IMAGES OF THE EXTENDED OUTER REGIONS OF THE DEBRIS RING AROUND HR 4796 A*

C. Thalmann, M. Janson, E. Buenzli, T. D. Brandt, J. P. Wisniewski, A. Moro-Martín, T. Usuda, G. Schneider, J. Carson, M. W. McElwain, C. A. Grady, M. Goto, L. Abe, W. Brandner, C. Dominik, S. Egner, M. Feldt, T. Fukui, T. Golota, O. Guyon, J. Hashimoto, Y. Hayano, M. Hayashi, S. Hayashi, T. Henning, K. W. Hodapp, M. Ishii, M. Iye, R. Kandori, G. R. Knapp, T. Kudo, N. Kusakabe, M. Kuzuhara, T. Matsuo, S. Miyama, J. -I. Morino, T. Nishimura, T. S. Pyo, E. Serabyn, H. Suto, R. Suzuki, Y. H. Takahashi, M. Takami, N. Takato, H. Terada, D. Tomono, E. L. Turner, M. Watanabe, T. Yamada, H. Takami, M. Tamura

ABSTRACT

We present high-contrast images of HR 4796 A taken with Subaru/HCI AO in H-band, resolving the debris disk in scattered light. The application of specialized angular differential imaging methods (ADI) allows us to trace the inner edge of the disk with high precision, and reveals a pair of “streamers” extending radially outward from the ansae. Using a simple disk model with a power-law surface brightness profile, we demonstrate that the observed streamers can be understood as part of the smoothly tapered outer boundary of the debris disk, which is most visible at the ansae. Our observations are consistent with the expected result of a narrow planetesimal ring being ground up in a collisional cascade, yielding dust with a wide range of grain sizes. Radiation forces leave large grains in the ring and push smaller grains onto elliptical, or even hyperbolic trajectories. We measure and characterize the disk’s surface brightness profile, and confirm the previously suspected offset of the disk’s center from the star’s position along the ring’s major axis. Furthermore, we present first evidence for an offset along the minor axis. Such offsets are commonly viewed as signposts for the presence of unseen planets within a disk’s cavity. Our images also offer new constraints on the presence of companions down to the planetary mass regime (∼9 MJ at 0\′′.5, ∼3 MJ at 1″).

Subject headings: circumstellar matter — planetary systems — techniques: high angular resolution — stars: individual (HR 4796 A)

1. INTRODUCTION

Vega-type debris disks were first identified by infrared (IR) excesses around nearby main sequence stars (Aumann et al. 1984). The dust content of these second-generation disk systems is believed to be continuously replenished via collisional breakup of remnant planetesimals (cf. Wyatt 2008). Since the imaging of the β Pic system (Smith & Terrile 1984), nearly two dozen nearby debris disks have been spatially resolved. The morphological appearance of resolved debris disks is predicted to be influenced by interactions between dust in the disk and nearby planets (Ozernoy et al. 2000; Kuchner & Holman 2003), the local interstellar medium (Misson et al. 2009), recent stellar flybys and binary companions (Wyatt et al. 1999), mutual grain collisions (Thébault & Wu 2008), and interaction of dust with residual gas (Klahr & Lin 2005). Many resolved systems exhibit all morphological structures predicted by these mechanisms (Schneider et al. 1999; Kalas et al. 2005; Golimowski et al. 2006; Kalas et al. 2008). The observable morphology of resolved, optically thin debris disks is also wavelength dependent, as different bandpasses sample different grain size distributions (Wyatt 2006).

HR 4796 A is a young (∼8–10 Myr; Stauffer et al. 1995), nearby (72.8 ± 1.7 pc; van Leeuwen 2007), AOV-type star first identified as a debris disk system from an IR excess observed with IRAS (Jura 1991). It has a co-moving M-type stellar companion at a separation of 7.7″ (Jura et al. 1993). The HR 4796 A debris disk has been spatially resolved at numerous optical, infrared, and sub-millimeter wavelengths (e.g., Koerner et al. 1998; Jayawardhana et al. 1998; Schneider et al. 1999; Sheret et al. 2004; Hinkley et al. 2009; Schneider et al. 2009), appearing as a narrow, highly inclined belt with a radius of 1″/05. Models suggest a dual dust population including gravitationally confined grains at ∼9–10 AU in addition to those imaged at ∼70 AU (Augereau et al. 1999), possibly involving radiatively evolved organic materials (Debes et al. 2008). Wahhaj et al. (2005) present multi-wavelength observations showing that the outer disk cannot be modeled as a single dust component; these authors adopt a two-component model with two different grain sizes.
Here we present new ground-based near-infrared imaging
data at high spatial resolution, revealing the tapered outer
regions of the debris disk.

2. OBSERVATIONS AND DATA REDUCTION

Our observations of HR 4796 A were obtained with the
Subaru Telescope on May 24, 2011, within the SEEDS sur-
vey (Strategic Exploration of Exoplanets and Disks with
Subaru/HiCIAO, Tamura 2009). The HiCIAO instrument
(Hodapp et al. 2008) with a $20^\prime\times 20^\prime$ field of view and a plate
scale of 9.50±0.02 mas/pixel was used. The image rotator
operated in pupil-tracking mode to enable angular diferential
imaging (ADI, Marois et al. 2006). A sequence of 260 images
was taken in $H$-band with an exposure time of 10 s, for a total
integration time of $43.3$ min and a total field rotation of $23^\circ$.
Weather conditions were good (seeing $0^\prime.8$) and the A0188 adaptive optics system (Minowa et al. 2010)
provided a FWHM of 6.5 pixels = 62 mas.

The images were corrected for flatfield and field distortion
(Suzuki et al. 2010). Stellar position was estimated in each
frame by two different methods: (1) Fitting a Moffat profile
to the PSF halo, and (2) triangulating between symmetrical
pairs of static speckles. Both were consistent with an empiri-
cal drift model ($\vec{r}_i = \vec{r}_0 + \vec{v}_i t + 1/2 \vec{a}_i t^2$) plus measure-
ment noise. The difference between the two sets of centroids
showed no systematic behavior, and was consistent with in-
coherent combination of the two measurement noise sources.
We therefore used the drift model for image registration, for
an estimated centering accuracy of $0.3$ pixels = $2.9$ mas in
the co-added image.

ADI combined with the LOCI algorithm (Locally Op-
timized Combination of Images, Lafrenière et al. 2007)
is currently the most successful ground-based imaging
technique for the detection of planets (Martois et al.
2010; Lagrange et al. 2010; Currie et al. 2011) and substel-
lar companions (Thalmann et al. 2009; Biller et al. 2010;
Janson et al. 2011). Furthermore, it has proven useful in
revealing high-contrast circumstellar disks (Thalmann et al.
2010; Buenzli et al. 2010).

We applied three implementations of the ADI technique to
our data: (I) “Simple ADI”, consisting of subtracting a me-
dian background from the entire dataset before derotating
and co-adding. This method causes the least amount of flux loss
and is therefore useful for estimating the surface brightness
profile of the disk. (II) “Aggressive LOCI”, using frame selec-
tion criteria of 0.5 FWHM (minimum differential field rota-
tion between images to be used for mutual subtraction, to
limit self-subtraction of physical sources) and an optimiza-
tion region with an area of 300 PSF footprints. Although most
of the disk signal is lost and negative over-subtraction effects
appear, this method achieves excellent speckle suppression
and provides the best constraints on point sources, such as
planets. (III) “Conservative LOCI”, a compromise between
the previous two methods, first described in Thalmann et al.
(2010). This method preserves more disk flux than aggressive
LOCI while achieving significantly better speckle subtraction
than simple ADI. The resulting image proves ideal for deriv-
ing geometric parameters of the inner disk edge. Due to the
dataset’s limited field rotation budget, we do not use an in-
creased frame selection criterion to conserve more disk flux,
as Thalmann et al. (2010) do. Instead, we enlarge the opti-
mization area to 10,000 PSF footprints, lowering the impact
of the disk signal on the optimization process, as first demon-
strated in Buenzli et al. (2010). Unless otherwise noted, we
use the default numerical and geometric LOCI settings as de-
ferred in Table 1 and Fig. 1 of Lafrenière et al. (2007).

3. RESULTS

3.1. Imaging the debris disk

Figure 1 shows the results of applying the three ADI re-
duction methods to our data: Simple ADI in (a), conservative
LOCI in (b), and aggressive LOCI in (c). In panel (d), we
reprint the HST/STIS image by Schneider et al. (2009, Figure
8) for comparison. Starlight scattered from the disk is visible
as a strongly projected ellipse in all images, down to stellocen-
tric separations of $0^\prime.5$ in simple ADI and $0^\prime.4$ in LOCI. Dif-
erential imaging clearly resolves the inner edge of the disk.

While most of the flux concentrates around this edge, each
ansa appears radially smeared out, extending a “streamer”
outwards along the major axis. Similar streamers have been
observed in deep ADI or roll subtraction images of other de-
The sampling area for a given parameter set merit value is shaped sampling area described by the numerical parameters and center positions relative to star. We assign a the image into a signal-to-noise map SiN star and dividing the pixel values in each annulus by this noise calculating the standard deviation in concentric annuli around the maximized major and minor semi-axes angles of the method of Buenzli et al. maximum regional merit fitting the method of Buehning et al. (2009). (3) Errors in (x, y) are correlated; use the uncorrelated errors in (u, v) instead. (4) The axes of the (u, v) coordinate system are aligned with the disk’s major and minor axes, thus they are rotated counterclockwise from the RA/Dec coordinate system (x, y) by $\Omega = 26.4^\circ$. (5) Conversion from $H$-band contrast via the 2D-code-evolutionary models (Allard et al. 2001; Baraffe et al. 2003), assuming an age of 8 Myr.

### 3.2. Ring geometry from maximum regional merit fitting

The crisp representation of the disk’s inner edge in the conservative LOCI image allows accurate measurement of its geometrical properties. For that purpose, we have devised the maximum regional merit technique, which is loosely based on the method of Buenzli et al. (2010).

First, we apply a median filter on the spatial scale of 5 pixels ($\approx 1 \lambda/D$), which reduces the pixel-to-pixel noise while keeping larger edges and structures intact. We then convert the image into a signal-to-noise map (S/N; Figure 2a) by calculating the standard deviation in concentric annuli around the star and dividing the pixel values in each annulus by this noise level. The disk itself is masked during noise calculation. The S/N map emphasizes the well-resolved outer parts of the disk. We then generate a large number of ellipses with randomized major and minor semi-axes $(a, b)$, position angles $(\Omega)$, and center positions relative to the star $(x, y)$. We assign a merit value $\eta$ to each set of parameters, defined as the mean value of the pixels in the S/N map that lie within an ellipse-shaped sampling area described by the numerical parameters. The sampling area for a given parameter set $(a, b, \Omega, x, y)$ is defined as the area between two nested ellipses that share the same orientation and center $(\Omega, x, y)$ but have semi-axes of $(a + \delta, b + e)$ and $(a - \delta, b - e)$, respectively. We choose $e = 0.7$ px, which results in a single-pixel thickness along the minor axis, and $\delta = 4$ px, for a 7-pixel thickness along the major axis. The value for $\delta$ corresponds to the observed width of the high-flux areas in the ansae of the disk; this is to ensure that a well-fitted sampling ellipse will be delimited by strong gradients in the S/N image on all sides, and thus sensitive to displacement and scaling (Fig. 2b).

We find that this method yields more accurate results for our data than the conventional method of fitting of an ellipse to flux maxima in the ring (as applied to HST data by Schneider et al. 2009), since our data has finer spatial sampling but a higher photometric noise level than the HST data. The disk profile is flat around the flux maxima and thus vulnerable to noise, while the tracking of sharp gradients is robust and profits from the fine spatial sampling.

We find a maximum merit of $\eta_{\text{max}} = 3.46$. In order to estimate the noise inherent to this merit figure, we measure $\eta$ for $10^4$ sampling ellipses placed in the empty sky region $90^\circ$ away from the position angle of the disk. We find

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**TABLE 1**

| Maximum merit ellipse size | ang. sep. | projected (AU$^3$) |
|---------------------------|-----------|-------------------|
| Semimajor axis $a$        | $1.087 \pm 0.023$ | $79.2 \pm 1.7$ |
| Semiminor axis $b$        | $0.248 \pm 0.007$ | $18.0 \pm 0.5$ |
| Maximum merit ellipse orientation | degrees |
| Position angle $\Omega$ | $26.4 \pm 0.5$ |
| Inclination $i = \arccos(b/a)$ | $76.7 \pm 0.5$ |

**NOTES.**

1. Conversion from arcsec to projected AU assuming a distance of 72.8 pc; the uncertainty of 1.7 pc is not included in the errors.
2. Based on the model disk described in Section 4.1, the photometric peak-to-peak radius is $\sim 96\%$ of the maximum merit semimajor axis; this would yield a value of $\tilde{a} = 11.04 \pm 0.02$ consistent with Schneider et al. (2009).
3. Errors in $(x, y)$ are correlated; use the uncorrelated errors in $(u, v)$ instead.
4. The axes of the $(u, v)$ coordinate system are aligned with the disk’s major and minor axes, thus they are rotated counterclockwise from the RA/Dec coordinate system $(x, y)$ by $\Omega = 26.4^\circ$.
5. Conversion from $H$-band contrast via the 2D-code-evolutionary models (Allard et al. 2001; Baraffe et al. 2003), assuming an age of 8 Myr.
ordinatively, we produced innovative solutions within a fitting solution family. Axes, demonstrating approximately Gaussian error behavior. To further test the validity of this maximum regional merit value, the contours of those solution families are concentric ellipses with axes aligned along the debris ring’s axes, demonstrating approximately Gaussian error behavior. To further test the validity of this maximum regional merit technique, we produced 10 model disks (as discussed in Section 4.1) with random offsets from the star, injected them into the empty sky region in our data, reduced them with conservative LOCI, and retrieved the ellipse parameters as described above. Deviations between measured and real offset coordinates were consistently below 1 $\sigma$, with an RMS of 0.4 $\sigma$.

The best-estimate parameters and their errors, including both fitting errors and systematic errors from image registration and plate scale, are presented in Table 1. Most notably, we find that the ellipse center is offset along its major axis (towards the southwest) by $u = 16.9 \pm 5.1$ mas, deviating from the star’s position at 3.3 $\sigma$ significance. Since the major axis is unaffected by foreshortening from projection along the line of sight, this translates directly into a physical distance of $1.2 \pm 0.3$ AU, assuming an approximately circular cavity. Combined with Schneider et al. (2009)’s independent measurement of $19 \pm 6$ mas (3.2 $\sigma$ confidence), we can now confirm that HR 4796 A’s debris disk is offset from its star. Furthermore, our data suggest an offset along the minor axis of $15.8 \pm 3.6$ mas in projection. If confirmed, this would correspond to a physical offset of $\sim 5$ AU.

### 3.3. Constraints on planets

Aggressive LOCI reduction of our image data does not detect any planet candidates in the system, but imposes upper limits on the masses of potential unseen planets. We use the photometric calibration method described e.g. in Thalmann et al. (2011), estimating and correcting the separation-dependent partial flux loss from LOCI processing as described in Lafrenière et al. (2007), and converting the H-band flux into planet mass using the COND evolutionary models (Allard et al. 2001; Baraffe et al. 2003). Table 1 lists the resulting 5 $\sigma$ contrasts and planet masses for four separations. The noise is calculated in concentric annuli, and the spider artifacts are masked out for this purpose.

### 4. Modeling

#### 4.1. Simple power-law model

In order to understand the morphology of our disk images and gauge their usefulness for deriving disk properties, we generate a model disk by calculating synthetic scattered light images of inclined rings, with a power-law distribution of the scattering cross section $R$. We assume the inclination of the disk to be given by the axis ratio, and construct a Keplerian disk with a small but nonzero eccentricity to match our observed semi-major axis offset (1.2 AU, Table 1). The main free parameters of the disk model are the radial power-law slopes,

$$R(r) = \left\{ \left( \frac{r}{a_0} \right)^{-2\alpha_{in}} + \left( \frac{r}{a_0} \right)^{-2\alpha_{out}} \right\}^{-0.5},$$

where $r$ is the radial distance to the star projected onto an ellipse with the desired geometry, $a_0$ is the semi-major axis, $\alpha_{in} > 0$ and $\alpha_{out} < 0$, and $R(r)$ is related to the surface density by $\sigma(r) = \sigma_0 \cdot R(r) \cdot (r/a_0)^{\alpha}$. We use a Henyey-Greenstein phase function and assume it is the same throughout the disk. To compute images, we use the single-scattering radiative transfer code GReRaTeR (Augereau et al. 1999) to compute synthetic images. This approach is valid for an optically thin disk.

Given the scope of this model, we do not attempt to fit but merely approximate the real debris disk. Our working parameters are $\alpha_{in} = 35$, indicating a very steep inner edge, $\alpha_{out} = -10$, and an asymmetry factor $g = 0.1$0, implying a slight preference for forward scattering (cf. $g = 0.16 \pm 0.06$ in Schneider et al. 2009; $g = 0.03 - 0.06$ in Debes et al. 2008).
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The two disks appear virtually indistinguishable, demonstrating that our simple model adequately explains the observed profile. The real disk's observed profile is consistent with a single power law.

4. DISCUSSION

We have imaged and characterized the tapered outer boundary of HR 4796 A's debris disk using ground-based angular differential imaging, and find that its $H$-band surface brightness profile is well described by a simple power law with a slope around $-9.5$. Our observations are consistent with the expected result of a narrow planetesimal ring being ground up in a collisional cascade, yielding dust with a wide range of grain sizes. Radiation forces leave large grains in the ring and push smaller grains onto elliptical, or even hyperbolic trajectories. Simulations of such this process predict a smoothly tapered outer boundary, consistent with our findings (e.g., Krivov et al. 2006; Strubbe & Chiang 2006). Wahhaj et al. (2005) have demonstrated that the disk cannot be modeled with a single dust grain size, implying that dust populations of varying grain size must be involved. The brightness slope is a result of changing dust densities and grain properties with distance. More detailed modeling is needed to relate the observed slope to the disk's physical properties.

Using our maximum regional merit technique, we have corroborated the evidence for an offset between the debris disk's inner edge and the star. The dynamical influence of unseen planets orbiting within the disk cavity is most commonly invoked to explain such offsets (e.g., Kalas et al. 2005; Thalmann et al. 2009; Buenzli et al. 2010, and references therein), and may be the cause of the proposed but unconfirmed intra-ring gap. Our confirmation of the ring offset also speaks against a dynamically cold source planetesimal population as proposed by Thébault & Wu (2008) as an alternative to the planet hypothesis for explaining the morphology of the ring. The planets may well be detectable with the upcoming next-generation high-contrast imaging facilities.

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