TRUNCATED DISKS IN TW Hya ASSOCIATION MULTIPLE STAR SYSTEMS

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ABSTRACT

We present high angular resolution (down to 0′′.3 ≈ 13 AU in diameter) Submillimeter Array observations of the 880 μm (340 GHz) thermal continuum emission from circumstellar dust disks in the nearby HD 98800 and Hen 3-600 multiple star systems. In both cases, the dust emission is resolved and localized around one stellar component—the HD 98800B and Hen 3-600A spectroscopic binaries—with no evidence for circum-system material. Using two-dimensional Monte Carlo radiative transfer calculations, we compare the Submillimeter Array interferometer visibilities and broadband spectral energy distributions with truncated disk models to empirically locate the inner and outer edges of both disks. The HD 98800B disk appears to be aligned with the spectroscopic binary orbit, is internally truncated at a radius of 3.5 AU, and extends to only 10–15 AU from the central stars. The Hen 3-600A disk is slightly larger, with an inner edge at ≈1 AU and an outer radius of 15–25 AU. These inferred disk structures compare favorably with theoretical predictions of their truncation due to tidal interactions with the stellar companions.

Key words: binaries: spectroscopic – binaries: visual – circumstellar matter – protoplanetary disks – stars: pre-main sequence

Online-only material: color figures

1. INTRODUCTION

A large fraction of the stars in the solar neighborhood are members of gravitationally bound multiple systems (Abt & Levy 1976; Duquennoy & Mayor 1991; Lada 2006). Similar or higher multiplicity fractions are found in nearby young stellar associations (Ghez et al. 1993; Leinert et al. 1993; Simon et al. 1995), confirming that multiplicity is a common outcome in any star formation environment. With such a substantial number of stars residing in multiple systems, it is natural to also consider the potential impacts of stellar companions on the planet formation process. The structures of the circumstellar disks used to build planets can be strongly affected by tidal interactions with the stellar components in these systems (Lin & Papaloizou 1993; Artymowicz & Lubow 1994; Pierens & Nelson 2008). These interactions can open gaps in disks, truncate their edges, and potentially expedites their dissipation before planetesimals can be made. But remarkably, despite these formidable dynamical hazards, a relatively large fraction (~25%) of exoplanet host stars have stellar companions (Raghavan et al. 2006; Desidera & Barbieri 2007, and references therein). Observations of circumstellar material in young multiple star systems can be used to empirically characterize the impact of these tidal interactions on disk structures, and therefore to place constraints on when and where planet formation can potentially be accommodated in the presence of a stellar companion.

The fate of the circumstellar material in a young multiple star system is primarily dependent on the orbital separation (a), eccentricity (e), and mass ratio (μ) of the stellar components (Artymowicz & Lubow 1994). Systems with large separations (a ~ hundreds of AU) impart little or no dynamical effects on their circumstellar material, leaving disks around each stellar component that are similar to those around single stars. Conversely, individual disks in a small-separation system (a ~ a few AU or less) will likely not survive. Instead, these systems can host a single circum-system disk with a dynamically cleared central cavity out to a radius comparable to the stellar separation (~2–3a). Qualitatively, such theoretical predictions have been broadly supported by observations. The disks around small-separation spectroscopic binaries are like those around single stars except for a diminished dust emission signal shortward of ~5 μm, consistent with a lack of warm material inside a few AU (Jensen & Mathieu 1997). Likewise, disks in wide binary systems are comparable to their more isolated counterparts, although the secondary disk signatures are often weak or absent (e.g., Jensen & Akeson 2003; Andrews & Williams 2005a; Patience et al. 2008).

But most multiple systems in both the field and young clusters have orbits with intermediate separations (a ~ tens of AU; e.g., Mathieu et al. 2000). The disks in these systems suffer the most dramatic effects of star–disk interactions, resulting in their external truncation at a fraction of the component separation (~0.2a–0.5a), or perhaps their complete dispersal. Single-dish radio photometry surveys have demonstrated that the ~1 mm luminosities for medium-separation binaries are significantly lower than their more closely or widely separated counterparts (as well as single stars; Jensen et al. 1994, 1996b; Osterloh & Beckwith 1995; Andrews & Williams 2005b). Since the dust emission at these wavelengths is optically thin (Beckwith et al. 1990), this luminosity deficit is interpreted as indirect evidence for a diminished disk mass due to the tidal truncation of the outer disk. However, this total mass deficit does not necessarily have any bearing on the potential for making planets around medium-separation multiples. The likelihood for planet formation depends more on reaching a critical disk density, and therefore it is more important to identify how that total mass is distributed spatially in such systems. Doing so involves locating where the disks in multiple star systems are truncated using high angular resolution observations of their millimeter...
continuum emission (e.g., Jensen et al. 1996a; Akeson et al. 1998; Guilloteau et al. 1999, 2000; Huenemoerder et al. 2007).

In this article, we present the first set of high angular resolution millimeter observations of the circumstellar material in two nearby multiple star systems, HD 98800 and Hen 3-600. Both systems are members of the TW Hya association and are therefore among the nearest pre-main-sequence stars, with a distance of roughly 50 pc (Kastner et al. 1997; Webb et al. 1999). HD 98800 is a rare quadruple star system, consisting of a pair of spectroscopic binaries with \( \sim 1 \) yr periods separated by \( 0'8 \) (36 AU) on the sky (e.g., Torres et al. 1995; Tokovinin 1999). Infrared measurements have shown that only the HD 98800B system harbors a circumstellar dust disk (Koerner et al. 2000; Torres et al. 2003) and a secondary visual companion located 1'.5 (66 AU) to the southwest (de la Reza et al. 1989). The signatures of a circumstellar disk, including spectroscopic and X-ray line ratio evidence for accretion onto the central stars, have been identified around the Hen 3-600A disk (Jayawardhana et al. 1999; Muzerolle et al. 2000; Huenemoerder et al. 2007).

At their advanced ages of \( \sim 10 \) Myr, the nature of the circumstellar material in these low-mass pre-main-sequence systems is a topic of active debate. While the accretion signatures in the Hen 3-600A disk are supportive of a primordial reservoir (Muzerolle et al. 2000; Torres et al. 2003) and a secondary visual companion located 1'.5 (66 AU) to the southwest (de la Reza et al. 1989), it is unclear whether the HD 98800B disk contains gas or has evolved into a debris-only system (see the detailed discussion on this topic by Akeson et al. 2007). Regardless, the proximity of these systems offers unusually detailed views of their circumstellar structures. We aim to use the high spatial resolution afforded by that proximity to characterize how the disk structures have been shaped by their dynamical interactions with the stellar components in each system. We present our observations in Section 2 and a brief qualitative analysis of the data in Section 3. We discuss the results with theoretical predictions for disk truncation in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

The HD 98800 and Hen 3-600 systems were observed with the Submillimeter Array interferometer (SMA; Ho et al. 2004) at Mauna Kea, Hawaii in the compact (baselines of 16–70 m), extended (baselines of 28–226 m), and very extended (baselines of 68–509 m) configurations on 2008 March 9, February 21, and April 3, respectively. The SMA double-sideband receivers were tuned with a local oscillator (LO) frequency of 340.755 GHz (880 \( \mu \)m). Each sideband provides 24 partially overlapping 104 MHz spectral chunks centered \( \pm 5 \) GHz from the LO frequency. The correlator was configured to subdivide one chunk in each sideband into 128 spectral channels to sample any emission from the CO \( J = 3\rightarrow2 \) transition (345.796 GHz) at a velocity resolution of 0.7 km s\(^{-1}\). Each of the remaining chunks was split into 32 coarser spectral channels to observe continuum emission.

The observations cycled through the two targets and TW Hya (S. M. Andrews et al. 2010, in preparation) between integrations on the nearby quasar J1037\( -295\), with a total cycle time of 18 minutes (5 minutes for each disk target, 3 minutes on the quasar) in the compact and extended configurations and 12 minutes (3 minutes for each disk target and quasar) in the very extended configuration. The bright quasar 3C 279 was observed every other cycle to help assess the quality of phase transfer. Additional observations of bright quasars (3C 84, 3C 273, 3C 279, and 3C 454.3) and Callisto were made for bandpass and absolute flux calibration when the targets were at low elevations (\( <20^\circ \)). The observing conditions were excellent, with zenith opacities ranging from 0.04 to 0.08 (corresponding to 0.8–1.6 mm of precipitable water vapor) and well-behaved phase variations on timescales longer than the calibration cycle.

The extended array observations (2008 February 21) were conducted during a configuration change, and therefore only utilized four of the eight SMA antennas.

The data were edited and calibrated with the MIRIAD software package.\(^6\) The bandpass response was calibrated with observations of bright quasars, and broadband continuum channels in each sideband were generated by averaging the central 82 MHz in all coarse resolution spectral chunks. The visibility amplitude scale was set by bootstrapping quasar flux densities from the observations of Callisto. The absolute flux calibration uncertainty from this technique is estimated to be roughly 10%. The antenna-based complex gain response of the system as a function of time and elevation was determined with reference to the observations of J1037\( -295\) (the nearest sufficiently bright calibrator), located midway between and \( \sim 10^\circ \) from each of the science targets. The phase transfer between the calibrator and science targets over that angular separation is not ideal, especially given the low observing elevations for these southern systems. Atmospheric decoherence on these scales will add phase noise that acts to smear out the emission from the targets. Typically, observations of a second quasar are utilized to estimate the level of decoherence in terms of the size of the “seeing” disk. Unfortunately, the next nearest bright quasar, 3C 279, probes the atmosphere at a much larger 30–40\( ^\circ \) separation from the targets. Nevertheless, the observations of 3C 279 were used to estimate the quality of phase transfer in an extreme case and showed a seeing disk size of \( \sim 0.3\)'. The actual phase decoherence between the targets and J1037\( -295\) should be much less severe, producing significantly smaller (but still uncertain) seeing disks.

After the gain calibration, the independent sets of visibilities from each configuration and sideband were compared to check for consistency on overlapping spatial scales. After finding excellent agreement, all of the data for each target were combined. The standard tasks of Fourier inverting the visibilities, deconvolution with the CLEAN algorithm, and restoration with a synthesized beam were conducted with the MIRIAD package. Maps of the continuum and CO \( J = 3\rightarrow2 \) line emission were made by naturally weighting the visibilities. The resulting continuum maps have 1\( \sigma \) rms noise levels of 3.5 mJy beam\(^{-1}\), with synthesized beam dimensions of 0.92' \( \times \) 0.68' at a position angle of 11\( ^\circ \) for HD 98800 and 1.11' \( \times \) 0.74' at P.A. = 18\( ^\circ \) for Hen 3-600. To maximize the sensitivity to line emission, only data from the compact configuration were used to generate CO \( J = 3\rightarrow2 \) spectral images, with synthesized beam dimensions of 3.1' \( \times \) 1.8' at P.A. = 164\( ^\circ \) and 4.0' \( \times \) 1.8' at P.A. = 168\( ^\circ \) for HD 98800 and Hen 3-600, respectively. No line emission was detected for either

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6 See http://cfa-www.harvard.edu/~cqj/miricook.html.
target, with 3σ upper limits of ~0.6 Jy beam⁻¹ in a 0.7 km s⁻¹ channel.

3. RESULTS

The synthesized images of the 880 μm (340 GHz) dust continuum emission in the HD 98800 and Hen 3-600A systems are shown in Figure 1. The HD 98800 map exhibits emission with an integrated flux density of 110 mJy and peak of 82 ± 3 mJy beam⁻¹, centered at $\alpha = 11^h32^m05^s24, \delta = -24^\circ46'39''10$ (J2000). Based on the reference coordinates and proper motion estimates from Hipparcos (which resolved the HD 98800A/B system; Perryman et al. 1997), the SMA emission centroid is coincident with the HD 98800B spectroscopic binary position to within 50 mas, well below the SMA astrometric uncertainty of ~0.1 (and roughly on the scale of the Ba-Bb separation). The location of the HD 98800A spectroscopic binary is marked on Figure 1 with a star symbol 0.8' to the south of the map center. The Hen 3-600 system shows emission with an integrated flux density of 75 mJy and peak of 57 ± 3 mJy beam⁻¹, centered at $\alpha = 11^h30^m27^s84, \delta = -37^\circ31'51''71$ (J2000). Using the Two Micron All Sky Survey (2MASS) astrometry (Cutri et al. 2003) and the proper motion determined by Torres et al. (2006), we find that the SMA emission centroid is coincident with the Hen 3-600A spectroscopic binary position to within 15 mas in right ascension and 0.15' in declination (the measured position is offset to the north, away from Hen 3-600B). Given the astrometric errors that may occur for such a low declination target as well as the potential confusion in the 2MASS catalog astrometry from the close companion, we suggest that the continuum emission measured with the SMA is consistent with being centered on Hen 3-600A. The location of the Hen 3-600B companion is marked in Figure 1 with a star symbol ~1.5' to the southwest of the map center.

An examination of the SMA visibilities confirms that the emission from each target is partially resolved (see Section 4). An elliptical Gaussian fit to the HD 98800B visibilities indicates an elongated emission morphology, with a high aspect ratio corresponding to an inclination $i \approx 55° - 71°$ at a major axis orientation P.A. $\approx 130° - 159°$ east of north. This inferred disk geometry is in excellent agreement with the much more precisely determined orbital geometry of the HD 98800B spectroscopic binary, for which Boden et al. (2005) have measured $i = 67°$ and $\Omega = 338°$ (corresponding to P.A. = $158°$). Within the uncertainties of the SMA data, the HD 98800B disk and spectroscopic binary orbital plane are aligned. A similar fit to the Hen 3-600A visibilities suggests a more circular emission morphology, with inclination estimates of $i \approx 25° - 45°$ and a major axis orientation P.A. $\approx 145° - 185°$ east of north. Lacking orbital information for either the spectroscopic binary or the wider visual pair, the relative orientation of the star and disk axes in this system remains unclear.

4. DISK MODELS

The 880 μm visibilities presented here provide the first spatially resolved information about the HD 98800B and Hen 3-600A circumstellar disks. We aim to use these data to directly locate the outer disk edges, where the circumstellar material could be truncated by tidal interactions with their nearby stellar companions. Moreover, following the analysis of Jensen & Mathieu (1997), we seek to indirectly locate the inner disk edges sculpted by their central spectroscopic binaries based on the high-quality infrared spectra presented by Uchida et al. (2004) and Furlan et al. (2007). To determine these disk edges, we utilize a parametric truncated disk structure model and a two-dimensional Monte Carlo radiative transfer code (RADMC; see Dullemond & Dominik 2004) to compute synthetic 880 μm visibilities and spectral energy distributions (SEDs) that can be compared with observations. A detailed description of the modeling methodology was provided by Andrews et al. (2009), and so here we focus only on the key modifications made to accommodate truncated disk structures.

We parameterize the axisymmetric density structure for the disk models based on two different radial zones, including a standard “outer” disk and a central disk “cavity” that contains substantially less material. The surface densities have a $\Sigma \propto 1/R$ behavior for $R_{\text{in}} \leq R \leq R_{\text{out}}$ in the outer zone, and a constant value (depleted by a factor $\delta_\Sigma$ from the value at $R_{\text{cav}}$) inside the cavity ($R_{\text{in}} \leq R < R_{\text{cav}}$). The vertical density structure is assumed to be Gaussian and is parameterized by a scale-height distribution $H \propto R^{1+\psi}$ that can be artificially “puffed”-
up by a factor $\delta_H$ at the cavity edge ($R_{\text{cav}}$) to account for the locally increased energy input from the normal irradiation of the optically thick outer disk zone (e.g., Dullemond et al. 2001; D'Alessio et al. 2005). The densities in these structures are normalized with a total dust mass, $M_{\text{dust}}$.

We use the same set of dust opacities adopted by Andrews et al. (2009), computed for a power-law size distribution up to a maximum grain radius of 1 mm. For a small fraction, $f_{\text{sg}}$, of the dust mass inside the disk cavities, the maximum grain size was decreased to 1 $\mu$m (hereafter "small" grains) to more faithfully reproduce the solid-state dust emission features for each target. In these models, we assume the only heating source was irradiation from a central stellar photosphere, represented by appropriately scaled Lejeune et al. (1997) spectral templates that match the component-resolved optical and near-infrared photometry. Of these, we perhaps have the best handle on $R_{\text{cav}}$ due to the prominent role it has in shaping the mid-infrared spectrum and setting the wavelength of the secondary emission peak. Our estimate of $R_{\text{cav}} = 1$ AU for the Hen 3-600A disk is in good agreement with the original measurement from these data by Uchida et al. (2004), but the $R_{\text{cav}} = 3.5$ AU inferred here for the HD 98800B disk is somewhat smaller than the 5.9 AU derived by Furlan et al. (2007). Given the differences in the adopted stellar parameters, dust populations, and the prescribed physical structure of the cavity edge between these two studies, this apparent $R_{\text{cav}}$ discrepancy is probably irrelevant. However, if the cavity extended out to the radius determined by Furlan et al. (2007), we would expect to see a null in the $880 \mu$m visibilities on $\sim350-400$ k$\lambda$ baselines, corresponding to angular scales of $\sim0.3'$ (see Hughes et al. 2007). Since no such null is noted in the SMA data (see Figure 3), a smaller cavity size is appropriate.

The additional cavity parameters, $\{R_m, \delta_G, \delta_H, f_{\text{sg}}\}$, are not well constrained and are somewhat mutually degenerate. For example, one could adjust $R_m$ and compensate for the modified infrared emission by varying $\delta_G$. Nevertheless, in practice the range of viable parameter-space is relatively small, and the values selected here are meant only to be illustrative and facilitate reasonable estimates of the disk edges. Both disks contain only a miniscule $\sim10^{-10}$ $M_\odot$ of dust inside $R_{\text{cav}}$, a fraction $f_{\text{sg}}$ (by mass) of which is comprised of small grains. The scale-height modifications at $R_{\text{cav}}$ ($\delta_H$) are important, but also modest, amounting to a change from 0.19 to 0.26 AU for HD 98800B and 0.0026 to 0.0032 AU for Hen 3-600A.

### Table 1: Adopted Stellar Parameters

| Star          | $T_{\text{eff}}$ (K) | $R_e$ (AU) | log $g$ (cm s$^{-2}$) | $A_V$ (mag) |
|---------------|----------------------|------------|-----------------------|-------------|
| HD 98800Aa+Ab | 4500                 | 1.30       | 4.00                  | 0.0         |
| HD 98800Ba    | 4250                 | 1.16       | 4.25                  | 0.3         |
| HD 98800Bb    | 4000                 | 0.90       | 4.25                  | 0.3         |
| Hen 3-600Aa+Ab| 3350                 | 1.20       | 4.50                  | 0.0         |
| Hen 3-600B    | 3350                 | 1.00       | 4.50                  | 0.0         |

Notes. The effective temperatures, radii, gravities, and extinctions determined for each stellar component, based on matching resolved optical/near-infrared photometry to scaled Lejeune et al. (1997) spectral templates. The parameters for HD 98800B are based on the Boden et al. (2005) measurements; the templates were summed into a composite spectrum for the radiative transfer modeling. The $A_V$ estimates correspond to the Mathis (1990) extinction law.

The observed broadband SEDs and Spitzer IRS spectra from the literature are shown in Figure 2, with the composite stellar photosphere spectra overlaid in gray. The best-fit synthetic SEDs for disk models with several fixed values of the outer radius ($R_{\text{out}}$) are plotted for comparison. Neither disk exhibits dust emission in excess of the photosphere at wavelengths less than $\sim5\mu$m, as was noted in previous infrared studies (e.g., Jayawardhana et al. 1999; Uchida et al. 2004; Furlan et al. 2007). This lack of excess emission and the secondary emission peak near $20\mu$m were reproduced in the models by varying the disk cavity parameters, $\{R_m, R_{\text{cav}}, \delta_G, \delta_H\}$ (and to some extent $f_{\text{sg}}$). Of these, we perhaps have the best handle on $R_{\text{cav}}$ due to the prominent role it has in shaping the mid-infrared spectrum and setting the wavelength of the secondary emission peak. Our estimate of $R_{\text{cav}} = 1$ AU for the Hen 3-600A disk is in good agreement with the original measurement from these data by Uchida et al. (2004), but the $R_{\text{cav}} = 3.5$ AU inferred here for the HD 98800B disk is somewhat smaller than the 5.9 AU derived by Furlan et al. (2007). Given the differences in the adopted stellar parameters, dust populations, and the prescribed physical structure of the cavity edge between these two studies, this apparent $R_{\text{cav}}$ discrepancy is probably irrelevant. However, if the cavity extended out to the radius determined by Furlan et al. (2007), we would expect to see a null in the $880 \mu$m visibilities on $\sim350-400$ k$\lambda$ baselines, corresponding to angular scales of $\sim0.3'$ (see Hughes et al. 2007). Since no such null is noted in the SMA data (see Figure 3), a smaller cavity size is appropriate.

The additional cavity parameters, $\{R_m, \delta_G, \delta_H, f_{\text{sg}}\}$, are not well constrained and are somewhat mutually degenerate. For example, one could adjust $R_m$ and compensate for the modified infrared emission by varying $\delta_G$. Nevertheless, in practice the range of viable parameter-space is relatively small, and the values selected here are meant only to be illustrative and facilitate reasonable estimates of the disk edges. Both disks contain only a miniscule $\sim10^{-10}$ $M_\odot$ of dust inside $R_{\text{cav}}$, a fraction $f_{\text{sg}}$ (by mass) of which is comprised of small grains. The scale-height modifications at $R_{\text{cav}}$ ($\delta_H$) are important, but also modest, amounting to a change from 0.19 to 0.26 AU for HD 98800B and 0.0026 to 0.0032 AU for Hen 3-600A.

### Table 2: Estimated Disk Parameters

| Parameter | HD 98800B | Hen 3-600A |
|-----------|-----------|------------|
| $R_m$ (AU) | 2.0       | 0.4        |
| $R_{\text{cav}}$ (AU) | 3.5       | 1.0        |
| $R_{\text{out}}$ (AU) | 10−15     | 15−25      |
| $M_{\text{dust}}$ ($M_\odot$) | $3 \times 10^{-6}$ | $7 \times 10^{-6}$ |
| $\delta_G$ | $\sim1000$ | $\sim500$  |
| $H_{10\mu\text{m}}$ (AU) | 0.5       | 0.3        |
| $\psi$ | 0.10      | 0.07       |
| $\delta_H$ | 1.4       | 1.2        |
| $f_{\text{sg}}$ | 0.25      | 0.10       |
| $i$ (°) | 67        | 36         |
| P.A. (°) | 158       | 169        |

Note. Disk structure parameters estimated from the radiative transfer modeling. The parameter definitions are given in Section 4.
of the significantly cooler dust temperatures produced around the later-type Hen 3-600A stars.

Because there is no spatially resolved information in the SEDs alone, those data can be reproduced equally well with essentially any value for the outer disk edge. Not surprisingly then, the SED models for different $R_{\text{out}}$ values shown in Figure 2 are practically identical. However, the synthetic 880 $\mu$m continuum visibilities computed from the same disk models exhibit distinctive signatures for different outer edge locations. Figure 3 displays the azimuthally averaged representations of the observed and synthetic visibilities for the HD 98800B and Hen 3-600A disks, deprojected to account for the disk viewing geometries (see Lay et al. 1997). The real parts of the SMA visibilities decrease with deprojected baseline, demonstrating that both disks are resolved. Moreover, the imaginary parts of the visibilities are essentially zero, indicating that there is no strong evidence for large departures from axisymmetry. To facilitate a fair comparison of the data and models, the model visibilities are first convolved with a 0.15 Gaussian to compensate for the atmospheric decoherence discussed in Section 2. After this “seeing” correction, it is clear in Figure 3 that the SMA data are best reproduced for $R_{\text{out}}$ values of $\sim$10–15 AU for the HD 98800B disk and $\sim$15–25 AU for the Hen 3-600A disk. These values could be smaller if the decoherence is underestimated, but they could only be larger if $\Sigma$ were a steeper function of radius (see Andrews & Williams 2007a).

5. DISCUSSION

Through radiative transfer modeling of resolved 880 $\mu$m continuum emission and pan-chromatic SEDs, we have characterized the key properties of the circumstellar material in two of
the nearest pre-main-sequence multiple star systems. In principle, the disk structures determined here can be used to help assess the potential for planet formation in the presence of a stellar companion and to test theoretical calculations of star–disk tidal interactions. The latter task has further implications for disk studies, as empirical constraints on these dynamical interactions can be used as high mass ratio ($\mu$) touchstones for modeling the impacts of young giant planet companions on their local disk environments.

Unfortunately, very little is known about the stellar orbits in the Hen 3-600 hierarchical triple system. Muzerolle et al. (2000) noted that the primary appears to be a double-lined spectroscopic binary with a large radial velocity difference ($\sim 40$ km s$^{-1}$), although repeated measurements have not been able to extract a reliable set of orbital parameters (Torres et al. 2003). If the inner truncation radius estimated for the Hen 3-600A disk, $R_{\text{cav}} \approx 1$ AU, is indeed set by the dynamical clearing effects of the central spectroscopic binary, the calculations by Artymowicz & Lubow (1994) predict that the orbital separation should be in the range $a \approx 0.2–0.6$ AU, depending on the eccentricity (mass-ratio-related effects are small when $\mu \approx 0.1–0.5$). The visual companion Hen 3-600B has been located at angular separations of 1.4–1.5$^\prime$ to the southwest (P.A. $\approx 215^\circ–230^\circ$) of the spectroscopic binary system, corresponding to projected spatial separations of 63–67 AU (de la Reza et al. 1989; Reipurth & Zinnecker 1993; Webb et al. 1999; Brandeker et al. 2003). While there are no available constraints on the A–B orbit, projection effects should only produce up to a $\sim 20\%$ uncertainty in the physical separation if the disk plane and orbit are aligned. Assuming that the similar spectral types of the A and B components imply a roughly equal-mass system ($\mu \approx 0.5$), tidal interactions would externally truncate the Hen 3-600A disk at a radius of $\sim 25$ AU for a circular orbit (Artymowicz & Lubow 1994). The outer disk edge inferred here, $R_{\text{out}} \approx 15–25$ AU, is in good agreement with that prediction, with the uncertainty permitting moderate orbital eccentricities.

The stellar orbital parameters in the HD 98800 quadruple system are comparatively more robust, thanks to long-term and intensive monitoring efforts. Most recently, Boden et al. (2005) combined infrared interferometric observations with the extant spectroscopic data from Torres et al. (1995) to measure the orbital elements and individual stellar properties in the HD 98800B spectroscopic binary. According to the simulations of Pichardo et al. (2008), this nearly equal-mass ($\mu = 0.43$), eccentric ($e = 0.78$), and close ($a = 1.05$ AU) system can harbor a circumbinary disk with an innermost stable orbit at a radius of $\sim 3.7$ AU. A similar value can be deduced from the calculations of Holman & Wiegert (1999), or from a slight extrapolation of the results of Artymowicz & Lubow (1994). That value is practically identical to the internal truncation radius determined from the infrared spectrum morphology, $R_{\text{cav}} = 3.5$ AU. For the wider HD 98800A/B visual pair, Torres et al. (1995) compiled a relative astrometric record of the resolved system over the past century, along with a single-epoch measurement of the systemic radial velocity difference between the components. With that information and the Hipparcos parallax, Tokovinin (1999) determined a family of acceptable A–B orbits with $\sim 300–430$ yr periods, moderate eccentricities ($e = 0.3–0.6$), and $a \approx 50–80$ AU. For reference, the relative geometries of the HD 98800B disk and an example A–B orbit from Tokovinin (1999) are shown together in Figure 4, projected onto the plane of the sky. Note that the A–B orbital plane ($i \approx 88^\circ$, $\Omega \approx 185^\circ$) is not aligned with the B spectroscopic binary and disk plane ($i \approx 67^\circ$, $\Omega \approx 338^\circ$), making a quantitative prediction for the external disk truncation difficult. Although the aforementioned theoretical calculations all assume coplanar interactions, we can use them as a guide to assess whether or not the outer truncation radius determined here is reasonable. Assuming that the A and B spectroscopic binaries are roughly equal in total mass, the models of Artymowicz & Lubow (1994) or Pichardo et al. (2005) predict that the HD 98800B disk should be truncated at a radius of $\sim 8–20$ AU, depending on the assumed disk viscosity and which Tokovinin (1999) orbit is adopted. Those values are indeed consistent with the estimates based on modeling the resolved SMA data, where $R_{\text{out}} \approx 10–15$ AU.

In general, the locations of the disk edges derived from our radiative transfer modeling are in good agreement with the theoretical predictions of disk truncation due to star–disk tidal interactions. However, there are some notable problems in the details that should be brought to attention. One of these involves the proper interpretation of the inner disk radius, $R_{\text{in}}$, and the small amount of dust between it and the cavity edge ($R_{\text{cav}}$). For the disk models used here, that small dust mass is necessary to reproduce the weak infrared excesses and silicate emission features present in the observed SEDs. However, the dynamical models suggest that there are no long-term stable dust orbits inside the inferred $R_{\text{cav}}$. Perhaps the simplest way of reconciling this discrepancy is to argue that the adopted parameterization of the inner disk structure is inappropriate or incomplete. For

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Inferred geometry of the HD 98800B disk (grayscale) is compared with the A–B visual binary orbit (red) computed by Tokovinin (1999), projected onto the plane of the sky. The two-toned gray shading of the disk corresponds to the quoted range of possible $R_{\text{out}}$ values ($\sim 10–15$ AU). (A color version of this figure is available in the online journal.)
example, similar infrared excess features could potentially be reproduced by modifying the dust content, shape, or symmetry of the disk at the cavity edge (e.g., Isella & Natta 2005; Akeson et al. 2007). With the same data for the HD 98800B disk, Furlan et al. (2007) employed a narrow ring interior to their slightly larger cavity edge to reproduce the infrared spectrum with equivalent accuracy. The ability to obtain quality fits to the observations with such different interior structures highlights the model degeneracies, which will remain until the inner disk edge is spatially resolved.

But if the inner disk structures determined here are taken at face value, the material inferred to be inside the cavity edge could be interpreted as dynamically unstable, perhaps representative of a low-density inward flow due to Poynting–Robertson (P–R) drag or disk accretion (e.g., see Pierens & Nelson 2008). Furlan et al. (2007) suggested the former mechanism to explain the narrow ring from 1.5–2 AU they inferred in the HD 98800B system, but rightly acknowledged that the empty region from 2 AU to their \( R_{\text{cav}} \) (5.9 AU) was incompatible with such a flow (note also that a significant fraction of such a ring would be inside the spectroscopic binary orbit). The structure parameterization adopted here is continuous from \( R_{\text{cav}} \) inward to \( R_{\text{in}} \) (which corresponds to the spectroscopic binary apastron distance), and so avoids this complication. Therefore, P–R drag could potentially account for the material inside the stable orbit radius in this disk if there is a continually replenished dust supply near \( R_{\text{cav}} \) and viscous gas drag forces are negligible. At least the latter condition appears to be met for the HD 98800B disk, where no evidence for accretion or molecular gas has been uncovered (Dent et al. 2005; Salyk et al. 2009). The same is not true for the Hen 3-600A disk, or molecular gas has been uncovered (Dent et al. 2005; Salyk et al. 2009). Furlan et al. (2007) suggested the former mechanism to explain the narrow ring they inferred around the third component in (which corresponds to the spectroscopic binary orbit). The structure parameterization adopted here is continuous from \( R_{\text{cav}} \) inward to \( R_{\text{in}} \) (which corresponds to the spectroscopic binary apastron distance), and so avoids this complication. Therefore, P–R drag could potentially account for the material inside the stable orbit radius in this disk if there is a continually replenished dust supply near \( R_{\text{cav}} \) and viscous gas drag forces are negligible. At least the latter condition appears to be met for the HD 98800B disk, where no evidence for accretion or molecular gas has been uncovered (Dent et al. 2005; Salyk et al. 2009). The same is not true for the Hen 3-600A disk, or molecular gas has been uncovered (Dent et al. 2005; Salyk et al. 2009). Furlan et al. (2007) suggested the former mechanism to explain the narrow ring they inferred around the third component in (which corresponds to the spectroscopic binary orbit). The structure parameterization adopted here is continuous from \( R_{\text{cav}} \) inward to \( R_{\text{in}} \) (which corresponds to the spectroscopic binary apastron distance), and so avoids this complication. Therefore, P–R drag could potentially account for the material inside the stable orbit radius in this disk if there is a continually replenished dust supply near \( R_{\text{cav}} \) and viscous gas drag forces are negligible. At least the latter condition appears to be met for the HD 98800B disk, where no evidence for accretion or molecular gas has been uncovered (Dent et al. 2005; Salyk et al. 2009). The same is not true for the Hen 3-600A disk, or molecular gas has been uncovered (Dent et al. 2005; Salyk et al. 2009).

When future astrometric and spectroscopic monitoring has fully determined the visual orbits in the HD 98800 and Hen 3-600 systems, the lack of millimeter emission around the secondaries can also help constrain how their circumstellar material evolved. In principle, the tidal truncation calculations described above predict similar (perhaps slightly smaller) outer edge locations for the disks around the nearly equal-mass secondaries described above predict similar (perhaps slightly smaller) outer edge locations for the disks around the nearly equal-mass secondaries (Artyomowicz & Lubow 1994; Pichardo et al. 2005). If the individual disks initially had the same masses, the similar disk sizes would have produced comparable millimeter emission levels from both components. Obviously this is not the case for these targets, nor for a handful of other resolved multiple systems (Jensen & Akeson 2003; Patience et al. 2008). This could be an artifact of the multiple star formation process itself, as Bate & Bonnell (1997) have argued that competitive accretion will produce higher initial disk masses around primary stars (see also Bate 2000). Alternatively, the dynamical interactions in these systems could be considerably more complicated than the standard tidal truncation calculations have assumed, with the secondary disks suffering more severe disruption. For example, the interactions in non-coplanar systems like the HD 98800A/B visual binary could be catastrophic, producing a much more complex circumstellar structure (Verrier & Evans 2008).

The Hen 3-600 and HD 98800 multiple star systems should continue to be exploited as essential test cases for evaluating how external dynamical interactions can contribute to disk evolution, and therefore affect the potential for planet formation in the presence of stellar companions. The unique proximity of these particular systems is crucial, providing both high sensitivity and spatial resolution to circumstellar dust structures as well as rare opportunities to determine precise orbits for stellar pairs with different separations within the same system. While this study has tackled the initial challenge of resolving the millimeter emission in these systems and relating it to the global disk structures, the real utility of these targets now lies with continued work that focuses on the details. For example, future observations of these disks with the Atacama Large Millimeter Array could be sensitive to the structural asymmetries or recently ejected material streams expected from non-coplanar tidal interactions (Akeson et al. 2007; Verrier & Evans 2008). However, it is equally important to calculate the stellar orbits in these nearby systems, particularly in the less-studied case of Hen 3-600. In fact, there are exciting opportunities to simultaneously refine the stellar orbits and directly probe star–disk interactions for the HD 98800 system, as the visual A–B binary will reach periastron in the next ~15 years (Tokovinin 1999). Therefore, with continued monitoring the circumstellar material in the Hen 3-600 and HD 98800 systems can eventually serve as the primary observational calibrators for models of star–disk (as well as planet–disk) tidal interactions.

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