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A DUST DISK SURROUNDING THE YOUNG A STAR HR 4796A

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ABSTRACT

We report the codiscovery of the spatially resolved dust disk of the Vega-like star HR 4796A. Images of the thermal dust emission at $\lambda = 18\ \mu$m show an elongated structure approximately 200 AU in diameter surrounding the central A0V star. The position angle of the disk ($30^\circ \pm 10^\circ$) is consistent to the position angle of the M companion star (225°), suggesting that the disk-binary system is being seen nearly along its orbital plane. The surface brightness distribution of the disk is consistent with the presence of an inner disk hole of approximately 50 AU radius, as was originally suggested by Jura et al. on the basis of the infrared spectrum. HR 4796 is a unique system among the Vega-like or β Pictoris stars in that the M star companion (a weak-emission T Tauri star) shows that the system is relatively young, ~8 ± 3 Myr. The inner disk hole may provide evidence for coagulation of dust into larger bodies on a timescale similar to that suggested for planet formation in the solar system.

Subject headings: accretion, accretion disks — circumstellar matter — stars: formation —
stars: pre–main-sequence

1. INTRODUCTION

Planets are thought to form from the dusty disks that are the remnants of star formation (Shu, Adams, & Lizano 1987; Lissauer & Stewart 1993). The timescale for planet formation is uncertain but is currently thought to be roughly 10 Myr, as judged from both astronomical and solar system constraints (Strom et al. 1989; Strom, Edwards, & Skrutskie 1993; Podosek & Cassen 1994). This suggests that the young T Tauri stars of ages of 1 Myr, which frequently have optically thick, actively accreting disks (Bertout 1989; Hartmann & Kenyon 1996), represent a stage prior to the main epoch of planet formation. In contrast, the dust envelopes or disks of the so-called Vega-like objects (Backman & Paresce 1993), main-sequence stars whose ages could be as large as 1 Gyr, are thought to be much more evolved; most of the dust has coagulated into planets or planetesimals, and the remaining dust in the optically thin disk is continually replenished by collisions between larger bodies (Nakano 1988; Backman & Paresce 1993).

To date the dust cloud of one Vega-like object, the nearby main-sequence A star β Pictoris, has been imaged in scattered light with sufficient resolution and sensitivity to show disk structure (Smith & Terrile 1984); the dusty disk is also observable in spatially resolved mid-infrared thermal dust emission (Telesco et al. 1988; Backman, Gillett, & Witteborn 1992; Lagage & Pantin 1994; Pantin, Lagage, & Artymowicz 1997).

Here we report imaging observations of thermal dust emission for another Vega-like A star, HR 4796A. This star has a dust excess spectrum qualitatively similar to that of β Pic and has about twice the dust luminosity relative to the stellar luminosity of β Pic ($L_{\rm IR}/L_* = 5 \times 10^{-3}$; Jura 1991; Jura et al. 1993; Gillett 1986). Our 18 μm images show a disk, apparently seen nearly edge-on and with a position angle nearly aligned with the M star companion. The disk has an observed outer radius of 110 AU, which is comparable to that of T Tauri stars (Dutrey et al. 1995). This result has been found independently and simultaneously by Koerner et al. (1998).

2. OBSERVATIONS AND RESULTS

HR 4796 was observed in March 1998 with the 4 m Blanco telescope at Cerro Tololo Inter-American Observatory using the OSCIR mid-infrared camera. OSCIR uses a 128 × 128 Si:As Blocked Impurity Band detector developed by Boeing. On the Cerro Tololo Inter-American Observatory 4 m telescope, OSCIR has a plate scale of $0\farcs183$ pixel^{-1}, which gives a field of view of $23'' \times 23''$. Our observations were made using the standard chop/nod technique with a chopper throw of $25''$ in declination. Images of HR 4796 were obtained in the K (2.2 μm), N (10.8 μm), and IHW18 (18.2 μm) bands and flux-calibrated using the standard star γ Cru. Total on-source integration times for HR 4796 were 648 s in K, 1800 s in N, and 1800 s in IHW18.[4]

In the IHW18 band, the dust disk surrounding HR 4796A is clearly resolved along the major axis and marginally resolved along the minor axis (Fig. 1). The disk appears nearly edge-on in our images; considering our point-spread function (PSF), we estimate an angular diameter of $3''$, consistent with the $5''$ upper limit from Jura et al. (1993). We measure a total flux of 1.1 ± 0.15 Jy in a $3''$ aperture around HR 4796A. The position angle of the disk is $30^\circ \pm 10^\circ$.

In the N band, HR 4796A is marginally resolved along the direction of the disk's major axis and is not resolved perpendicular to it (Fig. 2). This result is as expected given our sensitivity limits and given that the dust excess at that wavelength is small in comparison to the stellar photospheric emission (Jura et al. 1998). Our N-band flux measurement of 244 ± 25 mJy in a $3''$ aperture agrees well with that of Jura et al. (1998). We place a 3 σ upper limit of 23 mJy at N on the flux from HR 4796B, consistent with the 65 mJy limit reported by Jura et al. (1998).

In the K band, both HR 4796A and HR 4796B are point

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[4] Additional information on OSCIR is available at www.astro.ufl.edu/iag/.

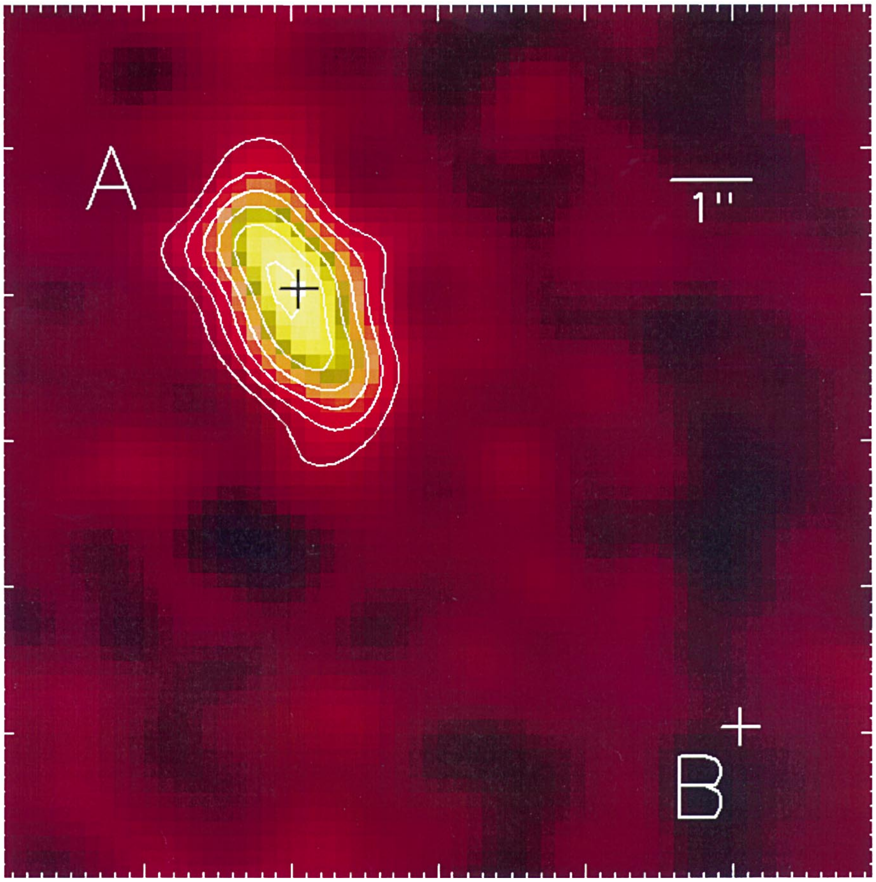

FIG. 1.—False-color image of HR 4796 disk in the IHW18 (118.2 μm) band with surface brightness contours overlaid. The contours are at 50, 75, 100, 125, 150, and 175 mJy arcsec^{-2}. The positions of star A and star B are marked with crosses, as determined from reference star offsets and the *K*-band image.

sources with FWHMs not appreciably larger than that of the standard star.

3. DISCUSSION

The infrared excess of HR 4796A can be fit by a blackbody at 110 K; the absence of shorter wavelength emission apparently requires a depletion or absence of dust inside of ~30 AU (Jura et al. 1993). To see whether our images are consistent with the inference of an inner disk hole, we have constructed preliminary dust disk models for HR 4796A. These models assume that the disk is optically and geometrically thin. We also adopt power-law distributions of surface density and temperature. Using a power-law dependence of the dust opacity on frequency at wavelengths ≥10 μm, we require that the models reproduce the infrared spectrum (Jura et al. 1998). The 18.2 μm stellar flux is extrapolated from the 10.8 μm flux. Finally, the *Hipparcos* distance of $67.1^{+3.5}_{-3.4}$ pc is used, consistent with the main-sequence spectral type of A0 V ($L_* \sim 21\ L_\odot$, effective temperature ~9500 K; Jura et al. 1998).

Because we only marginally resolve the disk along the minor axis, we have chosen to compare the models only with the strip surface brightness distribution, summed along the minor axis. We formally adopt an inclination angle of $\cos i = 0.3$ to be consistent with the observations, but since the disk is optically thin, this parameter makes no difference to the strip surface brightness.

Within the context of this simple model, an inner hole or region of dust depletion is needed to avoid having too large a central peak in the emission. As shown in Figure 3, models with constant surface density require an inner hole radius 40 AU $\lesssim R_i \lesssim$ 80 AU. The surface density distribution as a function of cylindrical radius R is not well constrained; models with $\Sigma \propto R^{-p}$, with $p \sim 0$–2, are consistent with the data (Fig. 3).

Although our model results are not unique, we note that the derived parameters are very similar to those inferred for the β Pic disk by Pantin et al. (1997). By modeling their 10 μm data, Pantin et al. find a relatively constant surface density between about 50 and 100 AU, with rapid decreases to shorter and larger radial distances. Thus, the size of the inner hole inferred here for HR 4796A is similar to the inner hole radius estimated for β Pic.

All of the models require dust temperatures of ≈80–90 K at 100 AU, which is much higher than the blackbody grain temperature of 60 K at this distance (Jura et al. 1998). This suggests that the grains must have reduced efficiency of emission at mid-infrared wavelengths. We have therefore adopted a power-law opacity of $\kappa_\nu \propto \nu^1$, so that the models all have a radiative equilibrium temperature distribution $T \propto R^{-0.4}$.

Calculations suggest that circumstellar disks will be truncated by the tidal effects of a companion star in circular orbit at approximately 0.9 of the average Roche lobe radius (Artymowicz & Lubow 1994), which for the estimated mass ratio of this object should be slightly more than half the orbital radius (Papaloizou & Pringle 1977). In the present case, this suggests the disk should be truncated at about 270 AU rather than at the observed 110 AU. Our simple model (Fig. 3) suggests that the 18 μm image does not trace emission from the outermost,

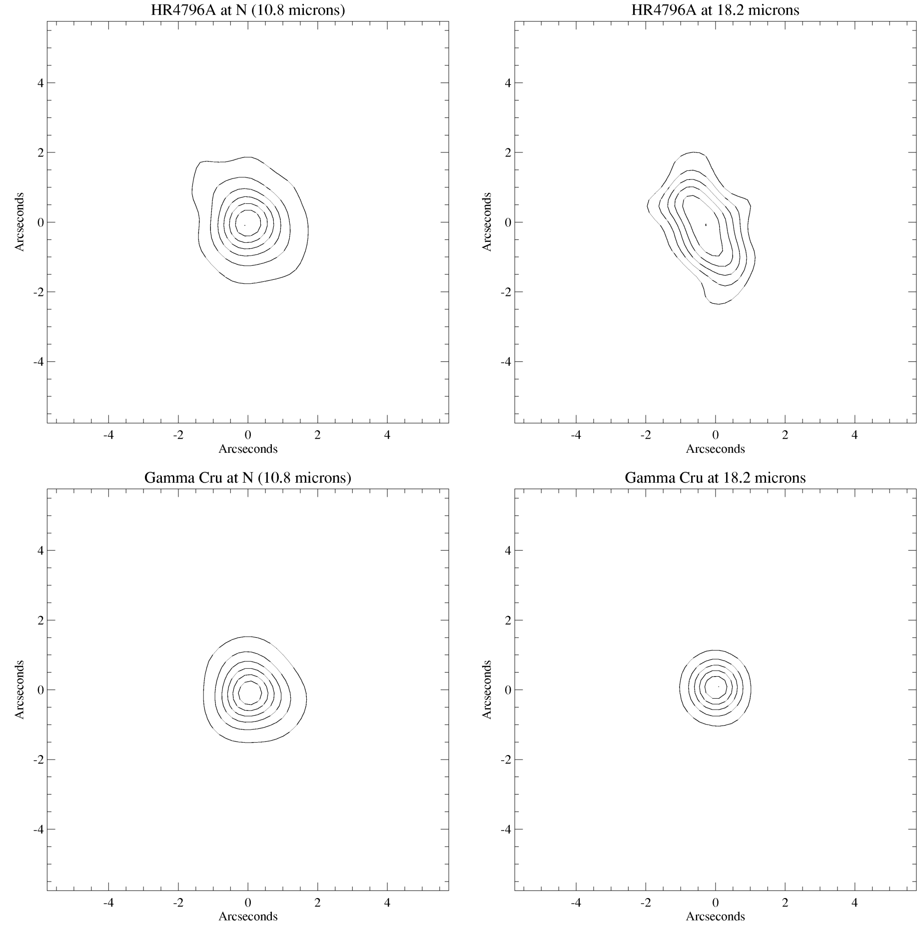

FIG. 2.—Surface brightness contour plots of the *N*-band (*top left*) and IHW18 (*top right*) images of HR 4796A smoothed with a 5 pixel Gaussian. In the *N* image, the lowest contour is at 6.6 mJy arcsec^{-2} and the contour interval is 9 mJy arcsec^{-2}. In the IHW18 image, the lowest contour is at 44 mJy arcsec^{-2} and the interval is 27 mJy arcsec^{-2}. In the bottom panels we show the corresponding PSFs, with contouring at the same fractional values of the peak emission as in the top panels. The lowest contour levels have been chosen to avoid the low-level, extended emission from the third diffraction ring in the PSF.

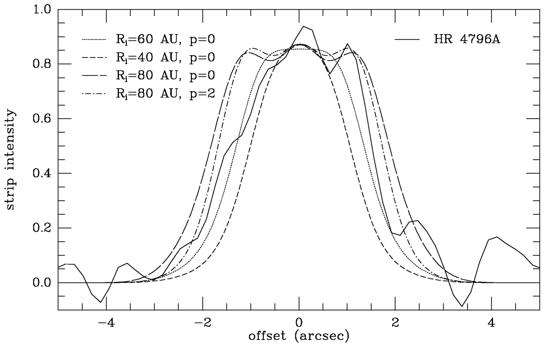

FIG. 3.—Observed intensity of HR 4796A at 18.2 μm summed along the minor axis (*solid line*) compared with simple disk models (*dashed lines*). The observations have been smoothed by 3 pixels (0.″54). The disk model is geometrically and optically thin; the dust opacity is proportional to $\kappa_\nu \propto \nu^1$; the temperature distributions are $T \propto R^{-0.4}$ and scaled to match the *IRAS* fluxes (Jura et al. 1998); and the surface density has a power-law form, $\Sigma \propto R^{-p}$. The models have the indicated inner disk radii and values of p. All models have been convolved with a Gaussian PSF with the same FWHM as the observed PSF.

coldest regions of the disk very well (the outer radius of our models is 200 AU), so that the disk may extend well beyond what we can detect at 18 μm. Alternatively, it may be that the orbit of the companion is eccentric and that the M star is currently near apastron.

At an angular separation of approximately 7.″7, the companion (spectral type M2.5; Stauffer et al. 1995, hereafter SHB) star must be a physical partner because the stars have not changed their relative positions for more than 60 yr (Jura et al. 1993). As discussed by SHB, the difficulty in assigning an age to the M star derives mostly from calibrations of theoretical evolutionary tracks. In effect, SHB use the distance above the Pleiades main-sequence in the H-R diagram to provide the calibration and find an age of 8 ± 2 Myr. Here we consider the effect of the new *Hipparcos* distance on this result. We adopt the temperature scale and bolometric corrections adopted by Briceño et al. (1998), along with the *I* (Cousins) magnitude reported by Jura et al. (1993) to determine an effective temperature of 3620 ± 60 K and luminosity 0.11 ± 0.02 $L_\odot$ for HR 4796B. Then, using the *Hipparcos* distance and the D'Antona & Mazzitelli (1994) evolutionary tracks (for which the above temperature scale is valid), the resulting age is 8 ± 3 Myr and the estimated mass is 0.38 ± 0.05 $M_\odot$. This is virtually identical to the SHB result; the (small) change in distance is compensated for by the change in bolometric correction. As noted by SHB, the measurement of the strong Li absorption line at 670.7 nm constrains the age to be less than ∼9–11 Myr for this mass range (see, e.g., D'Antona & Mazzitelli 1994). A lower limit to the age of a few Myr is indicated by the isolated location of HR 4796, since most stars of comparable or smaller ages are found in regions of molecular clouds and substantial interstellar dust extinction (Leisawitz, Bash, & Thaddeus 1989).

The inner disk hole has been attributed variously to either the tidal effects of a "sweeper" planet or brown dwarf or to inward migration of dust due to Poynting-Robertson drag, followed by sublimation of ice grains near 30 AU (see Jura et al. 1998). Our observations do not constrain these possibilities. We note that our upper limit of 23 mJy to the flux at 10.8 μm from the M star is consistent with the predicted photospheric flux of ∼15 mJy, implying little if any dust emission from a potential disk around the companion. This is consistent with the M star being a weak-emission T Tauri star, since WTTSs are not thought to be accreting from inner disks (Bertout 1989).

In the case of most Vega-like systems, it is assumed that the dust grains responsible for the far-infrared excess emission must be continually replenished by collisions and sublimation of larger bodies because the timescales for orbital decay by the Poynting-Robertson (PR) effect and sublimation of small bodies near the inner disk edge are smaller than the stellar main-sequence lifetimes (Nakano 1988; Backman & Paresce 1993). The HR 4796 system is so young that this conclusion may not be applicable. Jura et al. (1998) suggested that the grains need to be larger than 100 μm in order not to be removed from the disk by PR drag. However, radiative equilibrium for such large grains should be close to the blackbody case, resulting in lower dust temperatures and making it much more difficult to explain the size of the 18 μm image, as noted above. It is possible that small grains might be produced by collisions of larger bodies, as suggested for β Pic (see Backman & Paresce 1993); alternatively, if sufficient gas remains in the disk, as might be expected for a young system, PR drag can be overcome by gas drag. Attempts to measure gas directly in this disk should be made to see if the amounts are as small as found for β Pic (e.g., Ferlet, Hobbs, & Vidal-Madjar 1987).

Finally, it may be that there is not a universal evolutionary timescale for proto–planetary disks, especially when the influence of companion stars is taken into account. Highly simplified viscous disk models that are consistent with T Tauri star mass accretion rates suggest that the decay in disk mass as a function of time might be relatively slow for isolated stars, leaving 0.001–0.01 $M_\odot$ of gas in a disk of 1000 AU radius at an age of 10 Myr (Hartmann et al. 1998). In contrast, the mass of circumstellar dust in HR 4796A is estimated to be only 6×10^{26}–6×10^{27} g (Jura et al. 1995, 1998). However, the presence of a companion star at 500 AU is likely to dramatically accelerate the depletion of the disk due to accretion onto the central star (Papaloizou & Lin 1995). The disk around HR 4796 can serve as a valuable laboratory for understanding disk evolution and planet formation.

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