.1\) au).

### 4.2. Disk Forward Modeling

To infer additional disk properties, we generate a grid of synthetic scattered-light images using GRaTeR (Augereau et al. 1999) and forward-model these synthetic disks through A-LOCI to compare the processed model disk image with the real disk image (Esposito et al. 2014).

#### Table 1

| Parameter | Model Range | Best-fit Model | Well-fitting Models |
|-----------|-------------|----------------|---------------------|
| **Fixed values** | | | |
| PA | -1° | | |
| \(r_\text{osc} (\text{au})\) | 25, 36.9, 39.1, 41.3 | 39.1 | 39.1-41.3 |
| \(\Delta x (\text{au})\) | 4.3, 6.1, 7.9 | 7.9 | 4.3-7.9 |
| \(\Delta y (\text{au})\) | 0.5, 1.6, 2.7 | 0.5 | 0.5-1.6 |
| \(\alpha_{\text{in}}\) | 1, 2.5, 5, 10 | 5 | 1-10 |
| \(\alpha_{\text{out}}\) | -2.5, -5, -10 | -10 | -5 to -10 |
| \(g\) | 0, 0.1, 0.2 | 0 | 0-0.1 |
| \(k_{\text{iso}} (\text{au})\) | 3, 5 | 5 | 3-5 |

**Note.** Range of best-fit and well-fitting model parameters as determined by our \(\chi^2\) criterion (see Section 4).

Table 1 summarizes the model parameter space. For simplicity, we adopt the position angle determined from our ellipse modeling (–1°2). We consider a nominal inclination of

![Figure 1. Detection of the HD 141569A inner disk: (top left) Keck/NIR2 image with a nominal color stretch (the star’s position is identified as a cross), (top right) a less aggressive color stretch, showing a point-source-like disk bright peak at \(r \approx 0''28\), (bottom left) box-car smoothed image with a hard color stretch, more clearly showing the “hooks” of emission (H1/2), and (bottom right) VLT/NaCo image recovering the main disk and the “hook”-like features. The scale (horizontal bars) is in raw counts.](image-url)
56° and an inclination of 60° favored by a subset of our ellipse-fitting results. We tuned our parameter search to focus on addressing specific questions about the HD 141569A morphology. First, to assess whether the disk (made visible by small, scattering dust grains) coincides with the gas distribution or is radially segregated, we consider photocenters of 36.9, 39.1, and 41.3 au (consistent with our ellipse modeling) and a photocenter at 25 au: roughly, the separation corresponding to the half-maximum of the CO gas (Goto et al. 2006). Second, we assess whether the emission originates from a sharp debris ring with a steep drop in density away from the disk photocenter (in a, out a = −10, −10, ro = 39.1 au, PA = −1°2, i = 56°, ksi o = 5 au (χ 2 = 1)) or a dust torus (not a sharp ring) with an intermediate power-law decay at separations interior to the photocenter (α in = 2.5–5; see Augereau et al. 1999 for definitions). We consider power-law decays exterior to the disk photocenter of α out = −2.5 to −10, varying Henyey–Greenstein scattering parameters g (0–0.2), the disk offsets from the star in both x and y, and disk scale heights (ksi o = 3–5 au).

To identify the best-fitting disk models, we closely follow the methods from Thalmann et al. (2014). Briefly, we bin down the Keck image, the model image, and the noise profile to the Keck/NIRC2 spatial resolution to compare the data and model at effectively independent data points and compute χ 2 from the residuals of the binned image over the angular separation where the disk detection is significant and negligibly contaminated by residual speckles (r ~ 0°27–0°55). As noted in Section 3, determining a radial noise profile (and thus a robust SNRE for the disk) is extremely difficult due to biasing from the disk and self-subtraction footprints, impeding our ability to quantify a
Figure 4. Different circumstellar dust and gas components of HD 141569A (after Pérucaud et al. 2014): the two outer rings of dust first resolved by HST, the inner torus of dust (this work), extended 10–20 μm emission (Fisher et al. 2000; Marsh et al. 2002), the inner dust halo (Konishi et al. 2016), and multiple reservoirs of CO gas.

A robust estimate of the absolute goodness of fit for the models. Thus, we iteratively rescale the radial noise profile from the "optimistic" SNR map such that the best-fitting model has $\chi_2^2 = 1$ and focus simply on the family of best-fitting models: i.e., those fulfilling $\chi^2 \leq \chi_{\text{min}}^2 + \sqrt{2 \times N_{\text{datamod}}}$ (Thalmann et al. 2013), which for our case implies $\chi_2^2 \leq 1.124$.

The best-fit model accurately reproduces the disk morphology (Figure 2) and, when subtracted from the Keck image, nulls its signal, including the point-source-like peak, but leaves the hook-like features largely intact (SNR $\sim 3.5$–4.5 in the residual image). The integrated signal of the best-fit model is $\approx 20$ mJy. Its surface brightness along the major axis (i.e., the model shown in the top left panel prior to signal loss from PSF subtraction) ranges from $\approx 7.5$ mag arcsec$^{-2}$ at the photocenter (39 au) to $\approx 10$ mag arcsec$^{-2}$ at the widest separations where it is detected robustly ($r \sim 0''55$).

We can decisively rule out some model phase space and identify key trends. First, models with a photocenter of $r = 25$ au (or, by extension, at smaller separations) are inconsistent with the data, yielding especially high residuals on the south side (Figure 2, middle panels). Models with $\alpha_{\text{out}} = -2.5$ are ruled out: the disk requires a sharp density cutoff exterior to the photocenter. The dust is also likely (near-) neutral scattering.

While our analysis does not formally preclude models with weak depletion interior to the photocenter ($\alpha_{\text{in}} = 1$), even the best fit of these models (right panels) is marginally acceptable, yielding clearly higher residuals. The $\chi_2^2$ distribution for $\alpha_{\text{in}} = 2.5$–5 is systematically skewed toward smaller values, indicating a better fit: models with these power laws dominate the family of best-fitting solutions. Thus, our disk modeling favors a torus of neutral scattering dust at $\approx 36$–41 au with sharp truncation at larger disk radii and significant depletion at smaller radii. This material largely lies outside the CO gas concentrated at 11–25 au.

4.3. Limits on Planets

To place limits on the presence of unseen planets that may be perturbing the inner disk, we reprocess the data using aggressive A-LOCI settings (e.g., $\delta = 0.5$). We determine the throughput loss-corrected radial noise profile (Lafrenière et al. 2007; Marois et al. 2008). The Baraffe et al. (2003) hot-start evolutionary models allowed us to map between $L'$ brightness and planet mass.

While previous analysis suggests that HD 141569A is $\sim 5 \pm 3$ Myr old, we reinvestigated its age, comparing the HR diagram positions of the primary to Dotter et al. (2008) models. HD 141569A appears too low in luminosity to be consistent with a 5 Myr age. It’s placement on an HR diagram implies an age between 6 Myr and the zero-age main sequence (starting at $\approx 10$ Myr). For our planet mass limits, we consider the nominal age and an older, revised age of 7.5 Myr.13

At $r = 0''25$–0''5 (29–45 au), the azimuthally averaged sensitivity limit is roughly 7.5–10 $M_J$ (Figure 3), shallow since the disk’s bright signal substantially drives up the residual noise estimate. Exterior to the inner disk, our sensitivity curve excludes planets with masses of $2$–$3.5$ $M_J$ ($3$–$4$ $M_J$) at projected separations of 60–120 au assuming an age of 5 (7.5) Myr. If the planet luminosity evolution is better described by a cold start model, our mass limits are significantly poorer.

5. DISCUSSION

Figure 4 depicts an updated schematic of the complex HD 141569A circumstellar environment. The system now includes three scattered-light-resolved, concentric rings/torii of material spanning between 25 and 500 au, a halo of small dust emission located between the innermost and middle ring, and significant localized structure in the middle and outermost rings plus multiple (candidate) spirals/hooks in all three rings indicative of perturbations by stellar/substellar companions (this work; - Konishi et al. 2016; Mazoyer et al. 2016). Interspersed between these dust components are multiple gas reservoirs (Goto et al. 2006; Thi et al. 2014).

Furthermore, the inner disk dust and gas are likely not well mixed: dust is concentrated in a torus with a larger radius than the CO gas and is likely heavily depleted at smaller separations, implying that its dust cavity is larger than the gas cavity. Recent analysis of ALMA data by van der Marel et al. (2015, 2016) likewise provides strong evidence for radial

13 Conversely, the placement of the M star companions on the HR diagram implies a younger age. The discrepancies of pre-main-sequence tracks at high versus low masses is beyond the scope of this paper.
negligible accretion, is optically thin in the mid-infrared. Analyzed are generally massive, optically thick in the mid-infrared, and more depleted than gas cavities. However, the disks they dust cavities up to three $\mu$m, is well mixed with the gas. However, as the gas density drops, smaller grains such dust is well mixed with the gas. However, as the gas density drops, smaller grains more easily probed by scattered-light observations) decouple from the gas. The 4–20 $\mu$m dust particles, accessible by our observations, are indeed (marginally) decoupled from the gas (St $\sim 0.1–1$), the gas surface density should be of the order $\approx 0.004$ g cm$^{-2}$, assuming porous grains (1.25 g cm$^{-3}$). This is consistent with the gas number density found by Thi et al. (2014; 10$^{-21}$ cm$^{-2}$). Under the influence of radiation pressure, dust grains of these sizes in optically thin disks can be pushed outward and form ring/torus-like structures (Takeuchi & Artymowicz 2001).

The morphology of the newly discovered inner disk as probed by larger grains could be more striking. Since longer wavelength observations better probe large grains, the disk’s presence could be recovered and its structure clarified by high spatial resolution millimeter interferometry. Its measured submillimeter dust continuum emission (8.2 mJy; Flaherty et al. 2016) is easily within detectability with ALMA; mid-IR interferometry with VLTI/Matisse may also resolve its emission at high resolution.

We thank Scott Kenyon and Mengshu Xu for helpful comments. C.A.G. is supported under the NASA Origins of Solar Systems program NNG13PB64P. We wish to emphasize the pivotal cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the privilege to conduct scientific observations from this mountain.

REFERENCES

Aarnio, A., Weinberger, A. J., Stassun, K., et al. 2008, AJ, 136, 2483
Augereau, J. C., Lagrange, A.-M., Mouillet, D., et al. 1999, A&A, 348, 557
Baraffe, I., Chabrier, G., Barman, T. S., et al. 2003, A&A, 402, 701
Billot, B., Liu, M. C., Rice, K., et al. 2015, MNRAS, 450, 4446
Birnstiel, T., Dullemond, C., & Brauer, F. 2001, A&A, 513, 79
Clayton, M., Krist, J. E., Ardila, D. R., et al. 2003, AJ, 126, 385
Cloutier, R., Currie, T., Rieke, G. H., et al. 2014, ApJ, 796, 127
Currie, T., Burrows, A., Girard, J., et al. 2014a, ApJ, 795, 133
Currie, T., Burrows, A., Itoh, Y., et al. 2011, ApJ, 729, 128
Currie, T., Cloutier, R., Brittain, S., et al. 2015a, ApJL, 814, L27
Currie, T., Daemgen, S., Debes, J., et al. 2014b, ApJL, 780, L30
Currie, T., Debes, J., Rodigas, T., et al. 2012, ApJL, 760, L32
Currie, T., Lisse, C. M., Kuchner, M. J., et al. 2015b, ApJL, 807, L7
Currie, T., Muto, T., Kudo, T., et al. 2014c, ApJL, 796, L30
Dorot, A., Chaboyer, B., Jevremovic, D., et al. 2008, ApJS, 178, 89
Esposito, T., Fitzgerald, M., Graham, J., & Kalas, P. 2014, ApJ, 780, 25
Fisher, R. S., Telesco, C. M., Pina, R. K., et al. 2000, ApJL, 523, L141
Flaherty, K., Hughes, A. M., Andrews, S., et al. 2016, ApJ, 818, 97
Goto, M., Usuda, T., Dullemond, C. P., et al. 2006, ApJ, 652, 758
Grady, C. A., Muto, T., Hashimoto, J., et al. 2013, ApJ, 762, 48
Janson, M., Brandt, T. D., Moro-Martin, A., et al. 2013, ApJ, 773, 73
Kenyon, S., & Bromley, B. 2008, ApJS, 179, 451
Konishi, M., Grady, C., Schneider, G., et al. 2016, ApJL, submitted
Kraus, A., & Ireland, M. 2012, ApJ, 745, 5
Lafrenière, D., Marois, C., Duquennoy, R., et al. 2007, ApJ, 660, 770
Marois, C., Lafrenière, D., Duquennoy, R., et al. 2006, ApJ, 641, 556
Marois, C., Macintosh, B., Barman, T., et al. 2008, Science, 322, 1348
Marois, C., Macintosh, B., & Veran, J.-P. 2010, Proc. SPIE, 7736, 1
Marsh, K. A., Silverstone, M. D., Becklin, E. E., et al. 2002, ApJ, 573, 425
Mazoyer, J., Boccaletti, A., Choquet, E., et al. 2016, ApJ, in press (arXiv:1601.00505)
Mouillet, D., Lagrange, A.-M., Augereau, J.-C., & Menard, F. 2001, A&A, 372, L61
Périaux, J., Di Falco, E., Dufrey, A., et al. 2014, in Proc. Conf. Thirty Years of Beta Pic and Debris Disks Studies, ed. L. Anne-Marie, & B. Anthony
Pinilla, P., Benisty, M., & Birnstiel, T. 2012, A&A, 545, 81
Takeuchi, T., & Artymowicz, P. 2001, ApJ, 557, 990
Thalmann, C., Janson, M., Buenzli, E., et al. 2011, ApJL, 743, L6
Thalmann, C., Janson, M., Buenzli, E., et al. 2013, ApJL, 763, L29
Thalmann, C., Mulders, G., Hodapp, K., et al. 2014, A&A, 566, 51
Thi, W.-F., Pinte, C., Panin, E., et al. 2014, A&A, 561, 50
van der Marel, N., van Dishoeck, E. F., Bruderer, S., et al. 2013, Science, 340, 1199
van der Marel, N., van Dishoeck, E. F., Bruderer, S., et al. 2015, A&A, 579, 106
van der Marel, N., van Dishoeck, E. F., Bruderer, S., et al. 2016, A&A, 585, 58
van Leeuwen, F. 2007, A&A, 474, 653
Weidenschilling, S. W. 1977, MNRAS, 180, 57
Weinberger, A. J., Becklin, E. E., Schneider, G., et al. 1999, ApJL, 525, L53
Weinberger, A. J., Rich, R. M., Becklin, E. E., et al. 2000, ApJ, 544, 937
Williams, J. P., & Cieza, L. 2011, ARA&A, 49, 67
Wyatt, M. C. 2005, A&A, 440, 937
Wyatt, M. C. 2008, ARA&A, 46, 339
Yelda, S., Lu, J. R., Clarkson, W., et al. 2010, ApJ, 725, 331
Zuckerman, B., Forveille, T., & Kastner, J. H. 1995, Natur, 373, 494