DIRECT IMAGING AND SPECTROSCOPY OF A YOUNG EXTRASOLAR KUIPER BELT IN THE NEAREST OB ASSOCIATION

Thayne Currie¹, Carey M. Lisse², Marc Kuchner³, Nikku Madhusudhan⁴, Scott J. Kenyon⁵, Christian Thalmann⁶, Joseph Carson⁷, and John Debes⁸

¹National Astronomical Observatory of Japan, Subaru Telescope, Hilo, HI, USA
²Applied Physics Laboratory, The Johns Hopkins University, Laurel, MD, USA
³NASA Goddard Space Flight Center, Greenbelt, MD, USA
⁴Institute for Astronomy, University of Cambridge, Cambridge, UK
⁵Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA
⁶ETH-Zurich, Zurich, Switzerland
⁷Department of Physics and Astronomy, The College of Charleston, Charleston, SC, USA
⁸Space Telescope Science Institute, Baltimore, MD, USA

Received 2015 April 24; accepted 2015 May 16; published 2015 June 26

ABSTRACT

We describe the discovery of a bright, young Kuiper belt–like debris disk around HD 115600, a ~1.4–1.5 \( M_{\odot} \) (~15 Myr old member of the Sco–Cen OB Association. Our H-band coronagraphy/integral field spectroscopy from the Gemini Planet Imager shows the ring has a (luminosity-scaled) semimajor axis of (~22 AU) ~ 48 AU, similar to the current Kuiper belt. The disk appears to have neutral-scattering dust, is eccentric \((e = 0.1–0.2)\), and could be sculpted by analogs to the outer solar system planets. Spectroscopy of the disk ansae reveal a slightly blue to gray disk color, consistent with major Kuiper belt chemical constituents, where water ice is a very plausible dominant constituent. Besides being the first object discovered with the next generation of extreme adaptive optics systems (i.e., SCExAO, GPI, SPHERE), HD 115600’s debris ring and planetary system provide a key reference point for the early evolution of the solar system, the structure, and composition of the Kuiper belt and the interaction between debris disks and planets.

Key words: planetary systems – stars: early-type – stars: individual (HD 115600)

1. INTRODUCTION

Situated just beyond Neptune’s orbit (30–50 AU), the Kuiper belt is home to thousands of remnants of the earliest stages of icy planet formation, is the location of numerous dwarf planets such as Pluto, and provides keys to understanding the early, unevolved solar system (Jewitt & Luu 1992). Cold debris rings around nearby, young stars offer a critical reference for the Kuiper belt’s evolution and composition (Kenyon & Bromley 2008; Wyatt 2008). However, the few such rings imaged in scattered light surround stars at stellocentric distances farther than the Kuiper belt (e.g., Kalas et al. 2005; Schneider et al. 2009; Krist et al. 2012), are not located in massive OB association resembling the solar system’s likely birth environment (Adams 2010), and lack spatially resolved scattered-light spectroscopy to explore composition.

HD 115600 (\( d = 110.5 \) pc; van Leeuwen 2007) is a 1.4 \( M_{\odot} \), F2V/F3V 15 Myr old member of the Lower Centaurus Crux region of the Sco–Cen OB Association (Pecaut et al. 2012). The star has a large infrared excess with a dust mass and fractional luminosity (0.05 \( M_{\text{gas}} \) \( L_{\text{IR}}/L_{\odot} \sim 1.7 \times 10^{-3} \)) comparable to the well-known luminous, resolved ring around HR 4796A (Jura et al. 1998; Chen et al. 2011, 2014). Thus, HD 115600 is a promising target for high-contrast imaging.

We report the discovery of a bright debris ring around HD 115600 using integral field spectroscopy from the Gemini Planet Imager (Macintosh et al. 2014). The ring is plausibly sculpted by an unseen solar system–like planet, surrounds the star at a Kuiper belt–like distance, and has a spectrum consistent with major Kuiper belt constituents. The HD 115600 planetary system provides a valuable reference point for the early evolution and composition of the solar system, the structure of the early Kuiper belt, and the interaction between debris disks and planets.

2. OBSERVATIONS AND DATA REDUCTION

We obtained integral field spectroscopy of HD 115600 on 2014 March 23 with the Gemini Planet Imager (Macintosh et al. 2014) in the H band (\( \lambda_{\text{c}} = 1.6 \mu\text{m}, R = 44–49; 0′014 \) pixel\(^{-1}\) behind the apodized pupil lyot coronagraph \((r_{\text{mask}} \sim 0′12)\) and in angular differential imaging mode (Marois et al. 2006). Our observations consisted of 58 co-added 49.5 s frames, yielding a total integration time of \( \sim 48 \) minutes and a field rotation of \( 29′′ \) (3\( \lambda/\delta D \) at 0′125). Xe and Ar lamp observations provided wavelength calibration.

We carried out basic data reduction using the Gemini Data Reduction Pipeline, version 1.2.1 (Perrin et al. 2014). We modified the software, adding image registration steps as in Currie et al. (2011). Removing the middle 20 data cubes, which exhibited a pupil stop misalignment, and those with poorer AO correction reduced our total integration time to 28 minutes.

For point-spread function (PSF) subtraction, we used A-LOCI (Currie et al. 2012, 2014c) tuned to “conservative” settings (Thalmann et al. 2011) better suited for recovering extended emission, imposing a rotation gap criterion of \( \delta = 1.5 \), an optimization area of \( N_{A} = 1000 \), and a singular value decomposition (SVD) cutoff of \( \text{SVD}_{\text{min}} = 10^{-5} \) (see Lafrenière et al. 2007; Currie et al. 2014b). We construct a final data cube from a median combination of PSF-subtracted cubes and a band-averaged image by wavelength-collapsing the final cube.

---

¹ Masses and ages were derived using the Baraffe et al. (2015) isochrones. Slightly higher masses with the same 15 Myr age are also consistent (e.g., 1.5 \( M_{\odot} \); Pecaut et al. 2012).
using an outlier-resistant mean. Due to the small number of data cubes, we did not employ speckle filtering (Currie et al. 2012, 2014b) to truncate the set of reference PSFs. For initial flux calibration, we measured the average, background-subtracted signal of the four satellite spots (transmission = $2.035 \times 10^{-4}$) in an 8 pixel diameter aperture and divided the data cube by a normalized F2V spectrum (Pickles 1998).

3. DETECTION OF THE HD 115600 DEBRIS DISK

Figure 1 (top panels) displays our wavelength-collapsed disk image and an individual channel, clearly revealing a bright, thick debris ring visible from $r \sim 0''25$ to $r \sim 0''55$ and viewed close to edge-on. The disk ansae along the major axis extend from $r \sim 0''34$ to $0''5$, or $37.5$ to $55$ AU, comparable to the current Kuiper belt. Both sides of the disk are visible, ruling out strong forward-scattering anisotropy. The disk is offset from the star position and visually resembles a puffier version of the HR 4796 A disk (Debes et al. 2008; Schneider et al. 2009).

To estimate the disk’s signal-to-noise ratio (S/N) in the collapsed image and in each spectral channel, we consider two methods. First, for the collapsed image, we construct an S/N map as in Currie et al. (2011), replacing each pixel with the sum of values enclosed by a 3 pixel aperture ($\sim 1$ FWHM) and computing the robust standard deviation at each angular separation. For a given region of the disk, this procedure considers other disk regions (e.g., those on the opposite side) and negative self-subtraction residuals as “noise,” which leads to underestimating the significance of the disk signal compared to real residual speckle noise. Nevertheless, the disk ansae in the collapsed image are still detected at S/N $\sim 8$; the disk’s signal exceeds $2\sigma$ exterior to $r \sim 0''25$.

Second, we compute the ansae S/N in each spectral channel, defining the noise likewise as the robust standard deviation of the summed image in an FWHM-wide arc at the same angular separation ($10$–$50$ pixels away) chosen to avoid the disk signal and negative self-subtraction footprints. The S/N in each spectral channel in the disk ansae ranges between 5 and 8; the S/N of the collapsed image exceeds 10 in the ansae.

4. ANALYSIS

To derive the disk geometry and extract spectra, we follow a three-step approach. First, we derive the debris ring’s basic geometry from the wavelength-collapsed data cube using ellipse fitting. Second, we use forward-modeling to fine-tune these properties and calculate second-order properties of the disk (e.g., scattering function). Third, we extract the disk’s spectrum in the bright ansa regions, using the best-fit model to
Table 1: Debris Disk Forward Modeling

| Parameter | Model Range | Best-fit Model | Well-fitting Models |
|-----------|-------------|----------------|---------------------|
| \( r_e \) (AU) | 47-48 | 48 | 47-48 |
| \( e \) | 0-0.3 | 0.2 | 0.1-0.2 |
| \( \alpha_{\text{in}} \) | 7.5-10 | 7.5 | 7.5-10 |
| \( \alpha_{\text{out}} \) | -5 to -7.5 | -7.5 | -5 to -7.5 |
| \( \Delta y \) (AU) | 0-1 | 1 | 0-1 |
| \( g \) | 0-0.15 | 0 | 0 |
| \( \text{ksi}_e \) (AU) | 1-5 | 3 | 1-5 |

Note. We define the “best-fit” model as the one minimizing \( \chi^2 \) over \( i \)-convolved pixels where \( \chi^2 = \sum (\text{model-image})^2 \sigma^2 \).

The final data cube to calibrate the disk throughput in each spectral channel.

4.1. Geometry

To determine the basic geometry of the disk—including inclination, position angle, semimajor/minor axes, and disk center—we first used the IDL mpfitellips package to determine an approximate trace of the disk, where the pixels are weighted by their S/N. Second, we constructed a grid of ellipse parameters around the best-fit set determined by mpfitellips, and we calculated a more robust best-fit value using the “maximum merit” procedure, identifying the ellipse parameters that maximized the disk signal along the trace of the ellipse (Thalmann et al. 2011). We repeat this step using different ranges in radii and different cutoffs in S/N for the disk trace (e.g., S/N > 1.5, 2; \( r = 17.5-45 \), 20-40 pixels) to define best-estimated values and associated uncertainties.

We derive a best-fit position angle and inclination of \( \text{PA} = 24^0 \pm 0.5 \) and \( i = 79^0.5 \pm 0.5 \) (1\( \sigma \) errors). The disk semimajor/minor axes are \( r_{\text{major/minor}} = 0^0.425 \pm 0^0.010 \) (~48 ± 1.1 AU), \( 0^0.077 \pm 0^0.007 \) (8.5 ± 0.8 AU). The semimajor axis and visible extent of the disk ansae are within the range of radii encompassing the current Kuiper belt; the luminosity-scaled \( (r_{\text{major}}/L_e) \) semimajor axis (extent of the ansae) is ~22 AU (17–25 AU), comparable to the predicted distances of major models of the early, pre-stirred Kuiper belt, e.g., the Nice model (Levison et al. 2008) or Nesvorny (2015). The projected disk center is offset from the star \( \Delta x, \Delta y \) = \( 0^0.018 \pm 0^0.008 \), \( 0^0.029 \pm 0^0.014 \) (Figure 1; diamonds), and the peak signal of the two ansae differs by ~0.5 pixel in angular separation (~1 AU).

4.2. Disk Forward Modeling

To infer additional disk properties, we generate a grid of synthetic scattered-light images using the GRaTeR code (Augereau et al. 1999) and forward-model these synthetic disks using our pipeline to compare the processed synthetic disk image with the real disk image in each spectral channel, extending to integral field spectroscopy methods that have been applied to broadband imaging data (Esposito et al. 2014; Mazoyer et al. 2014). We insert a disk model into a sequence of empty data cubes with position angles identical to those of our science sequence and convolve the model in each spectral channel with the appropriately sized PSF. We performed PSF subtraction on the cubes containing the model disk using the same A-LOCI coefficients that were applied to the real data.

Table 1 describes the model parameter space we explore and our results. To reduce the dimensionality of our forward-modeling, we adopt the inclination and position angle determined from our ellipse modeling (79°.5 and 24°, respectively). We defined the argument of the pericenter to be [90, 270°], or 90° from the visible disk major axis: departures from these values resulted in brightness asymmetries between the disk ansae inconsistent with the data. We varied other parameters, including the the ring center (\( \alpha_{\text{in}} = 47 \) and 48 AU), the Henyey–Greenstein scattering parameter \( g \) (0–0.15), the disk scale height at the disk center (\( \text{ksi}_e = 1–5 \) AU), the density power laws describing the decay of ring emission away from the ring center (\( \alpha_{\text{in}} = 7.5 \), 10; \( \alpha_{\text{out}} = -5 \), -7.5), the disk eccentricity (0–0.3), and the offset along the major axis (0 and 1 AU). While our parameter space search is not exhaustive, values outside these ranges (e.g., \( g > 0.15 \)) yielded processed synthetic disk images strongly discrepant with the real data.

To match the observed brightness in each spectral channel, we fix the parameters in the model, scale the flux, and define the fit of the model to the data using the real and synthetic collapsed images convolved by the PSF as in our S/N calculations. Our “acceptably fitting” models are those fulfilling \( \chi^2 < \chi^2_{\text{min}} + \chi^2 \times N_{\text{data}} \) (Thalmann et al. 2013). We perform our optimization (and define \( \chi^2 \)) by the visible trace of the disk at separations where it is consistently visible at S/N > 2 along both sides (~0.028 and 0.052).

The best-fit model is an offset, eccentric ring with neutral-scattering dust (Figure 1, bottom panels). This model exhibits some discrepancies with the data, slightly over (predicting the signal on the southeastern (southwestern) side). However, our best-fit model generally reproduces disk shape, providing a good first investigation. More sophisticated models fit to higher S/N data and that explore more parameter space will better constrain disk properties. Additionally, much of our parameter space remains degenerate, admitting widely varying values. However, we strongly prefer models with \( g = 0 \): those with \( g > 0.05 \) predict disk ansae that are too faint compared to regions at small angular separations. Models with \( e < 0.1 \) or \( e = 0.3 \) fail to properly trace the observed disk. A single model with \( e = 0.1 \) fits our \( \chi^2 \) threshold, while all other acceptably fitting models have \( e = 0.2 \), suggesting a disk eccentricity \( (e = 0.1-0.2) \) comparable to that of the most eccentric known debris disks (Kalas et al. 2005; Krist et al. 2012). The deprojected, deconvolved, and azimuthally averaged best-fit disk model has a normalized FWHM of 0.37, among the largest for scattered-light-imaged debris rings (Rodigas et al. 2015).

4.3. Dynamical Sculpting of the Disk: Limits on Planets

Debris disk dynamical modeling sets stronger limits on unseen planets than from the GPI contrasts limits alone (contrast >10^-5 at \( r < 0.6^4 \) (44 AU) or \( M_{\text{planet}} > 7 M_J \); cf. Baraffe et al. 2003). The eccentric ring is plausibly due to dynamical perturbations from an unseen planet, which can open a gap in the disk and stir it via secular perturbations. In both cases, the planet’s eccentricity can be estimated assuming that the eccentricity of the ring equals the local value of the forced eccentricity (Quillen 2006). First, we place limits on the properties of the planet, sculpting the disk from the Nesvold & Kuchner (2015) gap opening model, where the planetsimals are initially dynamically hot (0.0 < \( e < 0.2 \)) and the planet interacts with the disk via mean-motion resonances, triggering
collisions and producing an inner hole. Gap opening depends on the system age in units of the grain collisional time, which in turn depends on the orbital period and optical depth: \( t_{\text{col}}/(4\pi r^2) \).

Second, we explore the Mustill & Wyatt (2009) planet stirring model; the planet stirs an initially cold disk from the inside-out via secular interactions, and the radius of the central hole extends to where planetesimal orbits begin to cross. We compute stirring from first-order secular theory (valid for low planet eccentricities), corresponding here to larger planet semimajor axes. Our two calculations assume 48 AU as the planet eccentricities – that is, \( e = 0.2 \) (e.g., a Saturn with \( e = 0.2 \)). In both cases, super-Earths just interior to the ring edge could sculpt the ring.

4.4. Spectral Analysis

We perform two spectral extractions. First, we extract the raw spectrum at both disk ansae, identifying the centroid positions from the collapsed image. We then extract the spectrum of the best-fit disk model at these centroid positions. In both cases, we measure the surface brightness: the mean brightness within the same 8 pixel diameter aperture used for flux calibration with errors calculated using method 2 described in Section 3. For the model disk, we average the results from the two ansae and correct for signal loss due to a finite aperture by comparing the surface brightness of the convolved and unconvolved best-fit disk models.

Figure 3(a) shows our extracted best-fit scaled model disk spectrum (blue), averaged raw spectrum (green), and raw spectra extracted for each ansa (dotted lines). The spectra have a relatively flat to slightly blue slope across the H band. Spectra extracted from the two ansae exhibit strong agreement.

The debris disk’s scattered-light spectral shape is sensitive to its dust’s composition. Instead of using advanced methods (e.g., Lisse et al. 2007), we model the reflectance of dust using simple Mie theory-based single constituents found among dust and large bodies in the Kuiper belt—carbonaceous dust, amorphous silicates, and water ice—drawn from Lisse et al. (1998), nominally using the best-fit Halley-like particle size distribution (Mazets et al. 1986; Krishna Swamy & Shah 1988) but exploring simple power laws with exponents between \(-3\) and \(-4\). To calculate reflectance, we divide the best-fit model disk’s spectrum by that of a Pickles F2V star.

The raw (black curve) and binned (cyan curve) disk reflectance spectra appear neutral/slightly blue at 1.5–1.75 \( \mu \)m (Figure 3(b)). Reflectance spectra of water ice (blue), amorphous silicates (green), and amorphous carbon (red) show differences across the H passband. Water ice (and silicates) with a Halley-like size distribution provide the best match, reproducing the spectrum’s neutral/blue slope. Amorphous carbon has a \( x^2 \) value 2.5 times higher than water ice’s and is marginally disfavored (at the 68% confidence limit) for the binned spectrum, having a goodness-of-fit statistic of 0.78. However, adopting a simple power-law exponent for the particle size distribution between \(-3\) and \(-4\), a subset of models from each species likewise fit. Thus, our spectrum’s large error bars and narrow wavelength range currently preclude us from making definitive statements about the dust composition.

Comparing the H-band spectrum with thermal IR data and properties of other debris rings may better reveal evidence for ice. HD 115600’s thermal disk emission (Figure 3(c)) peaks at 115 K, but blackbody-like emission should be located at 13 AU, not the observed 48 AU. Real dust around stars later than A0 should be located at increasingly larger distances than predicted by blackbody emission, over 2.5 times farther for an F2 star (see Figure 10 in Booth et al. 2013) or beyond 33 AU in HD 115600’s case. Steeper size distributions and sub-blowout dust sizes (expected for a collisionally active disk) may be sufficient to yield dust around HD 115600 at the right distances. However, organics (carbon) dominated dust yields dust locations an additional factor of four to eight larger than predicted by blackbody emission; ice and ice/silicate mixtures yield negligible enhancement (Figure 12 in Booth et al. 2013). A water-ice (dominating scattered light) and organics (dominating thermal emission) mixture, much like that found on Kuiper belt object surfaces, may fit as well.

HR 4796A’s fractional luminosity is over two times higher \((\sim 4.8 \times 10^{-3}; \text{Low et al. 2005; Chen et al. 2011})\). The H-band surface brightness contrast of HD 115600’s disk ansae is \(\sim 1.6 \text{mag} \) brighter than that of HR 4796A (Rodigas et al. 2015). Moving the HR 4796 A ring from 70 AU to HD 115600’s disk location (48 AU) still results in scattered-light emission about half as bright as HD 115600’s disk. Thus, HD 115600’s disk is reflecting light more efficiently than HR 4796A’s disk while having less thermal emission, a result explicable if HD 115600’s disk is dominated by higher albedo species like water ice. Multi-wavelength photometry/spectroscopy is needed to more decisively assess the composition of HD 115600’s disk.

5. DISCUSSION

HD 115600’s debris ring is the first object discovered using the new generation of extreme adaptive optics instruments (SCExAO, GPI, and SPHERE; Beuzit et al. 2008; Martinache & Guyon 2009; Macintosh et al. 2014) and the first debris ring with spatially resolved integral field spectroscopy. The ring is confined to a Kuiper belt-like stellocentric distance, and its reflectance is consistent with that of major constituents of Kuiper belt bodies and their ejecta, including water ice. As the disk orbits a 15 Myr old star only \(\sim 40\%–50\%\) more massive than the Sun located in the nearest OB association, it provides a
promising reference point for understanding the early evolution and composition of the Kuiper belt.

HD 115600’s disk shows evidence for dynamical sculpting by a solar system–like giant planet. With the exception of β Pic b (Lagrange et al. 2010), fully formed young planets directly imaged thus far have super-Jovian masses (5–10 $M_J$) and orbit at wide separations (15–150 AU; Marois et al. 2008; Kuzuhara et al. 2013; Rameau et al. 2013; Currie et al. 2014a). Southern hemisphere systems GPI and SPHERE could image even lower-mass planets located just interior to HD 115600’s debris ring and super-Jovian planets near their inner working angles ($r \sim 0''.1$–$0''.2$ or $\sim 10$–20 AU). Combining new planet detections/upper limits with more precise estimates of the disk’s properties will make HD 115600 an excellent laboratory for studying planet–disk interactions (Chiang et al. 2009; Rodigas et al. 2014).

We thank the anonymous referee, Wladimir Lyra, Eric Mamajek, and Mengshu Xu for helpful comments; Fredrik Rantakryo for executing these queue-mode observations; and the GPI Early Science Time Allocation Committee and Gemini Director Markus Kissler-Patig for supporting this program.

Figure 3. (top left) Surface brightness of the best-fit model disk spectrum (averaged between ansae). Due to low throughput, we trim the first and last two channels. The raw disk spectrum shows an almost identical shape but consistently ~15% lower signal; spectra extracted from individual ansae (dashed curves) agree within their error bars. (top right) Reflectance spectra of the best-fit model disk and a binned (to the spectral resolution of GPI) version of the best-fit model compared to Mie theory predictions for water ice, amorphous silicates, and amorphous carbon. (bottom) HD 115600’s optical/IR SED (Chen et al. 2014) revealing $115 \pm 6$ K (2$\sigma$) cold dust and favoring an icy/ice-silicate composition (see the main text).

REFERENCES

Adams, F. C. 2010, ARA&A, 48, 47
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
Baraffe, I., Homeier, D., Allard, F., & Chabrier, G. 2015, A&A, 577, A42
Beuzit, J.-L., Feldt, M., Dohlen, K., et al. 2008, Proc. SPIE, 7014, 41
Booth, M., Kennedy, G., Sibthorpe, B., et al. 2013, MNRAS, 428, 1263
Chen, C., Mamajek, E., Bitner, M., et al. 2011, ApJ, 738, 122
Chen, C., Mittal, T., Binner, M., et al. 2014, ApJS, 211, 25
Chiang, E., Kite, E., Kalas, P., et al. 2009, ApJ, 693, 734
Currie, T., Burrows, A., Ith, Y., et al. 2011, ApJ, 729, 128
Currie, T., Burrows, A., Girard, J., et al. 2014b, ApJ, 795, 133
Currie, T., Daemgen, S., Debes, J., et al. 2014a, ApJL, 780, L30
Currie, T., Debes, J., Rodigas, T., et al. 2012, ApJL, 760, L32
Currie, T., Muto, T., Kudo, T., et al. 2014c, ApJL, 796, L30
Debes, J. H., Weinberger, A., & Schneider, G. 2008, ApJL, 673, L191
Esposito, T., Fitzgerald, M., Graham, J., & Kalas, P. 2014, ApJ, 780, 25
Jewitt, D., & Luu, J. 1992, Natur, 362, 730
Jura, M., Malkin, M., White, R. J., et al. 1998, ApJ, 505, 897
Kalas, P., Graham, J. R., & Clampin, M. 2005, Natur, 435, 1067
Kenyon, S., & Bromley, B. 2008, ApJS, 179, 451
Krishna Swamy, K. S., & Shah, G. A. 1988, MNRAS, 233, 573
Krist, J., Stapelfeldt, K., Bryden, G., & Plavchan, P. 2012, AJ, 144, 45
Kuzuhara, M., Tamura, M., Kudo, T., et al. 2013, ApJ, 774, 11
Lafrenière, D., Marois, C., Doyon, R., et al. 2007, ApJ, 660, 770
Lagrange, A.-M., Bonnefoy, M., Chaumian, G., et al. 2010, Sci, 329, 57
Levison, H., Morbidelli, A., van Laerhoven, C., et al. 2008, Icar, 196, 258
Lisse, C. M., A'Hearn, M., Hauser, M. G., et al. 1998, ApJ, 496, 971
Lisse, C. M., Kraemer, K. E., Nuth, J. A., et al. 2007, Icar, 187, 69
Low, F., Smith, B., Werner, M., et al. 2005, ApJ, 631, 1170
Macintosh, B., Graham, I., Ingraham, P., et al. 2014, PNAS, 111, 35
Marois, C., Lafreniere, D., Duport, R., et al. 2006, ApJ, 641, 556
Marois, C., Macintosh, B., Barman, T., et al. 2008, Sci, 322, 1348
Martinache, F., & Guyon, O. 2009, Proc. SPIE, 7440, 0
Mazets, E. P., Aptekar, R., Golenetskii, S. V., et al. 1986, Natur, 321, 276
Mazoyer, J., Boccaletti, A., Augereau, J.-C., et al. 2014, A&A, 569, 29
Mustill, A., & Wyatt, M. 2009, MNRAS, 399, 1403
Nesvold, E., & Kuchner, M. 2015, ApJ, 798, 83
Nesvorny, D. 2015, AJ, in press (arXiv:1504.06021)

Pecaut, M., Mamajek, E., & Bubar, E. 2012, ApJ, 746, 154
Perrin, M., Maire, J., Ingraham, P., et al. 2014, Proc. SPIE, 9147, 3
Pickles, A. 1998, PASP, 110, 863
Quillen, A. 2006, MNRAS, 372, L14
Rameau, J., Chauvin, G., Lagrange, A.-M., et al. 2013, ApJL, 779, L26
Rodigas, T., Malhotra, R., & Hinz, P. 2014, ApJ, 780, 65
Rodigas, T. J., Stark, C., Weinberger, A., et al. 2015, ApJ, 798, 96
Schneider, G., Weinberger, A. J., Becklin, E. E., et al. 2009, AJ, 137, 53
Thalmann, C., Janson, M., Buenzli, E., et al. 2011, ApJL, 743, L6
Thalmann, C., Janson, M., Buenzli, E., et al. 2013, ApJL, 763, L29
van Leeuwen, F. 2007, A&A, 474, 653
Wyatt, M. C. 2008, ARA&A, 46, 339