SPECKLE SUPPRESSION THROUGH DUAL IMAGING POLARIMETRY, AND A GROUND-BASED IMAGE OF THE HR 4796A CIRCUMSTELLAR DISK

SASHA HINKLEY1,2, BEN R. OPPENHEIMER2, RÉMI SOUMMER3, DOUGLAS BRENNER2, JAMES R. GRAHAM4, MARSHALL D. PERRIN5, ANAND SIVARAMAKRISHNAN2,6,7, JAMES P. LLOYDS8, LEWIS C. ROBERTS JR.9, and JEFFREY KUHN10

1 Department of Astronomy, Columbia University, 550 West 120th Street, New York, NY 10027, USA; shinkle@astro.columbia.edu
2 Astrophysics Department, American Museum of Natural History, Central Park West at 79th Street, New York, NY 10024, USA
3 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
4 Department of Astronomy, 601 Campbell Hall, University of California Berkeley, CA 94720, USA
5 NSF Postdoctoral Fellow, UCLA Department of Astronomy, Los Angeles, CA 90095, USA
6 NSF Center for Adaptive Optics, University of California, Santa Cruz, CA 95064, USA
7 Stony Brook University, Stony Brook, NY 11794, USA
8 Department of Astronomy, Cornell University, Ithaca, NY 14853, USA
9 Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena CA 91109, USA
10 Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, Hawaii 96822, USA

Received 2009 March 12; accepted 2009 June 17; published 2009 July 27

ABSTRACT

We demonstrate the versatility of a dual imaging polarimeter working in tandem with a Lyot coronagraph and adaptive optics to suppress the highly static speckle noise pattern—the greatest hindrance to ground-based direct imaging of planets and disks around nearby stars. Using a double difference technique with the polarimetric data, we quantify the level of speckle suppression, and hence improved sensitivity, by placing an ensemble of artificial faint companions into real data, with given total brightness and polarization. For highly polarized sources within 0.5, we show that we achieve 3 to 4 mag greater sensitivity through polarimetric speckle suppression than simply using a coronagraph coupled to a high-order adaptive optics system. Using such a polarimeter with a classical Lyot coronagraph at the 3.63 m Advanced Electro-Optical System telescope, we have obtained a 6.5σ detection in the H band of the 76 AU diameter circumstellar debris disk around the star HR 4796A. Our data represent the first definitive ground-based near-IR polarimetric image of the HR 4796A debris disk and clearly show the two outer ansae of the disk, evident in Hubble Space Telescope NICMOS/STIS imaging. Comparing our peak linearly polarized flux with the total intensity in the lobes as observed by NICMOS, we derive a lower limit to the fractional linear polarization of <29% caused by dust grains in the disk. In addition, we fit simple morphological models of optically thin disks to our data allowing us to constrain the dust disk scale height (2.5σ) and scattering asymmetry parameter (g = ⟨cos θ⟩ = 0.20±0.05). These values are consistent with several lines of evidence suggesting that the HR 4796A disk is dominated by a micron-sized dust population, and are indeed typical of disks in transition between those surrounding the Herbig Ae stars to those associated with Vega-like stars.

Key words: instrumentation: adaptive optics – methods: data analysis – stars: individual (HR 4796A) – techniques: image processing

1. INTRODUCTION

Direct imaging surveys of the close-in (∼1000 AU) environments of nearby stars for companions and circumstellar disks are coming into maturity and returning spectacular results (Lafrenière et al. 2007; Nielsen et al. 2008; Kalas et al. 2008; Marois et al. 2008; Oppenheimer et al. 2008; Macintosh et al. 2008; Metchev & Hillenbrand 2009). Much of the technical effort in high-contrast imaging centers around suppressing the overwhelming luminosity of the host star, and the residual speckle noise, largely caused by uncorrected aberrations in the incoming wave front. This quasi-static source of noise, an especially bad problem for ground-based efforts, is stable for minutes or hours (Hinkley et al. 2007) and is the largest obstacle to direct detection of companions or circumstellar disks (Racine et al. 1999; Sivaramakrishnan et al. 2002; Marois et al. 2003; Soummer et al. 2007). Many authors have suggested useful techniques for direct subtraction of speckle noise through image post processing (Sparks & Ford 2002; Marois et al. 2006; Hinkley et al. 2007). Another technique using a dual-channel imaging polarimeter can extract a polarized signal due to circumstellar material (companions or a disk) from the array of unpolarized speckles (Kuhn et al. 2001; Potter 2003; Perrin et al. 2004; Oppenheimer et al. 2008). The Lyot Project (Oppenheimer et al. 2003, 2004; Sivaramakrishnan et al. 2007) employed this technique in addition to using a very high-order adaptive optics (AO) system (Roberts & Neyman 2002) and a classical Lyot coronagraph working at the diffraction limit (Lyot 1939; Malbet 1996; Sivaramakrishnan et al. 2001).

In this work, we carry out a sensitivity analysis for speckle suppression through polarimetry, and quantify the level of suppression (Section 2). In Section 3, we demonstrate the power of this technique with a detection of the debris disk surrounding the nearby (d = 72.8 ± 1.7 pc), young (8 ± 2 Myr) star HR 4796A (A0 V, V = 5.78 mag; Jura (1991); Koerner et al. (1998); Augereau et al. (1999); Schneider et al. (1999); van Leeuwen (2007)), achieved in the H band from the ground. To our knowledge this is the first high-contrast, near-IR polarimetric image of the the HR 4796A disk obtained from a ground-based observatory. This technique is especially well suited for regions of the image which are heavily dominated by speckle noise. Although circumstellar disk imaging has largely been performed using space-based observatories (Krist et al. 2000; Stapelfeldt et al. 2004; Kalas et al. 2005; Graham et al. 2007), this paper demonstrates the power of speckle suppression and its ability to image circumstellar disks from ground-based observatories.
2. SPECKLE SUPPRESSION THROUGH POLARIMETRIC OBSERVATIONS

The advantages of differential imaging polarimetry for high-contrast observations of circumstellar disks have previously been discussed at length by several authors (Kuhn et al. 2001; Potter 2003; Hales et al. 2006; Perrin et al. 2004, 2008). We briefly repeat here some basic concepts to establish consistency and notation. The polarization of light is usually represented by the Stokes vector \( \mathbf{I} \), \( \mathbf{Q} \), \( \mathbf{U} \), \( \mathbf{V} \). The usual astronomical convention is for the \( +Q \) direction to be oriented north-south, and \( +U \) northeast–southwest, with angles increasing counterclockwise from north to east. Linear polarization can also be expressed in terms of polarized intensity, \( (Q^2 + U^2)^{1/2} \), and position angle \( \theta = \frac{1}{2} \arctan(U/Q) \). The normalized polarized intensity \( (Q^2 + U^2 + V^2)^{1/2} / I \) is referred to as the degree of polarization, polarization fraction, or percent polarization. Notation is not always consistent: some authors use \( P \) to refer to polarized intensity while others use it for degree of polarization. In this work, capital \( I \), \( Q \), \( U \), \( V \), and \( P \) will always refer to intensities (e.g., with units of janskies or Jy arcsec\(^{-2} \)), not normalized quantities. Tinbergen (1996) and Keller (2002) provide excellent introductions to astronomical polarimetry, while Adamson et al. (2005) summarize the recent state of the art.

At its simplest level, a dual-channel differential imaging polarimeter consists of any device that splits an image into two orthogonal polarization states. This is frequently achieved through the use of a Wollaston prism, a two-element birefringent prism which separates an incoming beam into two orthogonal polarization states, while at the same time introducing an angular deflection between the two beams. The project described in this paper used such a configuration. A typical image showing the two displaced fields (left and right) resulting from the beam deflection, and their directions of polarization is shown in Figure 1. A measurement of the Stokes \( Q \) parameter can be obtained through a difference of the left and right channels. Such a subtraction (“Difference: +\( Q \)” in Figure 1) largely eliminates the unpolarized speckle halo common to both left and right channels. However, to eliminate the bulk of the remaining aberrations (aberrations not common to both channels) that persist in this difference image, we obtain a second measurement by modulating the polarization states by 90°. Subtracting these in turn gives a \( -Q \) image. We modulate the polarization through the use of Liquid Crystal Variable Retarders (LCVRs). This \( -Q \) image is obtained by swapping the positions of the polarization states and subtracting the two channels. After the subtraction, any astrophysical object will now possess negative counts in the image, but those non-common path aberrations will have the same sign and spatial characteristics present in the \( +Q \) image. Subtracting the \( -Q \) image from the \( +Q \) image (ideally) eliminates the non-common aberrations, leaving only the astrophysically interesting targets present. Different modulations of the polarization states can be used to obtain Stokes \( U \) and \( V \). Since no photons are lost in this process, the Stokes \( I \) image can be obtained by summing the left and right images of any polarization configuration. A schematic representation of the reduction process for a full polarimetric sequence is shown in Figure 1.

2.1. Observations

Under very good observing conditions on 2005 January 26 UTC at the 3.63 m Advanced Electro-Optical System (AEOS) telescope in Maui, we obtained three \( H \)-band (1.65 \( \mu \)m) coronagraphic polarimetric sequences (+\( Q \), \( -Q \), +\( U \) modes) of the star HR 4796A (Table 1). The data were gathered using the Lyot Project coronagraph (Oppenheimer et al. 2003, 2004; Sivaramakrishnan et al. 2007) and the Kermit infrared camera (Perrin et al. 2003). The coronagraph was a diffraction-limited, classical Lyot coronagraph (Lyot 1939; Malbet 1996) with a 455 mas diameter occulting mask and a hard-edged Lyot stop. The AEOS telescope is an altitude–azimuth design, equipped with an AO system using a 941 actuator deformable mirror Roberts.
& Neyman (2002). The total observing time for this data set was 1080 s, comparable to the 1024 s for the Schneider et al. (1999) F160W Hubble Space Telescope (HST) data. During the observations, the local Fried parameter, \( r_0 \), a measure of the strength of turbulence in the atmosphere above the observatory, spanned the range of 15 to 25 cm, indicating nearly ideal conditions for AO observations at AEOS. Over the course of the observations, we obtained only \( +Q \), \( -Q \), and \( +U \) images because our retarders did not provide sufficient retardance to obtain a \(-U\) image.

The polarimeter implemented in the Lyot Project for the data in this paper was unique in two regards. First, the Wollaston prism was located immediately after the Lyot pupil in the coronagraph. This post-pupil location is the correct location to minimize differential aberrations between the two beams. This setup is an improvement over other polarimeters designed for use in high-contrast imaging, e.g., Perrin et al. (2008). Second, the use of LCVRs as a polarization modulator is relatively rare for night-time polarimetry. The benefits of using LCVRs include a great deal of increased flexibility in modulation, a lack of any image motions induced by rotating optics, and slightly faster modulation (although still not faster than the atmospheric timescales involved). Disadvantages of using retarders of this type include a potentially reduced wavefront quality.

### 2.2. Polarimetric Dynamic Range

Our goal is to quantify the gain in dynamic range achievable using the dual-imaging polarimetry technique. As a reference, we start by illustrating the dynamic range achieved on our Stokes \( I \) images without taking advantage of the polarimetric capabilities. According to a technique we discussed previously (Soummer et al. 2007; Hinkley et al. 2007), we have derived the magnitude difference (dynamic range) between the occulted star and a 5\( \sigma \) point source as a function of position in the Stokes \( I \) images. The residual scattered light outside of our coronagraphic mask, usually in the form of highly persistent speckle noise, is the main limiting factor for detection of a point source (See Section 2.3.1). Local evaluation of the amplitude of this noise in turn determines the minimum brightness required for a 5\( \sigma \) point source detection. A radial curve of this sensitivity is shown in Figure 2 and labelled “Stokes-I Dynamic Range.”

All photometric values in this paper were calibrated to unocculted images of HR 4796A, directly prior to the occulted sequences. The raw data images were calibrated through standard dark current subtraction, application of bad pixel maps, and flat fielding. The flat-field images were acquired using incandescent lamps each night. Also, binary star observations with well known orbits were observed to calibrate the pixel scale and image rotation fiducials. Prior to the subtraction, the images are rotated so that north is up in the image, east is to the left, and registered to each other using a cross correlation with subpixel accuracy. The data reduction technique is discussed in greater detail in Soummer et al. (2006) and Appendix A of Oppenheimer et al. (2008).
can achieve up to 4 mag of improvement over the Stokes $I$ within 0.5. This level of polarimetric suppression is comparable to other AO-based polarimeters (Potter et al. 2000; Perrin et al. 2004, 2008), but results using this particular polarimeter on AEOS benefit from the extremely high-order AO system (Roberts & Neyman 2002), and the optimized coronagraph (Sivaramakrishnan et al. 2001) in the beam path before any of the polarimetry optics.

Modelling point sources are especially useful in the context of the data discussed in the next section, since the HR 4796A disk ansae are very near to point sources. Finding the required polarization for detection in our double-difference technique will thus help us to further constrain the value obtained directly (using published NICMOS Stokes $I$ values) described in Section 3. These calculations using point sources can be directly applied to extended objects with resolved surface brightnesses. We have recasted the sensitivity results in terms of surface brightness (mJy arcsec$^{-2}$), and those values are listed on the right-hand side axes of Figure 2. It should be noted, though, that in Figure 2 the brightness difference values (left-hand side axis) indicate the total brightness of a point source, while the surface brightness (mJy arcsec$^{-2}$) values reflect the brightness of the peak intensity of the point source. Nonetheless, our analysis for point sources translates over to extended sources since the key issue is the overall brightness of the source in comparison to the amplitude of the surrounding noise.

### 2.3.1. Post Speckle Suppression: A Return to the Read Noise Limited Regime

The uncorrected speckle noise in high contrast imaging data is due to highly static aberrations in the incoming wave front that are not corrected by the AO system, or are induced “downstream” from the wave front sensor. Consequently, the resulting speckle noise in the images is highly stable with time. As Hinkley et al. (2007) demonstrate (their Figure 2), since the speckle noise pattern persists with sequential images, simple co-adding of data does not significantly improve the coronagraphic sensitivity, as would be expected for uncorrelated Gaussian-type noise. The speckles must be removed to gain improvements in sensitivity. Marois et al. (2006) have performed speckle subtraction through image post-processing to greatly enhance their dynamic range, while Hinkley et al. (2008) employ an instrument which uses the wavelength dependence of the speckles to disentangle them from a true astrophysical source. In this work, we use a dual-imaging polarimeter to subtract the unpolarized speckle pattern from the images.

Once the highly-static, highly time-correlated, speckle noise has been removed through polarimetry, the resulting noise characteristics in the double difference image are distinctly similar to noise with Gaussian type properties. This is reminiscent of the read noise dominated regime in which speckles are not the dominant source of noise. In this regime, normal Gaussian-like noise properties of the image become applicable, and sensitivity to polarized sources should increase with the square root of exposure time. Indeed, our data show behavior quite close to this. The dashed and solid lines of the polarimetric dynamic range curves shown in Figure 2 show the sensitivity with double and triple the effective exposure time of that represented by the dotted line. If the image noise that dictates the sensitivity is similar to Gaussian type noise, the expected gain in sensitivity is $2.5 \log \sqrt{2} \simeq 0.38$ mag and $2.5 \log \sqrt{3} \simeq 0.60$ mag. In the lower panel, we show the deviation in the curves from this expected gain. These residual curves are within 0.1–0.2 mag of zero, consistent with a noise pattern with largely Gaussian properties. Moreover, the fact the the residual is consistently negative indicates that the speckle noise pattern in nearly, but not quite in the Gaussian regime. This is due to any residual speckle pattern that was not completely subtracted during the double difference process.

### 3. DETECTION OF THE HR4796A DEBRIS DISK

Using the method described in the previous section, we have obtained a modest, yet significant detection of the circumstellar disk around HR 4796A shown in Figure 3. Although the full ringlike structure of the disk is not immediately evident in our image, we clearly detect the two extreme edges of the disk (ansae) at the 6.5σ level above the residual image noise. We measure a position angle of 27.5 ± 2.5, in good agreement with the 27.01 ± 0.16 as measured by Schneider et al. (2009; Table 2). The intensity in linearly polarized light (shown in Figure 3) was determined from our double-difference $Q$ images (described schematically in Figure 1) as well as the trio of Stokes $U$ images to construct a normalized Stokes $P$ image: $P_{\text{linear}} = \sqrt{Q^2 + U^2}/I$. We find a peak polarized flux density on the brighter (north) lobe of 7.4 mJy arcsec$^{-2}$. Comparing this to the published peak brightness (Stokes $I$) from Schneider et al. (1999) of 17 mJy arcsec$^{-2}$, we derive a fractional polarization of 44 ± 5%, comparable to values found in other debris disks, e.g. AU Mic (Graham et al. 2007). Expressing this as the 3σ lower limit, we state that the true polarization is greater than 29%. However, it should be noted these values are only lower limits to the true fractional linear polarization: recent Lyot Project data from the AEOS telescope suggest some Stokes $V$ polarization.
induced by the AEOS telescope (Oppenheimer et al. 2008; Harrington & Kuhn 2008) may be present, reducing the amount of linearly polarized flux in the $Q$ and $U$ modes. Since this particular observing sequence did not have the capabilities to measure Stokes $V$, we present our result merely as a lower limit. Given these issues, along with the relatively small telescope aperture, this is still a significant demonstration of the speckle removal technique.

Shown in Figure 2 is the peak surface brightness (17 mJy arcsec$^{-2}$) of the brighter of the two disk ansae from Schneider et al. (1999). Inspection of the plot suggests this corresponds to a polarization level of 70%, still consistent with our direct lower limit calculation of 44%. However, such a comparison may not be completely valid, as the dynamic range analysis assumed point sources for the sensitivity derivation while the disk ansae are more extended lobes.

### 3.1. Morphological Models

To constrain the nature of the debris disk around HR 4796A, we model optically thin disks assuming a Henyey–Greenstein phase function (Henyey & Greenstein 1941) and a Raleigh-like variation of polarization with scattering angle, which is suitable for disks with small grains or larger grain aggregates (Kimura et al. 2006). The model is a two-dimensional generalization of the one-dimensional model used in Graham et al. (2007), appropriate for a solar system zodiacal Henyey–Greenstein dust model (Hong 1985; Graham et al. 2007). We have chosen to fit for the Henyey–Greenstein scattering asymmetry parameter $g = \langle \cos \theta \rangle$ and the disk scale height. We fit for these two parameters, since both are intrinsically related to the dust structure in the disk, and can most readily be constrained by the polarimetric data. A sample grid of models with scale heights $h_0 = 12$ AU, 25 AU, and 50 AU as well as Henyey–Greenstein parameters $g = 0.0, 0.3$, and 0.6 is shown in Figure 4 to guide the eye. A value $g = 0$ is completely isotropic scattering, while $g = 0.6$ signifies moderately strong forward scattering. A value of $g = 0.3$ is typical of Zodiacal dust and some debris disks. The model assumes a Gaussian vertical density distribution with an adjustable scale height based on the COBE model of zodiacal background light (Kelsall et al. 1998). Using cylindrical coordinates, we adopt the following density structure for the disk,

$$n(r, z) = n_0 \left( \frac{r}{r_0} \right)^\alpha e^{-\beta |z|/h_0} r',$$

with $\alpha = -1.803, \beta = 4.973, \gamma = 1.265$ motivated by Kelsall et al. (1998). We have used the inner and outer radii (69 AU and 83 AU, respectively), inclination (14°:12 from edge on), and position angle (63°:2) from Schneider et al. (2009). Each thumbnail image in Figure 4 was computed using the measured pixel scale of the Lyot Project’s infrared camera (13.5 mas pixel$^{-1}$) and has been convolved with a point-spread function (PSF) for the AEOS telescope at 1.65 μm. This PSF also reflects the reduced effective pupil diameter imposed by the Lyot mask in the Lyot Project coronagraph. During the fits, we also mask out the region covered by our coronagraphic mask. We generated an ensemble of models varying $h_0$ between 2.5 and 25 AU and $g$ between 0.0 and 0.7.

### 3.2. Model Fit Results

The $\chi^2$ fitting procedure was performed on a pixel-by-pixel basis, normalized with the peak brightness in the model matched to the peak brightness in the polarization image. Ideally, such a fit should simultaneously use the polarized intensity and the total intensity of the disk image (Graham et al. 2007) in the fits to avoid degeneracies between dust properties and disk structure (Duchêne et al. 2004; Pinte et al. 2007). Given the relatively low signal-to-noise of this detection, and the lack of a detection in a total intensity image, we chose only to perform a $\chi^2$ fit to the polarization image. Also, the data showing the fractional polarization may give a better handle on the disk scale height. In addition, the speckle noise pattern in highly corrected AO images can be well modelled with a Rician Probability Distribution Function (Aime & Soummer 2004; Fitzgerald & Graham 2006; Soummer et al. 2007), so a model fit should take this fact into account. However, given that the speckle noise pattern has been significantly subtracted away, as discussed above, a $\chi^2$ minimization employing a Gaussian noise variance is suitable.

Our best $\chi^2$ fit ($\chi^2 \approx 1.1$) is a model with dust disk scale height of $2.5 \pm 1.3$ AU and Henyey–Greenstein phase function of $0.20^{+0.07}_{-0.10}$. These findings are consistent with several lines of evidence suggesting that HR 4796A is dominated by a micron-sized dust population. Such a value of the asymmetry parameter is similar to models employing interstellar medium (ISM)-type dust grain distributions (Wood et al. 2002; Kim et al. 1994), with the dominant grain size lying between 0.1 and 1 μm. This population is similar that of the (8 ± 2 Myr, A1 V) 49 Cet disk as discussed by Wahhaj et al. (2007), with small (0.1 μm) grains between 30 and 60 AU from the star. On the other extreme, in their analysis of HR 4796A, Debes et al. (2008) suggest that the minimum grain sizes for this disk are between 1 and 5 μm in size, with a dominant population of 1.4 μm grains. Although the Debes et al. (2008) study employed the use of Tholins in their model fits, Köhler et al. (2008) find that the disk spectra can be well fit using less exotic compounds...
at the Maui Space Surveillance System, operated by Detachment 15 of the U.S. Air Force Research Laboratory Directed Energy Directorate. JRG, AS, and MDP were supported in part by the National Science Foundation Science and Technology Center for Adaptive Optics, managed by the University of California at Santa Cruz under cooperative agreement No. AST - 9876783. A portion of the research in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The Lyot Project is also grateful to the Cordelia Corporation, Hilary and Ethel Lipsitz, the Vincent Astor Fund, Judy Vale and an anonymous donor, who initiated the project.

REFERENCES

Adamson, A., Aspin, C., Davis, C., & Fujiyoshi, T. 2005, in ASP Conf. Ser. 343, Astronomical Polarimetry: Current Status and Future Directions, ed. A. Adamson, et al. (San Francisco, CA: ASP), 3

Aime, C., & Soummer, R. 2004, ApJ, 612, L85

Augereau, J. C., Lagrange, A. M., Mouillet, D., Papaloizou, J. C. B., & Grrood, P. A. 1999, A&A, 348, 557

Beuzit, J.-L., et al. 2006, The Messenger, 125, 29

Brandeker, A., Liseau, R., Olofsson, G., & Fridlund, M. 2004, A&A, 413, 681

Chandrasekhar, S. 1946, ApJ, 104, 110

Clampin, M., et al. 2003, AJ, 126, 385

Debes, J. H., Weinberger, A. J., & Schneider, G. 2008, ApJ, 673, L191

Duchêne, G., McCabe, C., Ghez, A. M., & Macintosh, B. A. 2004, ApJ, 606, 969

Fitzgerald, M. P., & Graham, J. R. 2006, ApJ, 637, 541

Gisler, D., et al. 2004, Proc. SPIE, 5492, 463

Graham, J. R., Kalas, P. G., & Matthews, B. C. 2007, ApJ, 654, 595

Haldes, A. S., Gledhill, T. M., Barlow, M. J., & Lowe, K. T. E. 2006, MNRAS, 365, 1348

Harrington, D. M., & Kuhn, J. R. 2008, PASP, 120, 89

Henney, L. G., & Greenstein, J. L. 1941, ApJ, 93, 70

Hinkley, S., et al. 2007, ApJ, 654, 633

Hinkley, S., Oppenheimer, B. R., Brenner, D., Parry, I. R., Sivaramakrishnan, A., Soummer, R., & King, D. 2008, Proc. SPIE, 7015, 701519

Hong, S. S. 1985, A&A, 146, 67

Jura, M. 1991, ApJ, 383, L79

Kalas, P., Graham, J. R., & Clampin, M. 2005, Nature, 435, 1067

Kalas, P., et al. 2008, Science, 322, 1345

Keller, C. U. 2002, in Astrophysical Spectropolarimetry, Instrumentation for Astrophysical Spectropolarimetry, ed. J. Trujillo-Bueno, F. Moreno Inseritis, & F. Sánchez (Cambridge: Cambridge Univ. Press), 303

Kelsall, T., et al. 1998, ApJ, 508, 44

Kenyon, S. J., Wood, K., Whitney, B. A., & Wolff, M. J. 1999, ApJ, 524, L119

Kim, S.-H., Martin, P. G., & Hendry, P. D. 1994, ApJ, 422, 164

Kimura, H., Kolokolova, L., & Mann, I. 2008, ApJ, 686, L95

K¨ohler, M., Mann, I., & Li, A. 2008, ApJ, 686, L95

Krist, J. E., Stapelfeldt, K. R., Ménard, F., Padgett, D. L., & Burrows, C. J. 2000, ApJ, 538, 793

Kuhn, J. R., Potter, D., & Parise, B. 2001, ApJ, 553, L189

Lafreni`ere, D., et al. 2007, ApJ, 670, 1367

Lucas, P. W., Hough, J. H., Bailey, J. A., Tamura, M., Hirst, E., & Harrison, D. 2009, MNRAS, 393, 229

Lyot, B. 1939, MNRAS, 99, 580

Macintosh, B. A., et al. 2006, Proc. SPIE, 6272, 627209

Macintosh, B. A., et al. 2008, Proc. SPIE, 7015, 701518

Malbet, F. 1996, A&A, 315, 161

Marois, C., Doyon, R., Nadeau, D., Racine, R., & Walker, G. A. H. 2003, in Astronomy with High Contrast Imaging, ed. C. Aime & R. Soummer (Les Ulis: EDP Sciences), 233

Marois, C., Lafreni`ere, D., Doyon, R., Macintosh, B., & Nadeau, D. 2006, ApJ, 641, 556

Marois, C., Macintosh, B., Barman, T., Zuckermond, B., Song, I., Patience, J., Lafreni`ere, D., & Doyon, R. 2008, Science, 322, 1348

Metchev, S. A., & Hillenbrand, L. A. 2009, ApJS, 181, 62

Nielsen, E. L., Close, L. M., Biller, B. A., Masciadri, E., & Lenzen, R. 2008, ApJ, 674, 466
Oppenheimer, B. R., Sivaramakrishnan, A., & Makidon, R. B. 2003, in Imaging Exoplanets: The Role of Small Telescopes, ed. Terry D. Oswald (Dordrecht: Kluwer), 155

Oppenheimer, B. R., et al. 2004, SPIE, 5490, 433

Oppenheimer, B. R., et al. 2008, ApJ, 679, 1574

Perrin, M. D., Graham, J. R., Kalas, P., Lloyd, J. P., Max, C. E., Gavel, D. T., Pennington, D. M., & Gates, E. L. 2004, Science, 303, 1345

Perrin, M. D., Graham, J. R., & Lloyd, J. P. 2008, PASP, 120, 555

Perrin, M. D., Graham, J. R., Trumpis, M., Kuhn, J. R., Whitman, K., Coulter, R., Lloyd, J. P., & Roberts, L. C. 2003, in Proc. 2002 AMOS Technical Conf., ed. P. W. Kervin & J. L. Africano (Kihei: Maui Econ. Development Board) (available at http://www.astro.ucla.edu/~mperrin/kermit/kermit-amos.pdf)

Pinte, C., Fouchet, L., Ménard, F., Gonzalez, J.-F., & Duchêne, G. 2007, A&A, 469, 963

Potter, D. E. 2003, PhD thesis, Univ. Hawaii

Potter, D. E., Close, L. M., Roddier, F., Roddier, C., Graves, J. E., & Northcott, M. 2000, ApJ, 540, 422

Racine, R., Walker, G. A. H., Nadeau, D., Doyon, R., & Marois, C. 1999, PASP, 111, 587

Roberts, L. C., & Neyman, C. R. 2002, PASP, 114, 1260

Schneider, G., et al. 1999, ApJ, 513, L127

Schneider, G., Weinberger, A. J., Becklin, E. E., Debes, J. H., & Smith, B. A. 2009, AJ, 137, 53

Sivaramakrishnan, A., Koresko, C. D., Makidon, R. B., Berkefeld, T., & Kuchner, M. J. 2001, ApJ, 552, 397

Sivaramakrishnan, A., Lloyd, J. P., Hodge, P. E., & Macintosh, B. A. 2002, ApJ, 581, L59

Sivaramakrishnan, A., et al. 2007, Comptes Rendus Physique, 8, 355

Soummer, R., Ferrari, A., Aime, C., & Jolissaint, L. 2007, ApJ, 669, 642

Soummer, R., et al. 2006, in Astronomy with High Contrast Imaging III: Instrumental Techniques, Modeling, and Data Processing, ed. M. Cariblet, A. Ferral, & C. Aime (Les Ulis: EDP Sciences), 199

Sparks, W. B., & Ford, H. C. 2002, ApJ, 578, 543

Stapelfeldt, K. R., et al. 2004, ApJS, 154, 458

Stokes, G. G. 1852, Trans. Camb. Phil. Soc., 3, 399

Tinbergen, J. 1996, Astronomical Polarimetry (New York: Cambridge Univ. Press)

van Leeuwen, F. 2007, A&A, 474, 653

Wahhaj, Z., Koerner, D. W., & Sargent, A. I. 2007, ApJ, 661, 368

Wood, K., Lada, C. J., Bjorkman, J. E., Kenyon, S. J., Whitney, B., & Wolff, M. J. 2002, ApJ, 567, 1183