DEEP 10 AND 18 MICRON IMAGING OF THE HR 4796A CIRCUMSTELLAR DISK: TRANSIENT DUST PARTICLES AND TENTATIVE EVIDENCE FOR A BRIGHTNESS ASYMMETRY

C. M. Telesco,2 R. S. Fisher,2 R. K. Piña,2 R. F. Knacke,3 S. F. Dermott,2 M. C. Wyatt,2 K. Grogan,2 E. K. Holmes,2 A. M. Ghez,4 L. Prato,4 L. W. Hartmann,5 and R. Jayawardhana5

Received 1999 January 28; accepted 1999 August 19

1. INTRODUCTION

Planets form in dusty circumstellar disks, and so the exploration of circumstellar disks contributes fundamentally to a broader understanding of the origin and evolution of our own and other planetary systems. Vega-type disks, often called debris disks, are those that surround main-sequence stars (see the review by Backman & Paresce 1993). Unlike the disks surrounding pre-main-sequence stars, the dust masses of debris disks are generally much smaller than ∼0.01 M⊙, which is roughly the minimum mass required for the formation of a planetary system like our own (see, e.g., Beckwith & Sargent 1993; Strom et al. 1993). The lower mass of debris disks conforms with the expectation that disks disperse with time as the material accretes onto the stars, forms planets, and/or is blown out of the systems (e.g., Strom et al. 1993). The elucidation of these evolutionary processes is a key challenge of observational astronomy.

High angular resolution, multiwavelength imaging of circumstellar disks can provide unique insight into these processes, since a disk’s detailed structure should bear traces of its history and of any developing or mature planets. Until recently, the disk surrounding the A5 star β Pictoris (Smith & Terrile 1984; Telesco et al. 1988; Lagage & Pantin 1994; Kalas & Jewitt 1995) was the only debris disk that was spatially well resolved at optical or infrared wavelengths. However, many new results have emerged over the past few years, including the following: possible optical imaging of a disk around the binary star BD +31°643 (Kalas & Jewitt 1997); submillimeter imaging of impressive structure in several debris disks, including the class archetype Vega (Holland et al. 1998; Greaves et al. 1998); and ∼20 μm imaging of the nearly edge-on disk around the A0 V star HR 4796A (Jayawardhana et al. 1998, hereafter K98), results that were recently complemented with NICMOS images revealing what appears to be a sharply defined ring (Schneider et al. 1999).

Here we present new 10.8 and 18.2 μm images, obtained at the Keck II telescope, of the HR 4796A debris disk. Jura (1991) first drew attention to HR 4796, pointing out that its...
infrared spectral energy distribution resembles that of β Pic but with twice the IR excess (LIR/L⊙). The IRAS data showed no discernible emission from dust hotter than ~110 K, implying that there is little dust closer to the star than 40 AU (Jura et al. 1993). The existence of one or more planets was suggested as one of the possible causes of this central hole in the dust distribution (Jura et al. 1995, 1998). J98 and K98 determined that the disk’s diameter is ~3″, which corresponds to 200 AU at the star’s distance of 67 pc, and they confirmed directly the existence of the central hole. An especially significant aspect of the discovery is that, based on isochrone fitting and the strong lithium absorption line, the presumably coeval companion HR 4796B, located 7.7 away at P.A. = 226° (Jura et al. 1993), is an M2–M3 pre-main-sequence star with an age tightly constrained to be (8 ± 3) × 10⁶ yr (Stauffer et al. 1995; Jura et al. 1998).

Observational and theoretical studies of our solar system, including chronological data for meteorites, suggest that ~10⁸ yr is a reasonable estimate of the timescale for the duration of the solar nebula and the growth of the planets to nearly their final masses (see reviews by Lissauer 1993 and Podosek & Cassen 1994). Thus, the constraints on the age of HR 4796A place it within a critical stage of planetary disk evolution.

Our new images clarify the structure of the central clearing zone, or hole, which may be indirect evidence for a planet orbiting HR 4796A (see, e.g., Roques et al. 1994). They may also reveal an asymmetry in the disk, possibly confirmed by the NICMOS images (Schneider et al. 1999), which could reflect the influence of the stellar companion or a hypothetical planet. Finally, these multwavelength data provide a reasonable basis for estimating a characteristic size for the mid-infrared-emitting dust particles, an estimate with implications for our understanding of the disk evolution. Our results and discussion complement those in a companion paper by Wyatt et al. (1999, hereafter W99).

2. MID-INFRARED IMAGING WITH OSCIR AT KECK II

We imaged HR 4796A in the N (10.8 μm) and IHW 18
(18.2 \mu m) bands at the Keck II Telescope in 1998 May 7–12 with OSCIR, the University of Florida mid-infrared imager/spectrometer. OSCIR contains a 128 x 128 pixel, Si:As Blocked Impurity Band (BIB) array developed by Boeing. The plate scale was 0.062 pixel^{-1} with the f/40 chopping secondary at the Keck II visitor bent-Cassegrain port, which gave an array field of view of 7.9' x 7.9'. We used a guide star and the off-axis autoguider, which ensured excellent tracking and image stability, and the standard chop/nod technique, with a chop frequency of 4 Hz and a throw of 8'' in declination. The stars \alpha Sco, \gamma Aql, and \delta Vir were used for flux calibration. The seeing was generally very good for our observations. Typical values of the FWHM intensity of the observed point-spread functions (PSFs) were 0'32 at 10.8 \mu m and 0'45 at 18.2 \mu m, compared to the diffraction-limited values (\lambda/\lambda) of 0'22 and 0'37, respectively. Quadratic subtraction of these implies 10–20 \mu m “seeing” of \sim 0'2–0'3 (which may include other contributions, e.g., from autoguider jitter). The diffraction limits at 10 and 18 \mu m correspond to 4 and 6 pixels, respectively, and thus OSCIR spatially samples the diffraction-limited PSF more finely than conventional Nyquist sampling. We encountered light cirrus throughout much of our Keck run. By comparing observations within and among the nights, we believe that we have been able generally to remove the data for which the photometry is most uncertain. However, because of the cirrus, some unquantifiable uncertainty remains in the photometry. Key properties of the observations, including flux densities and noise estimates, are listed in Table 1. The images are presented as contour plots in Figures 1a and 1b. Figure 1c shows the unsmoothed 18.2 \mu m image, which indicates the quality of the original data.

3. DISK MORPHOLOGY IN THE THERMAL INFRARED

The discovery images clearly showed the disk around HR 4796A to be extended at 18 \mu m, but both teams only marginally resolved it at 10 \mu m (J98; K98). Figure 1 demonstrates that the emission ridge corresponding to the edge-on disk is well resolved at both 10 and 18 \mu m in these new images. For comparison, the PSFs determined from nearby stars are presented in Figure 2 on both logarithmic and linear brightness scales. At 10 \mu m, the disk is evident as very low-level wings protruding from the strong stellar point source (which, for convenient display, is therefore plotted logarithmically in Fig. 1a). The ridge is much more prominent at 18 \mu m (plotted linearly in Fig. 1b). The line connecting the two outer peaks is oriented along PA = \sim 26° ± 2°, and the maximum extent of the lowest 18 \mu m contour display in Figure 1 is about 3'1, or 208 AU. The maximum extent at 10 \mu m is about 2'8, or 85%–90% that of the 18 \mu m emission, and thus the 10 and 18 \mu m sources are roughly equal in size along the ridge. We also resolved the 18 \mu m disk along the minor axis, as indicated by the scans through the lobes and a comparison star shown in Figure 3.

Three peaks of comparable brightness are embedded in the 18 \mu m ridge. Each of the two outer 18 \mu m peaks, which

![Fig. 2](image-url)
we refer to as the lobes, is separated from the central peak by 0.8 (54 AU). The brightest region within the central 18 \( \mu m \) contour is indicated in Figure 1b by a filled circle. That point is slightly offset from the centroid of the highest central contour; it lies on the line connecting the two lobes and midway between them. By imaging sequentially at the two wavelengths with the Keck II visitor-port autoguider in operation, which facilitated accurate registration, we determined that the central 18 \( \mu m \) peak coincides with the 10 \( \mu m \) peak to within 0.3. As described below, most of the 10 \( \mu m \) emission is direct starlight, and therefore the coincidence between the central 10 and 18 \( \mu m \) peaks implies that the central 18 \( \mu m \) peak also coincides with the star, which we therefore assume is coincident with the filled circle in Figure 1b. In the 10 \( \mu m \) contour plot in Figure 1a, we indicate (crosses) the location of the peaks of the 18 \( \mu m \) lobes. The 18 \( \mu m \) lobes clearly coincide with the 10 \( \mu m \) wings, and therefore much, possibly most, of the 10 \( \mu m \)-emitting dust must be mixed with, or identical to, the 18 \( \mu m \)-emitting dust. The 18 \( \mu m \) brightness at the lobes is comparable to that at the star, whereas their 10 \( \mu m \) brightness is only 4%–5% that at the star. The disk morphology that we see at 18 \( \mu m \) is consistent with that seen by K98 in their Keck images. K98 did not resolve the disk at 10 \( \mu m \).

The mid-infrared radiation from HR 4796A originates both in the stellar photosphere and in dust that is heated by the starlight. The stellar photospheric flux densities at 10 and 18 \( \mu m \) are about 80% and 5%, respectively, of the total observed flux densities. Although the 18 \( \mu m \) stellar flux is a small fraction of the total, it contributes a large fraction of the emission of the central peak itself. To determine the contribution of the stellar photosphere to the image, we subtracted the stellar PSF from the image of HR 4796A after registering the peaks and normalizing the comparison star’s flux to that inferred for HR 4796A (Table 1). The PSF star was located near HR 4796A and observed just before and just after it. Due to the hexagonal shape of the Keck primary and secondary mirrors, the PSF is hexagonally shaped, so that, for the most accurate point-source subtraction or deconvolution, one cannot assume circular symmetry of the PSF. During the 18 \( \mu m \) observations of HR 4796A, the PSF rotated about 23° relative to the imager field of view (a rotation inherent in the altitude-azimuth mount). From the observed PSFs we constructed a time-averaged PSF appropriate to the rotational range of the PSF during our observations of HR 4796A.

The slightly smoothed (3 pixel) original and star-subtracted 18 \( \mu m \) images are shown in Figures 4a and 4b, respectively. The star was assumed to be coincident with the brightest part (Fig. 1b, filled circle), of the central maximum. Subtraction of the stellar flux removes the central peak, leaving a hole at that position. Because of the apparent absence in HR 4796 of significant dust hotter than about 110 K, Jura et al. (1995) concluded that the disk has a roughly 40 AU radius central hole in it. This conclusion was subsequently confirmed by the first direct images of the disk at ~20 \( \mu m \) (J98; K98) and, more recently, by NICMOS images at 1–2 \( \mu m \) (Schneider et al. 1999; see below). We see the hole directly in our 18 \( \mu m \) image (Figs. 1b and 4a) as a depression between the central peak and each of the two lobes; it is obvious in the image with the starlight subtracted (Fig. 4b). Some tenuous emission may also be present in the inner region, i.e., the region within ~0.5 of the star. The appearance of this residual emission depends on how we characterize and position the subtracted stellar PSF. In the Appendix we address briefly some aspects of
how the computed residual is affected by slight errors in the position and width of the PSF used to subtract HR 4796A’s starlight.

We also subtracted the stellar photospheric 10 μm flux from the 10 μm image. The central hole is evident in that subtracted image, but the disk is so much fainter than the star that the subtraction procedure is very uncertain. Therefore, we do not have confidence in the accuracy of this result, insofar as it bears on the structure of the inner part of the emitting region. However, those 10 μm results are useful in the context of estimating the characteristic size of the mid-infrared-emitting particles (§ 6).

There is some evidence that the lobes are not of equal maximum brightness: the northeast lobe is 5.9% ± 3.2% brighter than the southwest lobe, where this asymmetry corresponds to the difference in the lobe peak brightnesses divided by their mean. This value for the asymmetry includes a 0.8% correction for an asymmetry in the PSF. The formal statistical significance of the brightness asymmetry of the lobes is therefore 1.8σ. The brightness asymmetry itself was determined by fitting a polynomial to a 10 pixel × 10 pixel (0.6 × 0.6) region approximately centered on each peak. The uncertainty associated with this asymmetry was established by convolving the best-fit model (§ 4) with a Gaussian approximation to the PSF, applying Gaussian noise like that observed across the array, and fitting the polynomial as mentioned above. After repeating this procedure 50,000 times, we computed the rms deviation, which constituted the formal uncertainty. This asymmetry may also be apparent in the 10 μm image.
The largest value, used for the semimajor axis of the orbits that are circular, which is approximately the case for the number of orbits per unit semimajor axis. For particle grains, with an alternative, W99 assume that larger particles are distributed essentially like the smaller, 2 µm grains. The spatial distribution of larger particles in the HR 4796A disk is unknown, so, as an alternative, W99 assume that larger particles are distributed essentially like the smaller, 2–3 µm size, Mie grains emitting the observed mid-infrared radiation. By accounting for the temperature dependence of the dust as a function of distance from the star, they determine the spatial distribution of the mid-infrared–emitting grains from our 18 µm image.

The model disk is not flat but flared, with a distribution of orbital proper inclinations and proper eccentricities identical to those of the main-belt asteroids in our own solar system. The distribution of semimajor axes for the particles is assumed to follow the relation \( n(a) \propto a^\gamma \), where \( n(a) \) is the number of orbits per unit semimajor axis. For particle orbits that are circular, which is approximately the case for the model orbits, the surface number density as a function of distance \( r \) from the star is therefore proportional to \( r^{\gamma-1} \). The largest value, \( a_{\text{max}} \), used for the semimajor axis of the dust orbits is 130 AU, although the results of the modeling are not sensitive to this value, since relatively little flux arises near the outer edge of the disk. Key model parameters that are varied to match the observations are (1) the exponent \( \gamma \); (2) the minimum value, \( a_{\text{min}} \), of the dust semimajor axis, which controls the diameter of the central clearing; (3) the normalization of the density distribution; and (4) the inclination of the disk symmetry plane to the line of sight. In addition, observed asymmetries in the brightness distribution are modeled by adjusting the common forced eccentricity and the direction of the forced pericenter of the disk particle orbits.

Figure 4c shows the model brightness distribution at 18 µm that is the best fit to the star-subtracted image in Figure 4b. The residual (observed minus model) is shown in Figure 4d. The model fits the lobes well, with nearly all of the residual flux located within 0\(^\circ\) of the star. We are not certain of the nature of the residual flux. Some of it may represent real flux from HR 4796A’s inner disk, but some of it may result from imperfect subtraction of the stellar photospheric flux stemming from variations in the seeing not manifest in the PSF-star images (which were of shorter duration). We briefly address this issue in the Appendix.

The model disk inclination is 13° ± 1° from edge-on. A flat disk would be modeled as more face-on than this, since the disk flaring that we assume in the model accounts for some of the resolved disk extension that we see along the minor axis (Fig. 3). For the distribution of semimajor axes, \( \gamma = -2 \pm 1 \). The resultant model distribution of surface number density (i.e., integrated normal to the disk) of 2.5 µm grains is shown in Figure 5 in the form of a radial cut through the azimuthally averaged disk (solid curve). The surface density is relatively sharply peaked near 70 AU. Exterior to this position, the surface density decreases with distance approximately as \( r^{-3} \). Interior to this position, the surface density drops steeply by a factor of 2 between 70 and 60 AU, falling to zero by 45 AU. The model fit implies \( a_{\text{min}} = 62 \pm 2 \) AU, but because the dust particle orbits are assumed to be noncircular, the hole is not sharply defined in the models; i.e., the orbital eccentricity results in a small range in a particle’s radial location, which softens the hole’s edge. Flat-disk models based on the disk-discovery images indicate comparable values for the hole radius (J98; K98), but the dynamical models considered here provide an a priori basis for understanding why a hole should have an indistinct, or soft, edge.

How empty is the hole in the disk? We can estimate the optical depth in the hole by comparing the brightness of the residual emission there (assumed to represent an upper limit to emission from dust) to the observed brightness of the lobes. Consider first the optical depth in the disk lobes. The southwest lobe is 54 AU in projection from the star. The model temperature there is 113 K (compared to the blackbody temperature of 81 K) and, ignoring projection effects, the corresponding edge-on optical depth at 18 µm is \( \sim 0.002 \). The residual emission (observed minus model; Fig. 4d) at 20 AU (0\(^{\circ}\)) from the star is typically 0.2 times that of the lobes. The model temperature at 20 AU is 163 K, and thus the 18 µm edge-on optical depth there is \( \sim 5 \times 10^{-5} \), which is about 3% of that of the lobes. Assuming that the ratio of the face-on optical depth to the edge-on optical depth in the hole is comparable to that ratio at the lobes, then the average optical depth of 18 µm–emitting dust in
the hole appears to be about 3% of that in the main part of the disk at 60–100 AU from the star. If any of the residual emission results from poor PSF subtraction and is not intrinsic to the source, the optical depth of the dust in the hole could be even less than this. The central cleared region appears to be relatively very empty.

There has been speculation about the causes of holes in the centers of circumstellar disks (Lagage & Pantin 1994; Jura et al. 1998; Strom, Edwards, & Skrutskie 1993; Roques et al. 1994; J98; K98), and the disk in HR 4796A is likely to become a strong focus for these discussions (e.g., Jura et al. 1995; W99). We only wish to emphasize here that the possible disk brightness asymmetry is an interesting and perhaps unexpected manifestation of the central hole. The brightness asymmetry in the model results from the gravitational perturbation of the disk particle orbits by the low-mass companion HR 4796B even if the companion’s orbit is only moderately eccentric (W99). To first order, the effect of the perturbation is to shift the center of symmetry of the circular disk from HR 4796A toward the companion’s apocenter, where the companion spends most of its time; i.e., the long-term average of the perturbation on the disk particles is directed toward the companion’s apocenter. The side of the disk, and therefore the hole edge, that is closest to the companion’s pericenter is shifted closer to the primary star and is therefore warmer (“pericenter glow”). The pericenter glow is a direct result of there being a hole in the disk. If this model is valid and these perturbations do arise from HR 4796B, then HR 4796B’s pericenter must be located northeast of HR 4796A, and HR 4796B is currently located near its apocenter southwest of HR 4796A. The scale of the shift of the disk’s center of symmetry is indicated by comparing the dashed and dotted curves in Figure 5, which shows the density distribution through the disk toward and away from the stellar companion’s pericenter. The disk is shifted only a few AU, which, while a small amount, leads to an arguably measurable brightness asymmetry. The perturber responsible for the shift of the disk need not be exterior to the disk. A star or planet within the hole could cause the same effect (W99); however, based on near-infrared speckle observations (Jura et al. 1995), the mass of any stellar companion located between 11 and 120 AU from HR 4796A must be less than 0.13 $M_\odot$. The fact that we may be detecting a brightness asymmetry resulting from a shift of a few AU in the disk centroid implies that the detection of significant dynamical effects on circumstellar disks by stellar or planetary companions is now within reach. The HST/NICMOS images presented by Schneider et al. (1999) may confirm this pericenter glow (§ 5 below).

5. COMPARISON OF MID-INFRARED AND HST/NICMOS IMAGES

Schneider et al. (1999) have imaged the HR 4796A disk at 1.1 and 1.6 μm with NICMOS. They used a 0′6 diameter coronagraphic spot, but, owing to a variety of instrumental effects, the data in a 1.3′ diameter region are unsusable. Their images show clearly what appears to be a relatively narrow ring inclined to the line of sight. Assuming that the ring is intrinsically circular, they determine a major-axis position angle of 26:8 ± 0′6 and an inclination of the line of sight of 73:1 ± 1′2, in agreement with our estimates (W99; see §§ 3 and 4 of this paper) and those of K98. The mean radius of the ring is 70 AU, and, after quadratic subtraction of the PSF, the full width of the annulus is estimated to be 17 AU (Schneider et al. 1999). The relatively sharp maximum in the density near 70 AU determined from our modeling of the OSCIR observations agrees precisely with the value derived by Schneider et al. (1999) for the mean radius of the ring based on the NICMOS observations. We now consider a more detailed comparison.

In Figure 6 we show our 10 and 18 μm contours overlaid on the 1.1 μm NICMOS image. Keeping in mind the differ-
Fig. 6.—Overlay of (a) 10.8 and (b) 18.2 μm contours on the 1.1 μm HST/NICMOS image of HR 4796A disk from Schneider et al. (1999). The angular resolutions (FWHM) of the images are: 0″.12 at 1.1 μm; 0″.32 at 10.8 μm; 0″.45 at 18.2 μm. In both images, east is approximately down, and north is to the left (see Schneider et al. 1999). In this orientation, the companion star HR 4796B is located to the upper right.

ences in the resolutions of the images (FWHM: 0″.12 at 1.1 μm; 0″.32 and 10.8 μm; 0″.45 at 18.2 μm), we see that the overall coincidence of the mid-infrared and near-infrared emission is excellent. However, the 18 μm lobes are located noticeably closer to the star than are the bright 1.1 μm peaks. The peaks of the 18 μm lobes are separated by 1″.73, compared to 2″.10 for the peak-intensity positions at 1.1 μm (Schneider et al. 1999). To assess the nature of this offset, we considered a perfectly thin ring (annulus) of dust with uniform number density and the temperature distribution derived in the W99 models. We assumed a mean annular radius of 70 AU and an annular width of 17 AU and computed the 18 μm brightness at each point in the ring, which we convolved with the observed 18.2 μm PSF. In Figure 7 we compare the brightness distribution along the major axis expected for this convolved model to the observed brightness distribution.

This comparison implies that ~60% of the 0″.37 difference in the separation of the peaks at 1.1 and 18.2 μm results from the lower resolution of the 18 μm image. Figure 7 indicates that the uniform-annulus model results in an 18 μm distribution with lobes displaced to larger radii and
appearing somewhat narrower than actually observed. The discrepancy in slope is primarily on the insides of the lobes. The observed outer slope of the northeast lobe is well matched by the model, while the match of the southwest lobe is noticeably poorer. We do not think that these differences between the NICMOS-based model and the 18 μm observations result from inaccurate subtraction of the stellar PSF from the 18 μm image. Figure 7 gives some indication of the small dependence of the shape inferred of the inside of the disk lobes on the assumed shape of the PSF; we show the flux distributions resulting from use of the nominal, observed PSF (solid curve) and the same PSF with an additional 0.35 of seeing (dashed line; see Appendix). Rather, the difference in the observations and the brightness expected from the model may result from the annulus having a somewhat soft inner edge. Primarily because of the lower resolution of the 18 μm observations, a more gradual density falloff on the inside of the annulus will both shift the observed peaks inward and decrease the inner slope of the lobes. The excellent agreement in the location of the peak density in the disk, as determined from models of the OSCIR images, and the average radius of the annulus determined from models of the HST/NICMOS images, suggests that it is this inner density rolloff, or a similar refinement such as excess emission in the hole, that accounts for the relative locations of the observed emission peaks in the two data sets. A slower density falloff on the outside of the annulus would elevate the 18 μm wings, although we see this only on the southwest side of the disk. As shown by W99 and discussed in the previous section, one may account for a soft-density rolloff on the inside of the annulus by the kinds of dynamical properties anticipated (and assumed in the W99 models) for the orbiting dust particles.

Figure 6 shows that at 1.1 μm the northeast side of the annulus is noticeably brighter than the southwest side. This asymmetry is not evident in the 1.6 μm NICMOS image. This asymmetry may support our, albeit marginal, detection of the pericenter glow at 18 μm. However, one is seeing emission from dust particles at 18 μm but scattering from dust (and probably a different population) at 1–2 μm. We speculate that the mass shift that may result in the enhanced lobe brightness at 18 μm could also enhance the scattering of light there. Detailed models that incorporate realistic scattering functions must be carried out to explore this interesting possibility.

6. THE MID-INFRARED–EMITTING DUST

6.1. The Characteristic Particle Size

Circumstellar dust spans a range of compositions and sizes. However, for a given composition, one can derive from observations at two wavelengths a unique particle size that is arguably characteristic of the dust responsible for that emission. The basis for this estimate is that the emission efficiency, and therefore the temperature, of a dust particle depends on its size. We made an initial estimate of the size of dust particles in HR 4796A by taking the ratio of the characteristic particle size

![Graph showing comparison of major-axis cut through the lobes of our 18 μm star-subtracted image (solid curve) to that expected (dotted curve) from the simplest disk model inferred by Schneider et al. (1999) from their NICMOS image. The left side of the scan is northeast of the star. The model disk is a thin annulus with a mean radius of 70 AU, a width of 17 AU, a uniform density, and the temperature falloff with radius determined by W99. The Schneider et al. (1999) model has been convolved with the observed 18 μm PSF. The dashed curve shows the result of subtracting from the observations a stellar PSF that has an additional 0.35 seeing, as discussed in the Appendix.]
diameter to 2.5 μm, consistent with our original estimate. We conclude that, under the assumption that the particles we see in the lobes are astronomical silicate Mie spheres, 2–3 μm diameter grains provide a reasonable fit to the lobe mid-infrared colors. Of course, based on studies of interplanetary dust particles in our solar system (e.g., Gustafson 1994), it is evident that the dust particles in HR 4796A’s disk are unlikely to be simple spheres, the implications of which we are in the process of considering.

6.2. Particle Evolution

We can consider the effects of the stellar radiation on 2.5 μm size grains by estimating the value of the parameter β, the ratio of the radiation pressure force to the gravitational
force on a particle. As summarized in Artymowicz (1988) and elsewhere, \( \beta \propto <Q_{pr}/(L_*/M_*)>/\rho \), where \( R \) is the particle radius, \( \rho \) is its density, \( <Q_{pr}> \) is the radiation pressure efficiency averaged across the stellar spectral energy distribution, and \( L_*/M_* \) is the ratio of the stellar luminosity and mass. W99 have computed the value of \( \beta \) for 2.5 \( \mu m \) diameter silicate spheres near HR 4796A; they assumed \( L_*=21 L_\odot \) and \( M_*=2.5 M_\odot \), and \( \rho = 2.5 \text{ g cm}^{-3} \), and they compute \( <Q_{pr}> \) using a stellar spectral energy distribution for the A0 V star Vega (M. Cohen 1999, private communication). They derive the value \( \beta = 1.7 \) for the grains that characterize the mid-infrared–emitting particles in HR 4796A’s disk. If one takes into account the differences in spectral type and assumed grain density, this value agrees reasonably well with the one that can be derived from the results in Artymowicz (1988; see his Fig. 1), who computed \( \beta \) for the star \( \beta \) Pic and for a variety of grain materials including the astronomical silicates of Draine & Lee (1984). Dust grains that are created in collisions, and for which \( \beta \) is greater than \( \sim 0.5 \), have hyperbolic orbits; they are blown beyond \( \sim 100 \) AU and out of the system on essentially free-fall timescales, on the order of a few hundred years. Thus, the 2–3 \( \mu m \) grains we see orbiting HR 4796A are not primordial; one expects very few of them in this disk (see also Jura et al. 1995). The detailed analysis by W99 (see also Artymowicz 1997) implies that the collisional lifetime of the dust in HR 4796A is roughly \( 10^4 \) yr across the disk. The mid-infrared–emitting particles are probably relatively recent fragments of collisions that dominate both the creation and destruction of dust there.

7. SUMMARY AND CONCLUSIONS

1. Our new 10 and 18 \( \mu m \) images of the circumstellar disk around the A0 Vega-type star HR 4796A images show extended, well-resolved emission at 10 \( \mu m \) in addition to the previously discovered 18 \( \mu m \) emission (J98; K98). The resolution of both images is close to the Keck diffraction limit. The size of the 10.8 \( \mu m \)–emitting region is comparable to that at 18 \( \mu m \), implying that most of the 10 \( \mu m \)–emitting particles are mixed with, or identical to, those emitting at 18 \( \mu m \).

2. Modeling of the disk brightness distribution (W99) implies that a pronounced maximum in the surface density occurs at approximately 70 AU from the star. This value equals the mean annular radius deduced by Schneider et al. (1999) from their HST/NICMOS images. The best-fit model surface density exterior to 70 AU falls steeply with distance as \( r^{-3} \). Interior to 70 AU, the density drops steeply by a factor of 2 between 70 and 60 AU, falling to zero by 45 AU, which corresponds to the edge of the previously discovered central hole; in the context of the dynamical models, this “soft” edge for the central hole results from the fact that the dust particle orbits are noncircular.

3. Based on the images, the optical depth in the central clearing zone, or hole, is \( \sim 3\% \), or less, of that in the main part of the disk. Thus, the hole is indeed relatively empty.

4. We present tentative evidence (1.8\( \sigma \)) that the 18 \( \mu m \) lobes are of unequal brightness. Detailed modeling of the 18 \( \mu m \) brightness distribution based on dynamical considerations and presented in a companion paper (W99) indicates that such a brightness asymmetry could result from gravitational perturbation of the disk particle orbits by the low-mass stellar companion or a planet. The perturbation shifts the disk center of symmetry away from the companion’s pericenter; to first order, this shift corresponds to a spatial shift of the center of the circularly symmetric disk. This shift brings the inside edge of the annulus closer to HR 4796A, which makes that edge warmer and more infrared-emitting ("pericenter glow") than the other side of the annulus. This measurable brightness asymmetry corresponds to a spatial shift of the disk of only a few AU, and so the detection of even fairly complex dynamical effects of planets on disks appears to be within reach. The recent 1.1 \( \mu m \) NICMOS image (Schneider et al. 1999) may show evidence in support of the pericenter glow.

5. We compare our 10 and 18 \( \mu m \) images with recent NICMOS images of HR 4796A at 1.1 and 1.6 \( \mu m \) that show what appears to be a relatively narrow ring, or annulus, inclined to the line of sight and with a mean radius of 70 AU and an annular width of \( \sim 17 \) AU. The overall coincidence of the near-infrared and mid-infrared structure is excellent. However, even after accounting for differences in angular resolution, we find that the 18 \( \mu m \) distribution expected from the NICMOS-based model differs somewhat from the observed distribution. These differences suggest that the annulus has a “soft” inner edge, which may correspond to the density falloff expected from considerations of particle dynamics.

6. Using the 10 and 18 \( \mu m \) images, we estimate that the mid-infrared–emitting dust particles in the main part of the disk have a characteristic diameter of \( \sim 2–3 \) \( \mu m \). This estimate is based on the assumption that the particles are Mie spheres composed of astronomical silicates. The corresponding value of the parameter \( \beta \), the ratio of the radiation-pressure force to gravitational force on a particle. As summarized in Artymowicz (1988) and elsewhere, \( \beta \propto <Q_{pr}/(L_*/M_*)>/\rho \), where \( R \) is the particle radius, \( \rho \) is its density, \( <Q_{pr}> \) is the radiation pressure efficiency averaged across the stellar spectral energy distribution, and \( L_*/M_* \) is the ratio of the stellar luminosity and mass. W99 have computed the value of \( \beta \) for 2.5 \( \mu m \) diameter silicate spheres near HR 4796A; they assumed \( L_*=21 L_\odot \) and \( M_*=2.5 M_\odot \), and \( \rho = 2.5 \text{ g cm}^{-3} \), and they compute \( <Q_{pr}> \) using a stellar spectral energy distribution for the A0 V star Vega (M. Cohen 1999, private communication). They derive the value \( \beta = 1.7 \) for the grains that characterize the mid-infrared–emitting particles in HR 4796A’s disk. If one takes into account the differences in spectral type and assumed grain density, this value agrees reasonably well with the one that can be derived from the results in Artymowicz (1988; see his Fig. 1), who computed \( \beta \) for the star \( \beta \) Pic and for a variety of grain materials including the astronomical silicates of Draine & Lee (1984). Dust grains that are created in collisions, and for which \( \beta \) is greater than \( \sim 0.5 \), have hyperbolic orbits; they are blown beyond \( \sim 100 \) AU and out of the system on essentially free-fall timescales, on the order of a few hundred years. Thus, the 2–3 \( \mu m \) grains we see orbiting HR 4796A are not primordial; one expects very few of them in this disk (see also Jura et al. 1995). The detailed analysis by W99 (see also Artymowicz 1997) implies that the collisional lifetime of the dust in HR 4796A is roughly \( 10^4 \) yr across the disk. The mid-infrared–emitting particles are probably relatively recent fragments of collisions that dominate both the creation and destruction of dust there.

We wish to acknowledge Kevin Hanna for his development of the superb OSCIR electronics; Kevin Hanna, Jeff Julian, and Chris Singer for their assistance in preparing for, and carrying out, the Keck observing run; Martin Cohen for providing us with the Vega spectrum; and the Keck Observatory personnel for their outstanding support of OSCIR as a Keck II visitor instrument. Use of OSCIR at Keck was supported in part by NSF and NASA grants to the University of Florida and the Pennsylvania State University at Erie.

APPENDIX

We pointed out in § 3 that some of the inner tenuous emission (within 0.5 of the star) apparent in the star-subtracted 18 \( \mu m \) image of HR 4796A (Fig. 4b) and as residual emission in Figure 4d may be an artifact resulting from the use of an unsuitable
PSF. This mismatch could occur if there are low-frequency seeing components sampled during the ~1 hr of chopped integration time on HR 4796A (Table 1) that are not sampled during the much shorter (~1 minute) integration time on the nearby star used to determine the PSF. (Given the limited amount of available observing time, it is unrealistic to observe the PSF star for the same amount of time that we observe the program objects.) Here we briefly examine this issue.

Figure 9a presents the star-subtracted 18 \( \mu \)m image presented previously in \( \S \) 3 (Fig. 4b). That image resulted from the subtraction of HR 4796A’s direct starlight (photospheric emission) using the observed stellar PSF (referred to as the nominal PSF) and assuming that the stellar peak is coincident with the location of maximum 18 \( \mu \)m brightness (Fig. 1, filled circle). Figure 9b shows the result of instead subtracting a somewhat broader PSF obtained by convolving the nominal PSF with a Gaussian profile with a FWHM of 0.35. This might represent some additional seeing that could have affected the image of HR 4796A but not the observed PSF star image. In Figures 9c and 9d, we repeat this exercise, but with the star assumed to be at the centroid of the highest central contour indicated in Figure 1b, i.e., at 0:1 west-northwest of the filled circle in Figure 1b. The intent of this exercise is to illustrate the sensitivity of the residual inner structure to the assumed stellar location.

We see that even this modest amount of extra “seeing” results in a star-subtracted image of HR 4796A that is noticeably less structured at the disk center. This comparison is also shown in the scans in Figure 7. Likewise, slight errors in positioning the star result in some differences in the inferred inner-disk structure. However, although the emission structure differs somewhat, the integrated residual flux is virtually unchanged, since the stellar flux is the same in both cases. As we have noted, the light cirrus evident throughout much of our Keck run may have resulted in poor photometric conditions, but we do not think this is the source of the residuals: the photometry is generally consistent to within ~20%, and even an error this large in the PSF flux normalization would only marginally affect the residual.

We conclude that the detailed structure of the inner disk (within 0:5 of the star), as inferred from the star-subtracted image or the resultant image of the residual emission (e.g., Fig. 4d), must be viewed with caution. However, the integrated residual flux is more robust and may be real. If so, it may correspond to low-level dust emission from within the central clearing.

REFERENCES

Artymowicz, P. 1988, ApJ, 335, L79

Backman, D., & Foreman, F. 1993, in Protostars and Planets III, ed. E. Levy & J. Lunine (Tucson: Univ. Arizona Press), 1253

Beckwith, S. V. W., & Sargent, A. I. 1993, in Protostars and Planets III, ed. E. Levy & J. Lunine (Tucson: Univ. Arizona Press), 521

Draine, B. T., & Lee, H. M. 1984, ApJ, 285, 89

Greaves, J. S., et al. 1998, ApJ, 506, L133
Gr"un, E., et al. 1985, Icarus, 62, 244
Gustafson, B. A. S. 1994, Annu. Rev. Earth Planet. Sci., 22, 553
Holland, W. S., et al. 1998, Nature, 392, 788
Jayawardhana, R., Fisher, S., Hartmann, L., Telesco, C., Pi"na, R., & Fazio, G. 1998, ApJ, 503, L79 (J98)
Jura, M. 1991, ApJ, 383, L79
Jura, M., Ghez, A. M., White, R. J., McCarthy, D. W., Smith, R. C., & Martin, P. G. 1995, ApJ, 445, 451
Jura, M., Malkan, M., White, R., Telesco, C., Pi"na, R., & Fisher, R. 1998, ApJ, 505, 897
Jura, M., Zuckerman, B., Becklin, E. E., & Smith, R. C. 1993, ApJ, 418, L37
Kalas, P., & Jewitt, D. 1995, AJ, 110, 794
———. 1997, Nature, 386, 52
Koerner, D. W., Ressler, M. E., Werner, M. W., & Backman, D. E. 1998, ApJ, 503, L83 (K98)
Kurucz, R. L. 1979, ApJS, 40, 1
Lagage, R., & Pantin, E. 1994, Nature, 369, 628
Lissauer, J. J. 1993, ARA&A, 31, 129
Podosek, F. A., & Casen, P. 1994, Meteoritics, 29, 6
Roques, F., Scholl, H., Sicardy, B., & Smith, B. A. 1994, Icarus, 108, 37
Schneider et al. 1999, ApJ, 513, L127
Smith, B. A., & Terrile, R. J. 1984, Science, 226, 1421
Stauffer, J. R., Hartmann, L. W., & Navascues, D. B. 1995, ApJ, 454, 910
Strom, S. E., Edwards, S., & Skrutskie, M. F. 1993, in Protostars and Planets III, ed. E. Levy & J. Lunine (Tucson: Univ. Arizona Press), 837
Telesco, C. M., Becklin, E. E., Wolstencroft, R. D., & Decher, R. 1988, Nature, 335, 51
Wyatt, M. C., Dermott, S. F., Telesco, C. M., Fisher, R. S., Grogan, K., Holmes, E., & Pi"na, R. K. 1999, ApJ, 527, 918 (W99)