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THE FATE OF THE SOLID MATTER ORBITING HR 4796A

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ABSTRACT

We have obtained optical spectra, 2 μm speckle images, and an upper limit to the 800 μm flux for HR 4796A, and optical spectra for its physical companion separated by 7″.7, HR 4796B. We detect Hβ, Hγ, and the calcium H and K lines in emission from HR 4796B; these data are consistent with the hypothesis that it is later than spectral type M2 and lies substantially above the main-sequence. From the location of HR 4796B on the H-R diagram, the estimated age of this star is 3×10^6 yr, and assuming this age for the entire system, we find from our 2 μm speckle data that there is no close stellar companion to HR 4796A ($M > 0.125\ M_\odot$) between 11 and 120 AU from the star.

From the *IRAS* and ground-based photometry, it seems that there is a hole in the dust distribution around HR 4796A with an inner radius of between ~40 and ~200 AU. The observed circumstellar dust grains, which lie at $D > 40$ AU from the star, are likely to be at least 3 μm in radius in order to be gravitationally bound to HR 4796A, if the circumstellar dust cloud is optically thin. Since they are larger than almost all interstellar grains, the circumstellar dust grains probably grew by coalescence. Because the existing grains at $D > 40$ AU have undergone measurable coalescence, it is possible that particles that presumably once existed at $D < 40$ AU, where the collision times were shorter than at $D > 40$ AU, grew into macroscopic objects.

A likely explanation for the dust hole is that there is a companion located at about half the inner radius of the dust hole, or between 20 and 100 AU from the star. If such a companion exists, it must have a mass less than 0.125 $M_\odot$. Since grain coalescence has occurred, this putative companion possibly could be a planet.

Subject headings: binaries: visual — circumstellar matter — infrared: stars — stars: individual (HR 4796)

1. INTRODUCTION

Although the majority of main-sequence stars lack evidence of circumstellar material, it is believed that all of these stars were initially surrounded by circumstellar dust as shown by studies of T Tauri stars and other pre–main-sequence objects. In the case of the Sun, this circumstellar dust presumably served as the building material for our planetary system. Therefore, dust orbiting main-sequence stars offers the opportunity to study solar system–like environments, including planets, around stars besides the Sun.

A useful measure of the amount of circumstellar dust is $\tau = L_{IR}/L_*$, the ratio of infrared energy radiated by dust grains, L_{IR}, to the total stellar luminosity, L_*. HR 4796A (A0 V, $m_V = 5.8$ mag, distance = 76 pc) has a value of τ of about 5×10^{-3}, more than twice the value of τ of the well-studied object β Pic (Jura 1991). HR 4796B (~M4, $m_V = 12.7$ mag), separated by 7″.7 from HR 4796A, appears to be a real physical companion. On the basis of its location on the H-R diagram, HR 4796B is a pre–main-sequence star with an age of approximately 3×10^6 yr (Jura et al. 1993). Although only ~0.2% of all main-sequence A-type stars have $L_{IR}/L_* > 10^{-3}$, it seems plausible that HR 4796A is undergoing a short-lived but relatively common phase of a few million years duration in the early evolution of A-type main-sequence stars rather than being in a rare but long-lived state of duration over 100 Myr.

The *IRAS* colors of HR 4796A, the only member of the binary system which could be detected from the ground at 20 μm, and thus the star assumed to dominate the *IRAS* data (Jura et al. 1993), can be explained by dust at a temperature of 110 K. The absence of dust warmer than 110 K indicates that there is little material closer to the star than about 40 AU. Here we explore the possibility proposed by Strom, Edwards, & Skrutski (1993), that a hole of this sort is evidence for the formation of planets (see Roques et al. 1994; Lazzaro et al. 1994; Lagage & Pantin 1994).

In this paper we assemble a variety of data and arguments in order to understand the origin and evolution of the dust orbiting HR 4796A. (1) Previous analysis of the photometry and low-resolution spectroscopy by Jura et al. (1993) suggested that HR 4796B lies above the main-sequence; we have searched for additional high-resolution spectroscopic confirmation of this view. (2) We have performed *K*-band speckle imaging to look for a stellar companion to HR 4796A that might be creating a hole in the circumstellar dust distribution, as has been

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observed to occur in younger T Tauri stars (Ghez et al. 1994; Dutrey, Guilloteau, & Simon 1994; Jensen, Mathieu, & Fuller 1994). (3) We have obtained a measure of the 800 μm flux from HR 4796A to estimate the mass of the dust orbiting HR 4796A. (4) We reconsider the size of the circumstellar particles around HR 4796A on the basis of recent models for interstellar grains (Kim, Martin, & Hendry 1994) to investigate whether the dust orbiting HR 4796A is simply the remnant, large-particle tail of the biggest interstellar particles or whether the circumstellar grains have undergone significant growth.

2. OBSERVATIONS

2.1. *High-Resolution Optical Spectroscopy*

On the nights of 1994 March 23 and 24, two of us (M. J. and R. C. S.) obtained spectra of both HR 4796A and HR 4796B with the bench-mounted echelle on the 1.5 m telescope at CTIO. We used the long blue camera, a TEK 2048 × 2048 CCD chip, and the KPGL2 grating. The spectra were measured between 3500 and 5900 Å with a resolution of about 5 km s^{-1}. The seeing was typically 2″, and most of the time the sky was clear. The data were reduced with standard IRAF routines.

2.2. 2 μm *Speckle Data*

Speckle imaging data in the photometric K band on HR 4796A were acquired on 1994 May 3 on the 4.0 m telescope at CTIO using the Steward Observatory 58 × 62 InSb speckle array camera (McCarthy, McLeod, & Barlow 1990). The scale was 0″.056 pixel^{-1}, which resulted in a field of view of 3″.5 × 3″.2. The point source SAO 223542 served as the reference star, and long exposures (50 s), which were obtained by co-adding the speckle data (100 ms exposures) on this source, indicate that the seeing was roughly 1″ during these observations. The processing and analysis of these data are described in Ghez, Neugebauer, & Matthews (1993). The speckle data are sensitive to structure such as the presence of companions between 0″.15 and 1″.6 from the star where the lower limit is set by diffraction and the upper limit is set by the size of the detector.

2.3. *Submillimeter Data*

We obtained CANSERV service time on the James Clerk Maxwell Telescope (JCMT) during 1994 January and May to observe HR 4796A at 800 μm with the UKT14 continuum bolometer. Data were obtained on two nights with a 14″ beam. We did not detect HR 4796A at 800 μm; the 3 σ upper limit to the flux is 28 mJy.

3. RESULTS AND INTERPRETATIONS

3.1. *Optical Spectra*

The most striking result from the optical spectroscopy is that we detected Hβ, Hγ, and the Ca H and K lines in emission from HR 4796B. The summed spectra from the data obtained on the two nights are shown in Figures 1 and 2 for the Hβ and the K-line emission, respectively. The heliocentric radial velocity of 4796B was 12 ± 2 km s^{-1} on both nights of our observations.

Although Balmer emission is found in nearly 30% of nearby field M-type dwarfs later than M2 (Stauffer & Hartmann 1986), this point is probably not relevant to HR 4796B, since it lies above the main-sequence. An argument in addition to those given in Jura et al. (1993) that the star is not a normal M-type dwarf is that its $(J-H)$ color of 0.75 mag measured by Jura et al. (1993) is distinctly larger than the value for this color for any of the 200 M dwarfs in a sample of local stars (Stauffer & Hartmann 1986), but is well within the range for this color found in M giants (Frogel & Whitford 1987). The emission lines in the spectrum of HR 4796B are consistent with the view that it is pre–main-sequence (Bastian et al. 1983; Walter 1986).

HR 4796 was found as an X-ray source both by *EXOSAT* and by *Einstein* (Giommi et al. 1991; Fabbiano, Kim, & Trinchieri 1992). Although the angular resolution of the X-ray telescopes is insufficient to determine which star in the HR 4796 system is the source of the X-ray emission, it is likely that HR 4796B is responsible for the observed X-ray flux, since it displays optical emission lines that are characteristic of stellar activity. However, a few young B-type main-sequence stars are X-ray sources, and it is not out of the question that HR 4796A contributes to the observed X-ray emission (Schmitt et al. 1993). In any case, the conversion from count rate to X-ray flux depends upon the temperature of the emitting gas and the amount of absorption between us and the source. Assuming

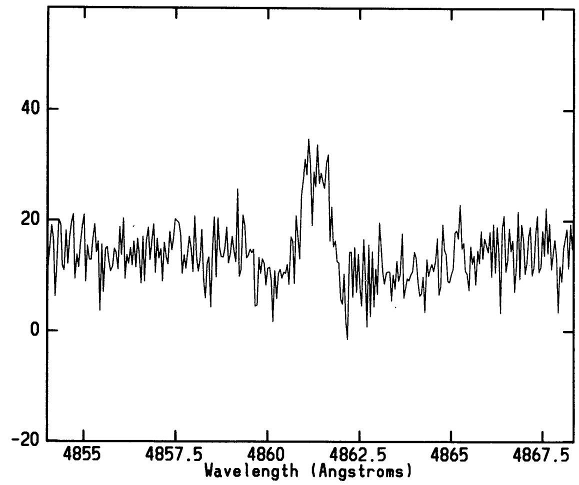

FIG. 1.—Summed spectra from two nights showing the Hβ emission line from HR 4796B.

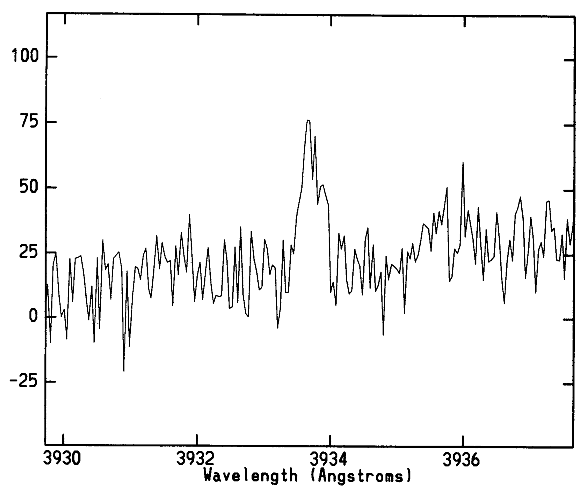

FIG. 2.—Summed spectra from two nights showing the calcium K emission line from HR 4796B.

the source has a "temperature" of 1 keV and that there is 10^{19} cm^{-2} of hydrogen between us and the source, then the *EXOSAT* count rate of 31.8×10^{-3} s^{-1} corresponds to a flux of 3×10^{-12} ergs cm^{-2} s^{-1} (Giommi et al. 1991). The flux measured with the *Einstein* telescope of 41×10^{-3} IPC counts s^{-1} corresponds to 7×10^{-13} ergs cm^{-2} s^{-1} if we assume a very small amount of interstellar absorption (D.-W. Kim 1994, private communication). At a distance of 76 pc, these measured fluxes indicate an X-ray luminosity in the range $(1.2–5) \times 10^{-4}$ $L_{\odot}$. Given that the bolometric luminosity of HR 4796B is 0.15 $L_{\odot}$ (Jura et al. 1993), the data imply that if HR 4796B is the X-ray source, then $L_X/L_{bol} \sim (0.8–3) \times 10^{-3}$, a ratio that is close to the value found for other pre–main-sequence stars (Walter 1986). The X-ray data are consistent with the hypothesis that HR 4796B is a pre–main-sequence star.

The optical spectrum of HR 4796A is that of a main-sequence A-type star. The rotational velocity, $v \sin i$, roughly equals 120 km s^{-1}. Because its lines are broad, we have a less precise value for the heliocentric radial velocity of HR 4796A, which we measured to be 8 ± 5 km s^{-1}, near the value in the Yale Bright Star Catalogue of 6 km s^{-1}. Given that the radial velocities of HR 4796A and HR 4796B are close to each other, there is no evidence that either is a close binary. Also, we did not detect any narrow features toward HR 4796A ($W_{\lambda} < 10$ mÅ) from either interstellar or circumstellar calcium H or K. Similarly, Grady (1994) has been unable to detect any ultraviolet absorption lines in the *IUE* spectrum of HR 4796A. This lack of detectable circumstellar gas is in contrast to β Pic, where the Ca II K line has been measured to vary in equivalent width, sometimes being in excess of 100 mÅ (Lagrange-Henri et al. 1992).

3.2. *Speckle*

As discussed in Ghez et al. (1993), a limit on the brightness of a secondary star is obtained by projecting the two-dimensional power spectra of the speckle data along 36 different azimuths spaced by 5° intervals, and inspecting how far these projected power spectra deviate from unity, which is expected from a perfectly unresolved source. The 36 distinct power spectra of the speckle data are shown in Figure 3, and within the noise they all agree with one another. Since the maximum deviation of $p(f)$ from 1.0 between 0 and 6.6 cycles $arcsec^{-1}$ is 0.1, our data indicate that any companion to HR 4796A separated by between 1″6 and 0″15 is fainter by at least 3.9 mag at *K*. This means that there is no companion with $m_K < 9.7$ mag between 11 and 120 AU from HR 4796A.

We interpret the speckle data to indicate that HR 4796A does not have any close stellar companion with a mass larger than 0.125 $M_{\odot}$. With M_K (HR 4796A) = 1.40 mag (Jura et al. 1993), our observational limit for m_K implies that any companion must have $M_K \geq 5.30$ mag. Since analysis of HR 4796B indicates that the system has an age of 3×10^6 yr, it is necessary to consider models for pre–main-sequence stars (Nelson, Rappaport, & Joss 1993; Burrows et al. 1993). In the models of Burrows et al. (1993), stars of 0.125 and 0.08 $M_{\odot}$ (each with an age of 3×10^6 yr) have luminosities of 0.063 and 0.045 $L_{\odot}$. These luminosities correspond to $M_{bol} = 7.72$ and 8.09 mag, respectively, for M_{bol}(Sun) = 4.72 mag (Saumon et al. 1994).

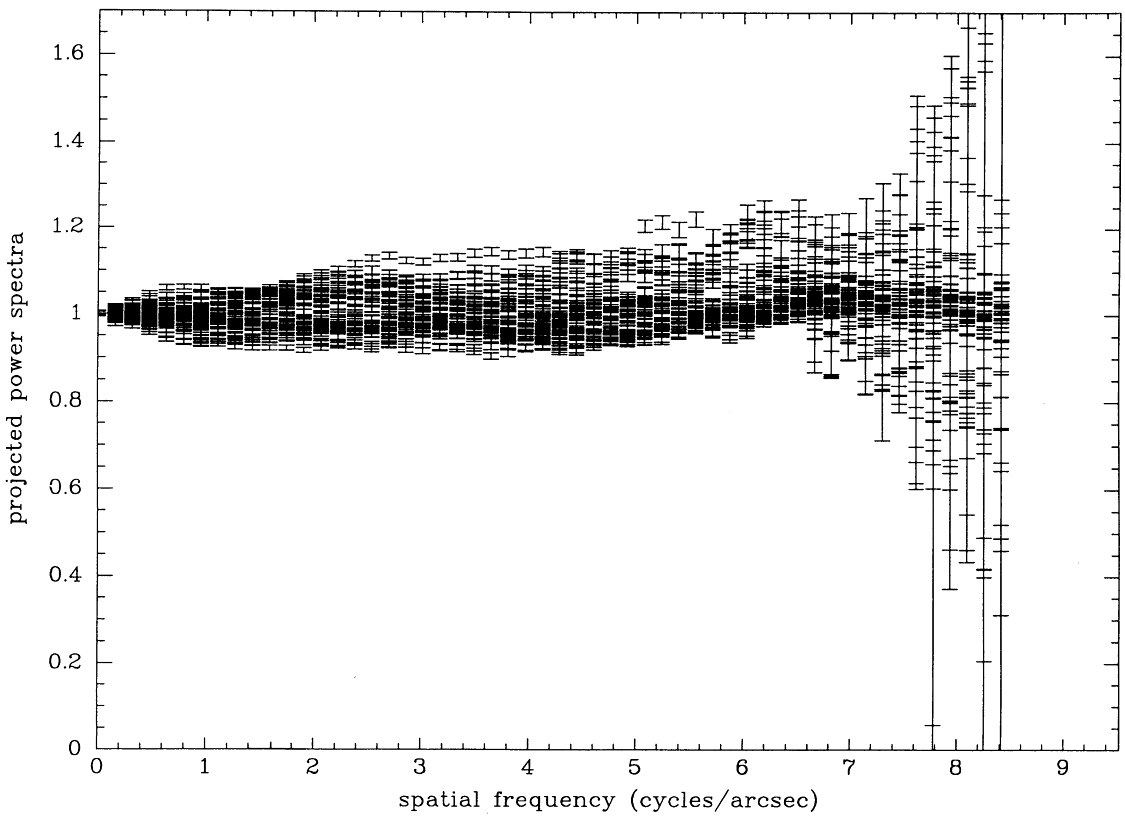

FIG. 3.—The 36 projected *K*-band (2.2 μm) power spectra of HR 4796A. Each power spectrum is computed for the speckle data along a specific azimuth, with each azimuth being spaced by 5°. Within the noise, these curves agree with each other and deviate very little from that expected for a point source, $p(f) = 1$. Consequently, there is no evidence for a close companion to HR 4796A.

With the assumption that the $(J-K)$ color of this putative close companion to HR 4796A is the same as that of HR 4796B, and by using the colors for old dwarfs from Bessell (1991), we would expect that $M_K = M_{bol} - 2.8$ mag. Consequently, the stars with masses of 0.125 and 0.08 $M_\odot$ would have $M_K = 4.92$ and 5.29 mag, respectively. Both absolute magnitudes are brighter than our observed upper limit, and by this analysis we could argue that there is no close stellar companion to HR 4796A.

Reid & Gilmore (1984) propose that the bolometric correction for M-type dwarfs is:

$$M_{bol} = 1.08 M_K + 2.05 \ . \tag{1}$$

In this case, from the models of Burrows et al. (1993), for a star of 0.125 $M_\odot$ and an age of 3×10^6 yr, the predicted value for M_K is 5.25 mag. Our speckle data rule out the presence of such a star. However, a star of 0.08 $M_\odot$ and an age of 3×10^6 yr is predicted to have $M_K = 5.59$ mag. Therefore, our data exclude a nearby companion to HR 4796A of 0.125 $M_\odot$, but a star of 0.08 $M_\odot$ could be near HR 4796A and not have been detected with our speckle observations. The exact lower bound to this putative close stellar companion is uncertain because of uncertainties in the distance to the system, its age, theoretical models, and the bolometric correction.

4. PHYSICAL CONDITIONS

4.1. *Interstellar Environment of HR 4796*

Jura et al. (1993) suggested that HR 4796 might be a very young member of the upper Centaurus-Lupus region, where stars that are 15 Myr old have been identified (de Geus, de Zeeuw, & Lub 1989). In Figure 4, we display on the sky the relative locations of HR 4796 and the stars identified by de Geus et al. (1989) as belonging to this ~15 Myr old group. We also show the proper motion of HR 4796 and the average of the proper motions of the young stars. Finally, we exhibit the location of the CO cloud 316.5+21.0 (Keto & Myers 1989) or MBM 112 (Magnani, Blitz, & Mundy 1985), which has an estimated mass of ~400 $M_\odot$ for an assumed distance of 100 pc. The apparent proximity of HR 4796 to molecular material from which stars can be forming provides additional support for the youth of this object.

4.2. *Size of the Circumstellar Dust Grains*

Following Artymowicz (1988) and his notation, the outward radiation pressure force exceeds the inward gravitational force for spherical grains of radius a if

$$a < 3 L_* Q_{pr} / (16 \pi G M_* c \rho_s) \ . \tag{2}$$

For the grains of interest and for the mainly optical and ultraviolet light from the A-type star, HR 4796A, we expect that $2\pi a/\lambda \gg 1$, and therefore the effective cross section of the grains is close to the geometric cross section. In this case, $Q_{pr} \approx 1$. For HR 4796A, we estimate that the luminosity and mass are 35 $L_\odot$ and 2.5 $M_\odot$, respectively (Jura et al. 1993). With $\rho_s = 2.5$ g cm^{-3} (Pollack et al. 1994), we find that the minimum radius of grains orbiting HR 4796A is about 3 μm if the particles are to remain gravitationally bound. This argument assumes that the circumstellar cloud is optically thin; if it is optically thick, the

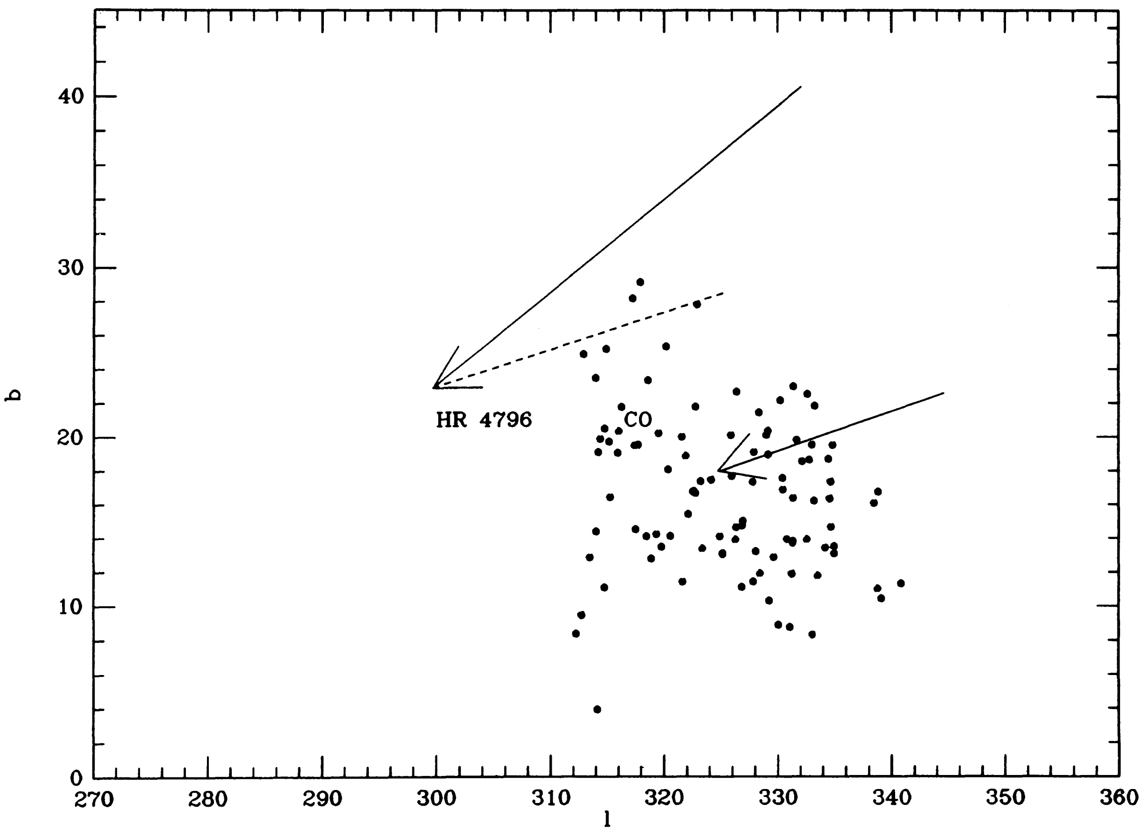

FIG. 4.—Map of the sky near HR 4796. We show all the stars in the upper Centaurus-Lupus association identified by de Geus et al. (1989). The position of the CO cloud, 316.5+21.0 or MBM 112, is also shown. The solid arrow near the stellar association shows the average of their proper motions during the past 10^6 yr. The solid arrow ending at HR 4796 shows its proper motion for the past 10^6 yr, and the dotted arrow shows the same motion if we apply the 2 σ variations listed in the Smithsonian catalog of stars.

radiation pressure is lower and the grains can be smaller than 3 μm in radius yet remain gravitationally bound to HR 4796A.

Another argument about the grain size can be derived from the Poynting-Robertson effect. According to Aumann et al. (1984), the lifetime t (yr) of a large ($Q \approx 1$) spherical grain in an optically thin environment in a circular orbit at a distance D (AU) from a star due to the Poynting-Robertson effect is

$$t = 7 \times 10^6 a\rho_s D^2/L_* \, . \tag{3}$$

We estimate that the grains probably lie between 40 and 200 AU from the star. The minimum radius of 40 AU for the dust hole is given by the calculation for the distance from the star that is required to produce a blackbody of 110 K. This estimate assumes that the grains emit as blackbodies; if there are strong emission bands, then this estimate of the grain temperature and inner radius of the hole may be somewhat in error. Also, if the grains are not large enough to act like blackbodies at infrared wavelengths, we can still estimate that the dust hole has a maximum radius of 200 AU because ground-based observations show that the 20 μm flux from the dust orbiting HR 4796A is smaller than 5″.4 in diameter (Jura et al. 1993). For $\rho_s = 2.5$ g cm^{-3}, $D = 40$ AU, $L_* = 35\, L_\odot$, and $t = 3 \times 10^6$ yr, we find that $a \approx 40$ μm. If the grains lie at 200 AU from the star, a could be as small as 1.5 μm, although this value seems unlikely because radiation pressure would then drive the particles into the interstellar medium unless the circumstellar cloud is optically thick.

4.3. *Mass of Circumstellar Dust around HR 4796A*

Because the submillimeter flux is less sensitive to the temperature of the grains than the infrared flux, the most accurate estimates of the dust mass can be made from the submillimeter flux. With $F_\nu(100\ \mu\mathrm{m}) = 4.1$ Jy (Jura 1991) and $F_\nu(800\ \mu\mathrm{m}) < 0.028$ Jy, then F_ν increases at least as rapidly as $\nu^{2.4}$ between 100 and 800 μm.

If F_ν denotes the submillimeter flux from the circumstellar dust, then the mass of the dust around a star, M_d, can be written (Zuckerman & Becklin 1993) as

$$M_d = F_\nu R^2 \lambda^2/[2kT_{\mathrm{gr}} K_{\mathrm{abs}}(\lambda)] \tag{4}$$

if R denotes the distance from the Sun to the star. Zuckerman & Becklin (1993) very conservatively used $K_{\mathrm{abs}}(800\ \mu\mathrm{m}) = 1.7$ cm^2 g^{-1} to estimate minimum masses. Because we want to place an upper limit on the mass, we adopt a value of K_{abs} that is a factor of 4 smaller than this value (Zuckerman & Becklin 1993). For $T_{\mathrm{gr}} = 110$ K, $R = 76$ pc, and our observation that $F_\nu(800\ \mu\mathrm{m}) < 28$ mJy, we find that $M_d < 8 \times 10^{27}$ g.

Another argument about M_d comes from the amount of optical and ultraviolet that is reprocessed, the result that $L_{\mathrm{IR}}/L_* = \tau$. If we assume a thin shell of dust at distance D from the star and if the particles are spheres of radius a, and if the cross section of the particles equals their geometric cross section, then

$$M_d \geq 16\pi\tau\rho_s D_{\mathrm{cm}}^2\, a/3 \, , \tag{5}$$

where D_{cm} is the distance from the star in centimeters. From equation (3) and an estimate of the age of the system of 3×10^6 yr, we can constrain the product $\rho_s D_{\mathrm{cm}}^2 a$. Therefore, with $\tau = 5 \times 10^{-3}$, we find that $M_d > 3 \times 10^{26}$ g. The upper limit to the flux at 800 μm together with this argument imply that

$$3 \times 10^{26}\ \mathrm{g} < M_d < 8 \times 10^{27}\ \mathrm{g}\, . \tag{6}$$

These limits bracket the value of 7×10^{26} g found by Zuckerman & Becklin (1993) for the amount of dust around β Pic, once again pointing to a similarity between β Pic and HR 4796A. Also, this mass in circumstellar dust around HR 4796A is comparable to the mass of the Earth.

5. IMPLICATIONS

Observations of pre–main-sequence Ae and Be stars indicate that the masses of dust in the regions between 10 and 100 AU are typically near 10^{30} g, but with a variation of at least a factor of 10 (Hillenbrand et al. 1992). Assuming that HR 4796A was once a typical Herbig Ae/Be star, it is possible that the dust presently detected orbiting HR 4796A at $D > 40$ AU is a remnant of the initial dust mass, although for older main-sequence stars with detected circumstellar dust this seems unlikely because of the short lifetime of the dust (Zuckerman & Becklin 1993).

Based on our inferred circumstellar dust particle size compared with models for the sizes of interstellar grains, we argue that the dust grains orbiting HR 4796A are not simply large particles left over from the interstellar cloud that formed this star. Kim et al. (1994) have derived a size distribution of interstellar grains given by

$$n(a)da = a^{-3.06} \exp{(-a/a_b)} \tag{7}$$

with $a_b = 0.14$ μm for silicates and

$$n(a)da = a^{-3.48} \exp{(-a/a_b)} \tag{8}$$

with $a_b = 0.28$ μm for graphite. The range of validity is up to about 1 μm, but with modest extrapolation these equations show that less than 10^{-6} of the mass of the interstellar grains is contained in particles with $a > 3$ μm. Because we think that $\sim 10^{-3}$ of the initial dust mass is now found in particles with $a > 3$ μm, it seems that there is much more mass in large grains than would be expected if we are simply observing the remnants of the large particle tail of the interstellar grain size distribution.

Even if the model of Kim et al. (1994) is not a fully accurate representation of the sizes of interstellar grains, there is additional evidence from meteorites that there is little mass in interstellar particles with radii larger than 3 μm. That is, on the basis of their isotopic abundances, surviving interstellar grains can be identified within meteorites. In laboratory studies of meteorites, there is a very strong preference to find the largest particles. However, about 95% of the mass in the laboratory-identified SiC is in particles with radii smaller than 1.5 μm, and most of the laboratory-identified graphite particles have radii smaller than 3.5 μm (Anders & Zinner 1993; Ott 1993).

Since the particles at $D > 40$ AU from HR 4796A are much larger than interstellar grains, they must have grown from the smaller interstellar particles by coalescing, which in turn ensures their survival in orbit. It seems quite plausible that the solid particles at $D < 40$ AU that were originally present around HR 4796A also underwent coalescence. Because the collisions were more frequent for the particles closer to the star (Shu, Adams, & Lizano 1987), there they could have undergone a much more pronounced degree of coalescence and grown into macroscopic objects which are expected to clear a hole in the dust distribution.

If a hole in a dust distribution is created by a close companion, Artymowicz & Lubow (1994) have argued that the companion should lie at about half of the inner radius of the hole.

This implies that any companion that produces the inferred dust hole around HR 4796A should lie between 20 and 100 AU from the star. Our data exclude any close stellar companion to HR 4796A with $M > 0.125\ M_{\odot}$ between 11 and 120 AU. A plausible explanation for the hole in the dust distribution is that a substellar object formed.

Although a straightforward interpretation of the data is that a very low mass star or a planet formed around HR 4796A, there are other models to explain the data. For example, it is possible that at some time in the past there had been a nearby companion to HR 4796A, but then its orbit was perturbed by another star that happened to pass nearby (Clarke & Pringle 1991). However, in this case, the orbit of HR 4796B might have been greatly affected as well. Also, the evolution of dust clouds around young stars is sufficiently complex that there may well be other explanations for the lack of dust at $D < 40$ AU around HR 4796A (Morfill, Spruit, & Levy 1993). Nevertheless, because dust coalescence has occurred, a simple interpretation of our results is that a planet formed around HR 4796A.

6. CONCLUSIONS

We have combined observations at several wavelengths to develop a better understanding of the HR 4796 system.

1. We find that Hβ, Hγ, and the calcium H and K lines are in emission from HR 4796B. These data are consistent with the picture that the star is later than M2 and that it lies above the main sequence with an indicated age from its location on the H-R diagram near 3×10^6 yr. This star is probably responsible for the X-rays from this system.

2. Speckle data show there is no companion star between 11 and 120 AU from HR 4796A with $M > 0.125\ M_{\odot}$ if the age of the system is 3×10^6 yr.

3. The dust particles orbiting HR 4796A are mainly located farther than 40 AU from the star; they most likely have radii larger than 3 μm if the circumstellar dust cloud is optically thin.

4. The existing particles at $D > 40$ AU are larger than the vast majority of interstellar dust grains; this implies that the circumstellar dust has undergone significant coalescence.

5. If dust coalesced to a moderate degree at $D > 40$ AU from the star, then it seems plausible that it coalesced into even larger objects closer to the star.

6. A dust hole with an inner radius between 40 and 200 AU can be understood if there is a companion object between 20 and 100 AU from HR 4796A. This putative companion has a mass less than $0.125\ M_{\odot}$; it might be a planet.

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