HD 98800: A 10 Myr Old Transition Disk

E. Furlan, B. Sargent, N. Calvet, W. J. Forrest, P. D’Alessio, L. Hartmann, D. M. Watson, J. D. Green, J. Najita, and C. H. Chen

Received 2006 December 1; accepted 2007 April 30

ABSTRACT

We present the mid-infrared spectrum, obtained with the Spitzer Infrared Spectrograph (IRS), of HD 98800, a quadruple star system located in the 10 Myr old TW Hydrae association. It has a known mid-infrared excess that arises from a circumbinary disk around the B components of the system. The IRS spectrum confirms that the disk around HD 98800B displays no excess emission below about 5.5 μm, implying an optically thick disk wall at 5.9 AU and an inner, cleared-out region; however, some optically thin dust, consisting mainly of 3 μm-sized silicate dust grains, orbits the binary in a ring between 1.5 and 2 AU. The peculiar structure and apparent lack of gas in the HD 98800B disk suggests that this system is likely already at the debris disks stage, with a tidally truncated circumbinary disk of larger dust particles and an inner, second-generation dust ring, possibly held up by the resonances of a planet. The unusually large infrared excess can be explained by gravitational perturbations of the Aa+Ab pair puffing up the outer dust ring and causing frequent collisions among the larger particles.

Subject headings: binaries: close — circumstellar matter — infrared: stars — planetary systems: formation — stars: individual (HD 98800)

1. INTRODUCTION

During the last few years, particular interest has arisen for a certain stage in the evolution of circumstellar disks surrounding T Tauri stars: so-called transition disks, which are characterized by cleared-out or optically thin inner disk regions and a truncated optically thick outer disk. They are thought to be in a phase when the disk dissipates rapidly from inside out (e.g., Strom et al. 1989; Skrutskie et al. 1990), on a timescale of ~10^7 yr. A few disks in transition have been identified in the 1–2 Myr old Taurus star-forming region (Forrest et al. 2004; D’Alessio et al. 2005; Calvet et al. 2005); the different amount of material left over in the inner and outer disks of these transition objects implies different formation mechanisms or stages in disk evolution (Calvet et al. 2005). Planet formation, which is thought to occur in circumstellar disks around T Tauri stars, might play a role in the clearing of inner disks (Marsh & Mahoney 1992; Calvet et al. 2002; Quillen et al. 2004; D’Alessio et al. 2005), but it is not well known whether other mechanisms, such as photoevaporation, can produce these transition disks (e.g., Alexander et al. 2006).

On the other hand, disks with inner gaps can also be found in stable, long-lived configurations: a binary star system surrounded by a circumbinary disk might create an inner gap due to resonant and tidal interactions (Artymowicz & Lubow 1994), thus generating a spectral energy distribution (SED) typical of transition disks. For example, the T Tauri star ST 34, which is a spectroscopic binary, has an inner disk depleted in dust, likely an effect of the gravitational perturbations of the binary on the inner disk regions (Hartmann et al. 2005). Since this system is likely older than 10 Myr, its disk configuration cannot be attributed to a short-lived transitional stage.

In the ~25 member TW Hya association, which is 5–15 Myr old (Stauffer et al. 1995; Webb et al. 1999; Weintraub et al. 2000), four objects are characterized by significant infrared excesses: TW Hya, Hen 3-600, HD 98800, and HR 4796A (e.g., Low et al. 2005). Except for HR 4796A, whose weaker infrared excess clearly places it into the debris disk category, these stars are surrounded by substantial, probably protoplanetary, disks. Both TW Hya and Hen 3-600 display close to no disk emission below 7 μm, an indication of truncated inner disks (Uchida et al. 2004). In particular, TW Hya has been suggested as the formation site of a protoplanet based on its inner disk gap (Calvet et al. 2002). Hen 3-600 consists of a spectroscopic binary (the A component) and a companion separated by 1.4′′ (e.g., Webb et al. 1999); the disk surrounds only Hen 3-600A (Jayawardhana et al. 1999a), implying that the inner disk gap might be a result of gravitational perturbations, as in the case of ST 34.

In this paper we introduce the mid-infrared spectrum from 5 to 36 μm of HD 98800 (TY CRI) obtained with the Infrared Spectrograph (IRS; Houck et al. 2004) on board the Spitzer Space Telescope (Werner et al. 2004). HD 98800 is a quadruple system consisting of a visual binary with a projected separation of 0.8″ (which corresponds to 38 AU at the distance of 47 pc determined by Hipparcos) whose components are spectroscopic binaries with separations of about 1 AU (Boden et al. 2005). Mid-infrared imaging revealed that the strong infrared excess of the system arises from component B only; in addition, it sets in at about 7 μm, implying cleared-out inner disk regions (Gehrz et al. 1999; Koerner et al. 2000; Prato et al. 2001). Our mid-infrared spectrum confirms that the disk around HD 98800 is a transition disk and allows us to determine the location of the circumstellar dust.

1 NASA Astrobiology Institute and Department of Physics and Astronomy, University of California, Los Angeles, CA 90095; furlan@astro.ucla.edu.
2 NASA Postdoctoral Program Fellow.
3 Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627; forrest@pas.rochester.edu, dmw@pas.rochester.edu, bsargent@pas.rochester.edu, joel@pas.rochester.edu.
4 Department of Astronomy, University of Michigan, Ann Arbor, MI 48109; ncalvet@umich.edu, lhartm@umich.edu.
5 Centro de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, 58089 Morelia, Michoacan, Mexico; p.dalesio@astrosmo.unam.mx.
6 National Optical Astronomy Observatory, Tucson, AZ 85719; cchen@noao.edu, najita@noao.edu.
7 Spitzer Fellow.
as well as to derive its mineralogical composition. This paper is structured as follows: in §2 we present our observations and data reduction; in §3 we construct the SED of HD 98800B, and fit dust and disk models to it; and in §4 we present a discussion of this transition disk and our conclusions.

2. OBSERVATIONS AND DATA REDUCTION

HD 98800 was observed during IRS campaigns 9 and 17 on 2004 June 25 and on 2005 January 3, respectively. The observations of campaign 17 repeated those of campaign 9, since the observations of the earlier campaign were somewhat compromised by a bright saturation event. However, the observations of campaign 17 were slightly mispointed; since we were able to mitigate the effects of the saturation on the array (apparent mostly in the form of additional rogue pixels), we used the IRS spectrum of campaign 9 for our analysis.

To obtain the full mid-infrared spectrum, we used the Short-Low (SL; 5.2–14 μm; λ/Δλ = 60–120), Short-High (SH; 9.9–19.6 μm; λ/Δλ = 600), and Long-High (LH; 18.7–37.2 μm; λ/Δλ = 600) modules. For a clearer presentation of the IRS spectrum, we rebinned the SH and LH spectra to a resolution of 300, and we truncated the SH spectrum below 14 μm. The observations were carried out in mapping mode, where we mapped the target in three steps separated by three quarters (for SL) or half (for SH and LH) of the slit width in the dispersion direction and two steps separated by a third of a slit length in the spatial direction.

We extracted and calibrated our data with the SMART software tool (Higdon et al. 2004) after fixing bad pixels in the arrays using a simple interpolation over good, neighboring pixels in the spectral direction. In SH and LH, we also fixed all so-called rogue pixels identified in darks from campaigns 1 to 18 (for LH) or from 1 to 28 (for SH). We subtracted the background of our SL spectrum by using the observation taken in the other nod position from 1 to 28 (for SH). We subtracted the background of our SL spectrum by using the observation taken in the other nod position from 1 to 28 (for SH). We subtracted the background of our SL spectrum by using the observation taken in the other nod position from 1 to 28 (for SH). We subtracted the background of our SL spectrum by using the observation taken in the other nod position from 1 to 28 (for SH). We subtracted the background of our SL spectrum by using the observation taken in the other nod position from 1 to 28 (for SH). We subtracted the background of our SL spectrum by using the observation taken in the other nod position from 1 to 28 (for SH).

To mitigate the effects of the saturation on the array (apparent mostly in the form of additional rogue pixels), we used the IRS spectrum of campaign 9 for our analysis.

By comparing the 10 and 24 μm emission derived from our IRS spectrum of HD 98800 with ground- and space-based measurements (Jayawardhana et al. 1999b; Low et al. 2005), we infer an absolute spectrophotometric accuracy of ~5%. Our relative accuracy, determined by the scattering of neighboring flux values, is higher in SL than SH and LH: features above the noise level are very likely real in SL, while LH is still dominated by calibration artifacts.

3. ANALYSIS

3.1. Spectral Energy Distribution

Previous observations of HD 98800 indicated that the infrared excess originates from a circumbinary disk around the component B spectroscopic binary. The SED is consistent with it being a transition disk, extending between a few and ~10–20 AU (Koerner et al. 2000; Prato et al. 2001). Observations of the Hα line, which did not distinguish the emission from the four components, revealed a total Hα equivalent width of 0.9 Å and a width comparable to that of Pleiades K dwarfs, suggesting an origin in chromospheric activity and not in an accretion flow (Soderblom et al. 1996). An upper limit to the mass accretion rate has not been determined, but it is likely well below 10^{-11} M_⊙ yr^{-1} (Muzerolle et al. 2000); thus, accretion onto HD 98800B has virtually come to a halt. The absence of accretion signatures (Soderblom et al. 1996; Webb et al. 1999) is in accordance with the lack of dust emission from the inner disk, i.e., the outer disk is prevented from accreting toward the star.

Our Spitzer IRS observations included emission of all four components of the system, since the narrowest IRS slit is 3.6″ wide. Therefore, in the SED shown in Figure 1, we used unresolved optical to far-infrared photometry of HD 98800 (see figure caption for details) and the IRS spectrum, all corrected for reddening using A_V = 0.44 (e.g., Soderblom et al. 1998) and Mathis’s reddening law (Mathis 1990). Also shown is the photospheric emission of a K5 star (Soderblom et al. 1998; Prato et al. 2001), based on the photospheric colors of a star with this spectral type (Kenyon & Hartmann 1995) and normalized at the unresolved Two Micron All Sky Survey (2MASS) J-band flux. Despite the fact that our IRS observation does not distinguish the emission from A and B, the SED suggests that none of the four components generate excess emission above the level expected from a stellar photosphere out to about 6 μm. This supports the idea that the inner disk of HD 98800 has been cleared out.

In order to retrieve the true IRS spectrum of the B component, we estimated the contribution of the A component and subtracted it from the spectrum. Component A does not display an infrared excess and has an extinction A_V ~ 0 (Koerner et al. 2000; Prato et al. 2001; Boden et al. 2005), while Ba+Bb seem to lie behind A_V = 0.44 (e.g., Soderblom et al. 1998). This difference in extinction likely indicates that we are observing HD 98800B through some circumbinary dust, as first noted by Tokovinin (1999); this could also explain the slight photometric variability observed by Soderblom et al. (1998).

We estimated the mid-infrared emission of HD 98800A by using the photospheric colors of a K5 star (Kenyon & Hartmann 1995) normalized at the J-band flux of the A component given in Prato et al. (2001). This estimate is consistent with the measurements by Prato et al. (2001), who determined that the contribution of A to the system flux decreases with wavelength (50%, 44%, 30%, and 20% at 2.2, 4.8, 7.9, and 8.8 μm, respectively,
and less than 10% at longer wavelengths). The subtraction of the estimated emission of the A component from the IRS spectrum will affect both the flux level and shape of the spectrum particularly in the 5–8 μm wavelength range; given that we do not account for atmospheric features, the resulting spectrum carries a higher uncertainty in this wavelength region.

The SED of HD 98800B is shown in Figure 2; it was constructed with photometry of the B component compiled by Prato et al. (2001), Multiband Imaging Spectrometer for Spitzer (MIPS) fluxes from Low et al. (2005), Infrared Astronomical Satellite (IRAS) fluxes, the IRS spectrum corrected for the contribution of A, and the photosphere of B (approximated using the colors of a K5 star normalized at the J-band flux of B). The emission of B is photospheric out to about 5.5 μm; beyond that, the infrared excess sets in rather sharply. The steep rise of the SED at 8 μm is reminiscent of that observed in CoKu Tau/4, a transition disk in the Taurus star-forming region with an inner disk hole of 10 AU (Forrest et al. 2004; D'Alessio et al. 2005). The SED peaks at 20 μm, then decreases as a single-temperature blackbody. The outer disk is likely truncated by component A, whose distance from B is almost 50 AU at closest approach (Torres et al. 1995; note that the orbit of B around A is very eccentric and seen almost edge-on). Thus, the disk around the spectroscopic binary HD 98800B seems to be truncated both at the inner and at the outer disk edge.

3.2. Dust Composition

Koerner et al. (2000) inferred from broadband photometry in the 10 μm region that the silicate emission feature of HD 98800B is broader and more structured than expected from amorphous silicates, indicating the presence of crystalline silicates. The IRS spectrum allows us to analyze the 10 μm silicate feature in greater detail and to derive the dust species that generate the infrared excess emission.

First, we subtracted the photospheric emission, constructed from the colors of a K5 star normalized at the J-band flux, from the dereddened IRS spectrum of HD 98800B. Next, given the large infrared excess and the presence of 10 and 18 μm silicate emission features, we fit the residuals with two components: an optically thick region modeled as a blackbody, and a warmer, optically thin region of constant source function (also modeled as a blackbody),

\[
F_\nu = \Omega_{\text{thick}}B_\nu(T_{\text{thick}}) + \Omega_{\text{thin}}B_\nu(T_{\text{thin}})(1 - e^{-\tau_\nu}),
\]

where \(T_{\text{thick}}\) is the blackbody temperature of the optically thick region, \(T_{\text{thin}}\) is that of the optically thin region, \(\tau_\nu\) is the wavelength-dependent optical depth of the optically thin cloud, and \(\Omega_{\text{thick}}\) and \(\Omega_{\text{thin}}\) are the solid angles of the emitting regions for the optically thick and thin components, respectively.

The optically thick component can be thought of as consisting of large (millimeter-sized) dust grains, which do not generate spectral features and whose opacities are independent of wavelength, thus creating a continuum component with a blackbody-type emission. Alternatively, a very large mass of small grains will generate blackbody-shaped, optically thick emission. Thus, the detailed composition of the dust only enters in the optically thin component.

For optically thin emission, the flux becomes linearly dependent on the optical depth, which can be expressed as the sum of the optical depth of each dust component \(\tau_\nu = \kappa_\nu N_i\), where \(\kappa_\nu\) and \(N_i\) are the mass absorption coefficient and column density for each dust species, respectively. Since the mass of each dust species is derived via \(m_i = N_i / \Omega_{\text{thin}} d^2\), where \(\Omega_{\text{thin}}\) is the solid angle subtended by the dust and \(d\) is the distance to the system (assumed to be 47 pc), the total optical depth of the optically thin component can be expressed as

\[
\tau_\nu = \sum_{i=1}^{N} \frac{\kappa_\nu m_i}{\Omega_{\text{thin}} d^2},
\]

where the sum is carried out over the number \(N\) of dust components. Thus, the dust emission is calculated as

\[
F_\nu = \Omega_{\text{thick}}B_\nu(T_{\text{thick}}) + \frac{1}{d^2} B_\nu(T_{\text{thin}}) \sum_{i=1}^{N} \frac{\kappa_\nu m_i}{\Omega_{\text{thin}} d^2}.
\]

We solved the linear model for the best-fitting set of temperatures \(T_{\text{thick}}\) and \(T_{\text{thin}}\), solid angle \(\Omega_{\text{thick}}\), and dust masses \(m_i\), starting with just one dust component and adding components as necessary to improve the fit.

For the optically thin dust species, we adopted amorphous carbon and silicates, which are typical for the interstellar medium (ISM). We used optical constants from Draine & Lee (1984) for \(\lambda < 7.5 \mu m\) and from Dorschner et al. (1995) for \(\lambda > 7.5 \mu m\) (using power laws to extrapolate values from 200 μm to 2 mm) for amorphous silicates of olivine (MgFeSiO4) and pyroxene (Mg0.8Fe0.2SiO4) composition, and optical constants from Zubko et al. (1996) for amorphous carbon. For submicron grains, we used a CDE2 shape distribution (Fabian et al. 2001) to compute opacities, while larger grains (≥1 μm) were adopted to be porous spheres with a 50% volume fraction of vacuum.

The first model attempts, using only submicron (i.e., ISM-like) olivine or pyroxene grains as the optically thin component, yielded poor fits (for an example, see Fig. 3); the emission at the long-wavelength side of both the 10 and 18 μm silicate features is underestimated, suggesting the presence of larger grains. Amorphous pyroxene represents a better fit to the observed peak positions of the 10 and 18 μm features than amorphous olivine, so it was assumed as the dominant large grain species.

The best-fitting models, ordered by decreasing reduced χ² values (χ²), which were calculated from 6.5 μm to 1.3 mm, are
shown in Figure 4 with the residuals of HD 98800B. The adopted model components and their parameters are displayed in Table 1. We note that most of the structure seen in the 5–6.5 μm region of the residuals is likely due to photospheric features from the four stellar components of the system, which we did not account for in our photosphere subtraction process. Thus, we expect a mismatch between models and residuals in this part of the spectrum, and we did not include these data points in the computation of our χ² values.

We first tried a model with an optically thick component at 155 K and a single optically thin component consisting of 5 μm amorphous pyroxene (Fig. 4a). This fit improved by adding submicron amorphous carbon to the dust mixture (Fig. 4b); in particular, the short-wavelength excess starting at about 6.5 μm is fit better. A slightly better fit of the silicate feature was achieved by using 3 μm amorphous pyroxene and small amorphous carbon as the optically thin component (Fig. 4c). Finally, the best fit was obtained by adding 3 μm amorphous olivine to the previous mixture and adopting an optically thick component at 152 K (Fig. 4d). For all of the models shown in Figure 4, the adopted solid angle lies in the (1.4–1.5) × 10⁻¹³ sr range, and the temperature of the optically thin grains is higher than that of the optically thick component by about a factor of 2 (see Table 1). Even though the differences between these four models are small (especially if judged by eye), the best fit determined here for the optically thin disk region around HD 98800B is confirmed by our disk model in §3.3.

The best model fit and its components are shown in Figure 5 with the residuals of HD 98800B over the mid-infrared to millimeter wavelength range. The model fits the entire excess emission from 6.5 μm to 1.3 mm remarkably well. Table 2 lists the parameter values of this model together with their 1σ uncertainties, which were estimated from models lying within Δχ² = 1 of the best-fitting model. Since the optically thin component is more dominant and tightly constrained by all the measurements beyond about 14 μm, the relative uncertainties for both T_thick and T_mult are smaller than for the parameters describing the optically thin component. We derive a combined mass for the optically thin dust grains of 4.7 × 10⁻⁴ lunar masses. The mass of the optically thick component cannot be constrained, but it is likely several orders of magnitude larger than the mass of the smaller grains.

The fact that dust grains larger than ISM-type amorphous grains (whose sizes are ≤1 μm) constitute the bulk of the optically thin component indicates that dust growth must have occurred in the disk of HD 98800B. The other two objects with substantial disks in the TW Hydrae association, TW Hya (K7 spectral type) and Hen 3-600A (M3 spectral type), are dominated by smaller grains and are characterized, in particular in the case of Hen 3-600A, by a notable fraction of crystalline grains (Sargent et al. 2006). Our dust model fit to HD 98800B excludes any sizable amount of small crystalline silicates, suggesting that the larger width of the 10 μm silicate feature already noted by Koerner et al. (2000) should likely be attributed to grain growth alone.

3.3. Disk Model

In order to derive the structure of the circumstellar material of HD 98800B, in addition to its composition, we computed a model following the methods of D’Alessio et al. (2005) and Calvet et al. (2005). The stellar luminosity of the Ba+Bb pair was adopted to be 0.7 L☉, a value obtained by integrating the photospheric fluxes of the unresolved B component, and the effective temperature was assumed to be 4350 K, typical for a K5 star (Kenyon & Hartmann 1995). The model has two components: an optically thick wall and an optically thin region, corresponding to the blackbody component and the optically thin dust grains, respectively, from the dust component fit of §3.2. Even though the model implicitly assumes the presence of gas in addition to the dust, no assumptions regarding the gas were made, since it does not enter any of the calculations.

The wall emission was calculated assuming amorphous carbon and silicate grains with sizes between 1 and 3 mm. Since the grains are so large, their opacities are gray (i.e., independent of wavelength), and thus their composition does not affect the fit; their emission corresponds to that of a scaled blackbody. Therefore, this wall matches the optically thick component of §3.2. The composition of the optically thin component was adopted from §3.2, namely submicron amorphous carbon, 3 μm–sized amorphous olivine, and 3 μm–sized amorphous pyroxene grains. The small amorphous carbon grains, which absorb stellar radiation more efficiently than the larger grains, are necessary to heat the dust and yield enough emission in the 6–8 μm range; the 3 μm–sized grains generate emission that provides a good fit to the silicate features at 10 and 20 μm.

The results of the model calculations are shown in Figure 6 and in Table 3. We show different model fits that result from varying the contribution of the optically thin and thick components. As in §3.2, the properties of the inner disk wall are well constrained by the flux measurements beyond about 14 μm; in order to obtain the correct blackbody shape, it has to be placed at a distance of 5.9 AU from the B pair, where the temperature in its upper layers (closest to the star) amounts to 140 K. Not surprisingly, this temperature is very similar to the one derived in §3.2 for the optically thick component. The height of the wall above the midplane is treated as a scale factor for the wall emission; it is adjusted such that the emission from the optically thick and thin components yields the best possible fit. For the best-fit model (Fig. 6d), this height is 0.75 AU. The solid angle subtended by the wall amounts to 1.57 × 10⁻¹³ sr (assuming a distance of 47 pc and an inclination angle of 67°, as determined by Boden et al. [2005]), which is just somewhat larger than the value of 1.46 × 10⁻¹³ sr derived from the best-fitting dust model in §3.2.
The optically thin component has to lie inside the region delimited by the optically thick wall in order to provide enough emission at wavelengths between 5 and 20 $\mu$m; in addition, its innermost location and radial extent are fairly well constrained by the observed $10^{10}$ $Y_{22}$ flux ratio. As can be seen in Figure 6a, an optically thin region extending from 2 to 5 AU will underestimate both the short- and long-wavelength excess emission; decreasing the outer radius results in a better match of the flux beyond 20 $\mu$m (Fig. 6b). Concentrating the optically thin region close to 2 AU yields a very good fit (Fig. 6c), while the best fit to the observations is obtained by an optically thin ring located between 1.5 and 2 AU (Fig. 6d). The dust grains in this ring are at a temperature between 307 and 266 K, similar to the value found for the best-fitting dust model of 3.2.

The wall radius of 5.9 AU we derive is comparable to the inner radius range of 5.0 ± 2.5 AU determined by Koerner et al. (2000) from simple SED models; both values are larger than the estimate of 2 AU derived by Prato et al. (2001) from fits to their unresolved mid-infrared images. However, our result is consistent with the fact that Prato et al. (2001) did not resolve the disk: the optically thin region is very compact and close to the binary, and even though at 12 $\mu$m the brightness of this region and that of

| Model | Dust Species | $T_{\text{thick}}$ (K) | $T_{\text{thin}}$ (K) | $\Omega_{\text{thick}}$ ($10^{-13}$ sr) | $\chi^2$ |
|-------|--------------|------------------------|-----------------------|---------------------------------|--------|
| a     | 5 $\mu$m amorphous pyroxene | 155 | 373 | 1.39 | 18.6 |
| b     | Small amorphous carbon + 5 $\mu$m amorphous pyroxene | 151 | 291 | 1.47 | 12.1 |
| c     | Small amorphous carbon + 3 $\mu$m amorphous pyroxene | 153 | 298 | 1.43 | 11.4 |
| d     | Small amorphous carbon + 3 $\mu$m amorphous pyroxene + 3 $\mu$m amorphous olivine | 152 | 310 | 1.46 | 8.0 |
the wall are comparable, the large inclination of the wall might have prevented its direct detection.

The optical depth of the optically thin component is displayed in Figure 7; it was computed using the best-fitting dust component model from $x_{3.2}$ and adopting a ring between 1.5 and 2 AU to determine $\Omega_{\text{thin}}$, which amounts to $5.85 \times 10^{-14}$ sr. Shown in the figure are the vertical optical depth (solid line) and the optical depth along the line of sight (dashed line), assuming an inclination angle of $67^\circ$. The latter quantity is actually an upper limit to the optical depth along our line of sight, since the thickness of the optically thin region is not known. Thus, since $\tau_0$ lies between 0.02 and at most 0.13 over the mid-infrared range and decreases steadily toward longer wavelengths, the inner disk region will appear as optically thin from infrared to millimeter wavelengths.

A sketch of the HD 98800 system is shown in Figure 8. There are two rings of material around the B component: an optically thick wall at 5.9 AU with a small radial extent, and an optically thin inner region between 1.5 and 2 AU, just outside the binary orbit. We discuss the implications of this peculiar structure in § 4.

4. DISCUSSION AND CONCLUSIONS

The mid-infrared spectrum of HD 98800B reveals that it is surrounded by a transition disk whose infrared excess emission starts at about $5.5 \mu m$ and decreases beyond $20 \mu m$. Its structure is somewhat reminiscent of that of the transition disks TW Hya (Calvet et al. 2002) and GM Aur (Calvet et al. 2005), which also harbor optically thin regions inside an outer, optically thick disk. However, as opposed to the these two objects, HD 98800 is a multiple system: the Ba and Bb stars form a close ($\sim1$ AU), eccentric ($e = 0.78$; Boden et al. 2005) binary system, and in addition the A pair comes as close as 50 AU to the B pair, with the orbital planes of the two binaries inclined by about $30^\circ$ with respect to each other (Torres et al. 1995; Boden et al. 2005).

The optical depth of the optically thin component is displayed in Figure 7; it was computed using the best-fitting dust component model from $x_{3.2}$ and adopting a ring between 1.5 and 2 AU to determine $\Omega_{\text{thin}}$, which amounts to $5.85 \times 10^{-14}$ sr. Shown in the figure are the vertical optical depth (solid line) and the optical depth along the line of sight (dashed line), assuming an inclination angle of $67^\circ$. The latter quantity is actually an upper limit to the optical depth along our line of sight, since the thickness of

the wall are comparable, the large inclination of the wall might have prevented its direct detection.

The optical depth of the optically thin component is displayed in Figure 7; it was computed using the best-fitting dust component model from $x_{3.2}$ and adopting a ring between 1.5 and 2 AU to determine $\Omega_{\text{thin}}$, which amounts to $5.85 \times 10^{-14}$ sr. Shown in the figure are the vertical optical depth (solid line) and the optical depth along the line of sight (dashed line), assuming an inclination angle of $67^\circ$. The latter quantity is actually an upper limit to the optical depth along our line of sight, since the thickness of

the wall are comparable, the large inclination of the wall might have prevented its direct detection.

The optical depth of the optically thin component is displayed in Figure 7; it was computed using the best-fitting dust component model from $x_{3.2}$ and adopting a ring between 1.5 and 2 AU to determine $\Omega_{\text{thin}}$, which amounts to $5.85 \times 10^{-14}$ sr. Shown in the figure are the vertical optical depth (solid line) and the optical depth along the line of sight (dashed line), assuming an inclination angle of $67^\circ$. The latter quantity is actually an upper limit to the optical depth along our line of sight, since the thickness of

the wall are comparable, the large inclination of the wall might have prevented its direct detection.

The optical depth of the optically thin component is displayed in Figure 7; it was computed using the best-fitting dust component model from $x_{3.2}$ and adopting a ring between 1.5 and 2 AU to determine $\Omega_{\text{thin}}$, which amounts to $5.85 \times 10^{-14}$ sr. Shown in the figure are the vertical optical depth (solid line) and the optical depth along the line of sight (dashed line), assuming an inclination angle of $67^\circ$. The latter quantity is actually an upper limit to the optical depth along our line of sight, since the thickness of

the wall are comparable, the large inclination of the wall might have prevented its direct detection.

The optical depth of the optically thin component is displayed in Figure 7; it was computed using the best-fitting dust component model from $x_{3.2}$ and adopting a ring between 1.5 and 2 AU to determine $\Omega_{\text{thin}}$, which amounts to $5.85 \times 10^{-14}$ sr. Shown in the figure are the vertical optical depth (solid line) and the optical depth along the line of sight (dashed line), assuming an inclination angle of $67^\circ$. The latter quantity is actually an upper limit to the optical depth along our line of sight, since the thickness of
Thus, gravitational perturbations likely play a role in the confinement and distribution of the dust around HD 98800B.

A circumbinary disk around an eccentric binary is expected to be tidally truncated at the inner disk edge (Artymowicz & Lubow 1994). If the eccentricity is large, several higher order resonances play a role in truncating the circumbinary disk by exerting tidal torques farther out in the disk; thus, gap sizes of $\sim 3.5a$ (where $a$ is the semimajor axis of the binary) can be explained (Artymowicz & Lubow 1994). However, these gravitational interactions apply to a gaseous disk, and the amount of gas in HD 98800 appears to be very small: the 1 $\sigma$ upper limit placed by Dent et al. (2005) on the submillimeter $^{12}$CO $J = 3-2$ line indicates an upper limit of $\sim 4 \times 10^{-4} M_{\odot}$ (which is less than 1/24 of the gas mass of TW Hya), assuming optically thin $^{12}$CO emission. Some warm gas could still be present in the inner disk regions, since the submillimeter $^{12}$CO line traces cold molecular gas in outer disk regions (where temperatures are below $\sim 100$ K), but given the lack of accretion signatures (Soderblom et al. 1996; Webb et al. 1999), the amount of gas in the inner disk should be small.

| TABLE 3 |
| --- |
| **Disk Model Fits of HD 98800B** |

| Model | $r_{in}$ (AU) | $r_{out}$ (AU) | $\tau_{10}$ | $T_{in}$ (K) | $T_{out}$ (K) | $R_{wall}$ (AU) | $H_{wall}$ (AU) |
| --- | --- | --- | --- | --- | --- | --- | --- |
| a | 2 | 5 | 0.04 | 266 | 175 | 5.9 | 0.56 |
| b | 2 | 4 | 0.04 | 266 | 193 | 5.9 | 0.68 |
| c | 2 | 2.2 | 0.22 | 267 | 255 | 5.9 | 0.75 |
| d | 1.5 | 2 | 0.06 | 307 | 266 | 5.9 | 0.75 |

Note.—The value $\tau_{10}$ is used a scaling factor for the emission of the optically thin component: $F_{\nu} = \int_{r_{in}}^{r_{out}} B_{\nu}(T_{dust})r_{\nu}[\tau_{10}/\kappa(10 \text{ \mu m})]^22\pi r dr$. 

Fig. 6.—Sequence of disk models for HD 98800B (thick gray lines); the SED is plotted as in Fig. 2. Also shown are the components of the disk models, the optically thick disk wall (dash-dotted lines), and the optically thin inner disk region (long-dashed lines). The four panels display different models where the optically thin region consists of a ring between $r_{in}$ and $r_{out}$, and the optically thick wall at 5.9 AU is scaled by means of the wall height to result in a good overall fit (see Table 3 for details).
In the absence of gas, the truncation of the outer disk at 5.9 AU could still be explained by the effect of resonances. Using the empirical formula determined by Holman & Wiegert (1999), who studied stable particle orbits around an eccentric binary, the smallest, stable orbit around HD 98800B \( (a = 0.98 \text{ AU}, e = 0.78, \mu = M_2/(M_1 + M_2) = 0.45; \text{Boden et al. 2005}) \) is at 4.06 AU, somewhat smaller than the result we obtained by fitting a disk model to the SED. However, Holman & Wiegert (1999) noted that the transition between stable and unstable orbits is likely not sharp due to the effects of overlapping mean motion resonances. They also found indications that, over time, the stable region moves farther out for high binary eccentricities.

While a tidally truncated disk at \( \geq 4 \text{ AU} \) could explain the location of the disk wall, it would not be able to account for the presence of optically thin dust grains at 1.5–2 AU. The most likely interpretation for the unusual structure of the circumstellar material of HD 98800B, also considering the probable scarcity of gas, is that the disk is already at the debris disks stage, when dust is its main constituent and is generated by collisions of larger bodies. The dust would be second-generation dust and not primordial material that survived for 10 Myr. The submicron carbon and 3 \( \mu \text{m} \)–sized silicate grains in the disk would be replenished on planetesimal collisions, which might occur in the optically thick ring at \( \sim 6 \text{ AU} \). Due to Poynting-Robertson (PR) drag, the larger dust grains would spiral in from 6 AU toward the binary on a timescale of a few \( 10^5 \text{ yr} \); since \( t_{PR} \propto aD^2/L_s \) (Burns et al. 1979), where \( a \) is the grain size, \( D = 6 \text{ AU} \), and \( L_s = 0.7 L_\odot \), smaller grains would migrate even faster. Since HD 98800 is about 10 Myr old, the optically thin, inner ring must be continuously replenished, assuming it is a long-lived structure.

If the inner dust ring is explained by PR drag, then the absence of grains from 2 to 5.9 AU is puzzling; drag forces acting on dust grains should distribute the dust uniformly inside the radius at which the dust grains are created. A possible explanation for the observed gap could be a planet that formed just outside the unstable region, i.e., close to the inner disk wall, and that is temporarily holding up dust grains (that were able to drift inward) at one of its inner mean motion resonances (Liou & Zook 1997; Moro-Martínez et al. 2005). In the case of TW Hya, a planet was thought to be responsible for clearing out the inner disk (Calvet et al. 2002), so it is conceivable that a planet also formed in the roughly coeval HD 98800 system. On the other hand, this system is probably governed by complex dynamics due to the presence of four stellar components, implying overlapping resonances and variable gravitational perturbations.

Given that the evidence supports that the disk around HD 98800B is rather a debris than a protoplanetary disk, the presence of an optically thick dust component and the large infrared excess \( (L_{IR}/L_{bol} = 17\%) \) of HD 98800B seem unusual, but they might be explained by the gravitational perturbations of the Aa+Ab pair. This type of perturbation can pump up eccentricities and inclinations of particles, and cause particles to be trapped in mean motion resonances, as was likely the case for Kuiper Belt objects under the influence of the giant planets and possibly a close encounter by a passing, nearby star (e.g., Duncan et al. 1995;
Ida et al. 2000; Gladman 2005). Periodic stirring of planetesimals in the outer disk around HD 98800B by the A pair could be responsible for generating copious amounts of dust (see Kenyon & Bromley 2002). HD 98800B is thus a unique type of debris disk, whose infrared excess is elevated to levels comparable to that of protoplanetary disks due to the particular configuration of the four components in this system, resulting in gravitational perturbations that prevent the dust from settling into a flat disk.

Even though HD 98800 appears to be a very dynamical system, it is unlikely to be in a short-lived transitional stage with ongoing clearing processes, in which the outer disk is being progressively eroded. HD 98800B belongs to a similar class of transition disks as St 34 and Hen 3-600A: a tight binary is responsible for tidal and resonant interactions with the disk, thus creating a stable, tidally truncated circumbinary disk. In addition, collisions between planetesimals in the outer disk of HD 98800B cause a collisional cascade of smaller grains, which then migrate toward the central binary. This outer disk is likely truncated due to the presence of the other component, as is the case with Hen 3-600A (Jayawardhana et al. 1999a). However, St 34 and Hen 3-600A are still accreting material, albeit at low levels ($2 \times 10^{-10} M_\odot$ yr$^{-1}$ for St 34; $\sim 5 \times 10^{-11} M_\odot$ yr$^{-1}$ for Hen 3-600A; White & Hillenbrand 2005; Muzerolle et al. 2000), while HD 98800B is probably not accreting any more. Thus, St 34 and Hen 3-600A are likely surrounded by evolved protoplanetary disks, while the disk around HD 98800 seems to have evolved even further.

The similarities and differences between the HD 98800 and Hen 3-600 systems could increase our understanding of disk evolution; the larger separation between Hen 3-600 Aa+Ab and B, and the fact that all three stars are of later spectral type, might play a role in the longer survival of primordial disk material around this system.

We thank an anonymous referee, whose comments led to a substantial improvement of this paper and a better understanding of this object. This work is based on observations made with the *Spitzer Space Telescope*, which is operated by the Jet Propulsion Laboratory, California Institute of Technology (JPL/Caltech), under NASA contract 1407. Support for this work was provided by NASA through contract 1257184 issued by JPL/Caltech. E. F. was supported by a NASA Postdoctoral Program Fellowship, administered by Oak Ridge Associated Universities through a contract with NASA. N. C. and L. H. acknowledge support from NASA grants NAG5-13210 and NAG5-9670, and STScI grant AR-09524.01-A. P. D. acknowledges grants from PAPIIT, UNAM, and CONACyT, Mexico. This publication made use of NASA’s Astrophysics Data System Abstract Service, and of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by NASA and the NSF.

### REFERENCES

Alexander, R. D., Clarke, C. J., & Pringle, J. E. 2006, MNRAS, 369, 229
Artyomov, P., & Lubow, S. H. 1994, ApJ, 421, 651
Boden, A. F., Sargent, A. I., Akeson, R. L., Carpenter, J. M., Torres, G., Latham, D. W., Soderblom, D. R., & Nelson, E. 2005, ApJ, 635, 442
Burns, J. A., Lamy, P. L., & Soter, S. 1979, Icarus, 30, 1
Calvet, N., D' Alessio, P., Hartmann, L., Wilner, D., Walsh, A., & Sitko, M. 2002, ApJ, 568, 1008
Calvet, N., et al. 2005, ApJ, 630, L185
Cohen, M., Megeath, S. T., Hamersley, P. L., Martin-Luis, F., & Stauffer, J. 2003, AJ, 125, 2645
D'Alessio, P., et al. 2005, ApJ, 621, 461
Dent, W. R. F., Greaves, J. S., & Coulsen, I. M. 2005, MNRAS, 359, 663
Dorschner, J., Begemann, B., Henning, T., Jäger, C., & Mutschke, H. 1995, A&A, 300, 503
Draine, B. T., & Lee, H. M. 1984, ApJ, 285, 89
Duncan, M. J., Levison, H. F., & Budd, S. M. 1995, AJ, 110, 3073
Fabian, D., Henning, T., Jäger, C., Mutschke, H., Dorschner, J., & Wehrhan, O. 2001, A&A, 378, 228
Forrest, W. J., et al. 2004, ApJS, 154, 443
Gehrz, R. D., Smith, N., Low, F. J., Krautter, J., Nollenberg, J. G., & Jones, T. J. 1999, ApJ, 512, L55
Gladman, B. 2005, Science, 307, 71
Hartmann, L., et al. 2005, ApJ, 628, L147
Higdon, S. J. U., et al. 2004, PASP, 116, 975
Holman, M. J., & Wiegert, P. A. 1999, AJ, 117, 621
Houck, J. R., et al. 2004, ApJS, 154, 18
Ida, S., Larwood, J., & Burkert, A. 2000, ApJ, 528, 351
Jayawardhana, R., Hartmann, L., Fazio, G., Fisher, R. S., Telesco, C. M., & Piña, R. K. 1999a, ApJ, 520, L41
Jayawardhana, R., Hartmann, L., Fazio, G., Fisher, R. S., Telesco, C. M., & Piña, R. K. 1999b, ApJ, 521, L129
Kenyon, S. J., & Bromley, B. C. 2002, AJ, 123, 1757
Kenyon, S. J., & Hartmann, L. 1995, ApJS, 101, 117
Koerner, D. W., Jensen, E. L. N., Cruz, K. L., Guild, T. B., & Gutlekin, K. 2000, ApJ, 533, L7
Liou, J.-C., & Zook, H. A. 1997, Icarus, 128, 354
Low, F. J., Smith, P. S., Werner, M., Chen, C., Krause, V., Jura, M., & Hines, D. C. 2005, ApJ, 631, 1170
Marsh, K. A., & Mahoney, M. J. 1992, ApJ, 395, L115
Mathis, J. S. 1990, ARA&A, 28, 37
Moro-Martín, A., Wolf, S., & Malhorta, R. 2005, ApJ, 621, 1079
Muzerolle, J., Calvet, N., Briceño, C., Hartmann, L., & Hillenbrand, L. 2000, ApJ, 535, L47
Prato, L., et al. 2001, ApJ, 549, 590
Quillen, A. C., Blackman, E. G., Frank, A., & Varnière, P. 2004, ApJ, 612, L137
Sargent, B., et al. 2006, ApJ, 645, 395
Skrutskie, M. F., Dutkevitch, D., Strom, S. E., Edwards, S., & Strom, K. M. 1990, AJ, 99, 1187
Soderblom, D. R., Henry, T. J., She trone, M. D., Jones, B. F., & Saar, S. H. 1996, ApJ, 460, 984
Soderblom, D. R., et al. 1998, ApJ, 498, 385
Stauffer, J. R., Hartmann, L. W., & Barrado y Navascues, D. 1995, ApJ, 454, 910
Strom, K. M., Strom, S. E., Edwards, S., Cabrit, S., & Skrutskie, M. F. 1989, AJ, 97, 1451
Sylvester, R. J., Dunkin, S. K., & Barlow, M. J. 2001, MNRAS, 327, 133
Tokovinin, A. A. 1999, Astron. Lett., 25, 669
Torres, G., Stefanik, R. P., Latham, D. W., & Mazeh, T. 1995, ApJ, 452, 870
Uchida, K. I., et al. 2004, ApJS, 154, 439
Webb, R. A., Zuckerman, B., Platais, I., Patience, J., White, R. J., Schwartz, M. J., & McCarthy, C. 1999, ApJ, 512, L63
Weintraub, D. A., Kastner, J. H., & Bary, J. S. 2000, ApJ, 541, 767
Werner, M. W., et al. 2004, ApJS, 154, 1
White, R. J., & Hillenbrand, L. A. 2005, ApJ, 621, L65
Zubko, V. G., Menella, V., Colangeli, L., & Bussoletti, E. 1996, MNRAS, 282, 1321