DISCOVERY OF A CIRCUMBINARY DISK AROUND HERBIG Ae/Be SYSTEM V892 TAUER

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ABSTRACT

We report the discovery of a circumbinary disk around the Herbig Ae/Be system V892 Tau. Our detailed mid-infrared images were made using segment-tilting interferometry on the Keck I telescope and reveal an asymmetric disk inclined at $\sim 60^\circ$ with an inner hole diameter of 250 mas (35 AU), approximately 5 times larger than the apparent separation of the binary components. In addition, we report a new measurement along the binary orbit using near-infrared Keck aperture masking, allowing a crude estimate of orbital parameters and the system mass for the first time. The size of the inner hole appears to be consistent with the minimum size prediction from tidal truncation theory, bearing a resemblance to the recently unmasked binary CoKu Tau/4. Our results have motivated a reanalysis of the system spectral energy distribution, concluding the luminosity of this system has been severely underestimated. With further study and monitoring, V892 Tau should prove a powerful testing ground for both predictions of dynamical models for disk-star interactions in young systems with gas-rich disks and for calibrations of pre–main-sequence tracks for intermediate-mass stars.

Subject headings: binaries: close — infrared: stars — stars: individual (V892 Tauri) — stars: pre–main-sequence — techniques: interferometric

1. INTRODUCTION

V892 Tau (Elias 1, Elias 3-1) is a young stellar object in the Taurus-Aurigae star-forming region ($d = 140$ pc; Kenyon et al. 1994). Its visible spectrum is classified as spectral type B8 V (Hernández et al. 2004), making V892 Tau one of the few Herbig Ae/Be stars in Taurus (in addition to AB Aur, MWC 480). The spectral energy distribution (SED) of V892 Tau is dominated by bright thermal emission in the mid-infrared (Hillenbrand et al. 1992), with relatively large line-of-sight extinction in the visible (one estimate is $A_V \sim 5.9$; Kenyon & Hartmann 1995). Despite being one of the closest Herbig stars and after decades of multiwavelength observations, the nature of V892 Tau is still uncertain.

The SED suggests V892 Tau is either a young embedded Class I source (Lada 1987) still surrounded by its nascent envelope or a more evolved, Class II object (i.e., Herbig Ae/Be star) seen through its edge-on disk. Spatially resolved imaging can easily distinguish between these two scenarios, and early speckle interferometry (Kataza & Maizara 1991; Haas et al. 1997; Leinert et al. 2001) suggested the presence of an extended and elongated nebula in the near-infrared that could be due to scattering in bipolar lobes.

The high-resolution speckle imaging of Smith et al. (2005) clearly resolved the $K$-band ($\lambda = 2.2$ $\mu$m) emission to be coming from two unresolved stars in V892 Tau with little or no sign of a nebula or extended emission. The two stars of roughly equal brightness had an apparent separation of 55 mas (7.7 AU), and some evidence of orbital motion was seen between epochs separated by 7 years.

Although this binary should have a dramatic effect on the infrared emission, carving out a large hole in the circumbinary disk, recent analysis of the SED of V892 Tau including ISO data (Acke & van den Ancker 2004) uncovered no distinct signature of the underlying binary. Other workers (Liu et al. 2005, 2007) made use of the technique of nulling interferometry in the mid-IR ($\lambda = 10.3$ $\mu$m) to marginally resolve V892 Tau (FWHM $\sim20$ AU) along PA $164^\circ$ consistent with normal (single-star) disk emission.

Here we report new mid-IR imaging of the V892 Tau system which resolves these mysteries, discovering very extended and resolved emission that we interpret to be coming from a circumbinary disk. We also confirm the presence of the binary at $K$ band, and our new data allow first crude estimates of the orbital elements. Lastly, we report a new SED analysis which provides an improved determination of the system luminosity and our viewing geometry.

2. OBSERVATIONS

We observed V892 Tau using the Keck I telescope as part of two separate experiments, the Keck segment-tilting experiment and the Keck aperture-masking experiment. Here we briefly describe these experiments and give pertinent observing details.

V892 Tau was observed on UT 2004 August 31, UT 2004 September 1, and UT 2005 February 19 at the Keck I telescope using the 10.7 $\mu$m filter ($\lambda_f = 10.7$ $\mu$m, $\Delta\lambda = 1.55$ $\mu$m) of the Long Wavelength Spectrometer (LWS; Campbell & Jones 2004) just before this instrument was decommissioned in 2005. In order to optimize our calibration against changes in seeing (e.g., Tuthill et al. 2000), we used the Keck’s segmented primary mirror in a novel “segment-tilting” mode, whereby we controlled the tilts and pistons of the individual mirror segments to create a set of four independent and non-redundant interference patterns (using six segments each) on the LWS detector focal plane. Furthermore, short exposures were used ($t_{exp} = 90$ ms $< t_o$, where $t_o$ is the atmospheric coherence time $\sim250$ ms in the mid-IR) to effectively freeze the atmospheric turbulence. For calibration we interleaved target observations with calibrations of the underlying binary.
brators α Tau, τ Aur, and α Cet. Details on this experiment and the implementation at Keck were first introduced by Monnier et al. (2004), and more information can be found in recently published science papers (Weiner et al. 2006; Ireland et al. 2007; Rajagopal et al. 2007).

The combined Fourier coverage of the four patterns over the three nights (total of six independent pointings) can be found in Figure 1 along with the visibility results. The visibility-squared data and the closure phases were compiled and saved using the OIFITS data format (Pauls et al. 2005) and are available upon request. Figure 1 shows the clear sign of highly elongated disk emission.

We also obtained diffraction-limited observations of V892 Tau in the near-IR on UT 2004 September 4 using the K-band filter (λ = 2.21 μm, Δλ = 0.43 μm) of the NIRC camera (Matthews et al. 1996) in conjunction with an annulus aperture mask placed in front of the secondary mirror. This observing mode was extensively utilized between 1997 and 2005 (see most recent science papers, Monnier et al. 2007; Tuthill et al. 2008) and details of the experimental design and performance can be found in Tuthill et al. (2000). We interleaved observations of the target with the unresolved calibrator 54 Per. The Fourier coverage and visibility-squared results are shown in Figure 1, where the binary nature is clearly revealed.

3. ANALYSIS

3.1. Image Reconstructions

We used the BS MEM image reconstruction software (Buscher 1994; Lawson et al. 2004, 2006) for aperture synthesis imaging. Figure 2 shows the reconstructed images for the mid-IR and near-IR data. In order to confirm the asymmetric features in the mid-IR image were not due to artifacts in the BS MEM algorithm, we also used the independent image reconstruction code MACIM (Ireland et al. 2006) and found good consistency between the basic morphology, size scale, and level of emission asymmetry. As an additional data quality check, separate images were made for each independent night of data and the resulting images all closely resembled the result shown in Figure 2. Note that we do not know the relative position of the near-IR image compared to mid-IR image and have presented each image centered in its corresponding frame.

Fig. 1.—Visibility data (color scale) for V892 Tau and the specific Fourier coverage (dots). The left panel shows results for 10.7 μm using the Keck segment tilting method while the right panel applies to the 2.2 μm Keck aperture-masking data.

Fig. 2.—Image reconstructions of V892 Tau at 10.7 μm (left) and 2.2 μm (right) using the BS MEM software. At the bottom left of each panel, we have included an estimate of the resolution of each image, corresponding here to 80 mas at 10.7 μm and 16 mas at 2.2 μm. Contour levels are shown for the extended emission in the mid-IR spaced logarithmically in factors of 4: 25%, 6.3%, and 1.6% of the peak. The scale bar applies for a distance of 140 pc. For orientation, east points left and north points up.

3.1.1. Mid-Infrared: Elongated Disk Structure

The mid-IR image shows elongated emission, approximately 320 mas × 180 mas in full extent, elongated along PA 50°. The two bright lobes in the image are separated by 210 mas (30 AU) with the southwest side being significantly brighter. A two-dimensional Gaussian fit to the visibility data gives a FWHM 244 ± 6 mas × 123 ± 9 mas along PA 49° ± 1°. For a simplistic “flat disk” model, this 2 : 1 ratio elongation suggests we are viewing this disk oriented at ∼60° inclination.

A more suitable model for a circumbinary or transitional disk would be a tilted and asymmetric ring of emission that is nearly unresolved along the minor axis (for example, see dramatic case of HR 4796; Koerner et al. 1998; Schneider et al. 1999). Following the parameterization of Monnier et al. (2006) we have fitted a “skewed asymmetric ring model” to our interferometry data here to better estimate the inner hole diameter. The best-fitting model had an inner-hole diameter of 247 mas × 121 mas (35 AU × 17 AU) along PA 53°, with a 40% skew along PA 284° (the thickness of the ring followed a Gaussian profile with a FWHM of 25% ring radius). For the purposes of § 4, we assume the central hole in the circumbinary disk has a radius of 17.5 AU.

Importantly, we want to emphasize that the scale of the emission is more than 4 times larger than the separation of the binary at the heart of this system, and the elongation is along a distinctly different position angle. Since our mid-IR data in 2004 were taken within 1 week of the near-IR data, we can clearly prove that the elongated mid-IR emission comes from a distinct and much larger component than the near-IR. We discuss the relationship between the circumbinary disk and the underlying binary orbit in § 4.

At first glance, it may seem surprising that Liu et al. (2005) did not more clearly resolve this large circumbinary disk using their nulling technique, finding a FWHM of only 20 AU. However, this nulling measurement was performed only for PA 164°, which is along the narrow dimension of the elongated emission we detected. Another possible explanation for the smaller size is that the bandpass filter used here has more contribution from 11.2 μm PAH emission, which could be more extended than the mid-IR continuum.
3.1. Near-Infrared: Binary Star

Figure 2 shows the BSMEM image of V892 Tau at 2.2 μm. We confirm the binary nature of this target as first reported by Smith et al. (2005). We also set a limit of <10% of the emission possibly coming from any sort of extended or “halo” component (e.g., Kataza & Maihara 1991; Haas et al. 1997; Leinert et al. 2001). In order to extract the separation and position angle of this binary, we have used both image fitting and direct fitting to the interferometric observables to yield the following result: ρ = 44.2 ± 1.0 mas, θ = 79.9° ± 1.0°, flux ratio 1.15 ± 0.04 (west component brighter than east component).

3.2. Binary Orbit

We combined our new binary measurement (at 2004.67) with the 1996.75 and 2003.76 measurements from Smith et al. (2005) and these data are plotted in Figure 3. The small proper motion (Δ ~ 10 mas = 1.4 AU) observed by Smith et al. (2005) over 7 years is problematic for this object since this would require a long-period orbit (≥100 yr) inconsistent with the spectral types and luminosities of the binary stars themselves.

Alternatively, the binary period could be approximately 7 years, meaning the stars had gone nearly exactly once around their orbit between epochs. Although the timing is suspicious, the scenario is plausible except that this would require a system mass >20 M⊙, much too high for the B8 spectral type and system luminosity.

The scenario we favor is that infrared variability affected the brightness ratio between 1996 and 2003, confusing the assignment of “primary” and “secondary” star. This variation could be intrinsic or be due to varying line-of-sight obscuration through this asymmetric disk. Smith et al. (2005) did report a change in flux ratio, finding a brightness ratio of 1.0 for 2003.76 which implies that their reported position angle had a ±180° ambiguity.

In our 2004.67 data, we definitively detect the southwest component as 15% brighter, consistent with the PA assignment of the published 2003.76 measurement. By flipping the position angle of the earlier 1996 measurements, we find a robust family of orbits with periods of ~14 years, compatible with the measured binary separations and the expected system mass. Note that future orbital refinement will lead to precise stellar masses for these intermediate-mass, pre-main-sequence stars (see also MWC 361A; Monnier et al. 2006), a rare opportunity to advance the calibration of pre-main-sequence tracks for this mass range.

To estimate the orbital parameters for V892 Tau, we used Monte Carlo sampling of the measured stellar separations along with a system mass constraint of 5.5 ± 0.5 M⊙ expected for two stars of spectral type B8 V (Palla & Stahler 1993). Figure 3 shows the main results of our orbital study: P = 13.8 ± 1.5 yr, a = 72.4 ± 6.3 mas (10 AU), e = 0.12 ± 0.05, i = 60.6° ± 3.8°, ω = 233° ± 42°, Ω = 28° ± 5°, T0 = 55,480 ± 900 MJD.

4. DISCUSSION

We interpret the mid-IR emission of V892 Tau as a circumbinary disk based on several arguments. The mid-IR emitting region is much larger than the separation between the binary components, ruling out models which have all the mid-IR emission coming from disks around the individual stars. In theoretical models of tidal truncation (Artymowicz & Lubow 1994), the circumbinary disk has an inner hole approximately 1.8–2.6 times larger than the semimajor axis of the binary system (for eccentricity between 0 and 0.25). For comparison, our best estimates of the hole radius and orbital semimajor axis are 17.5 and 10 AU, respectively, giving a ratio of 1.75 which is close to the theoretical expectation. In addition, the position angle and derived inclination angle of the mid-IR emission (PA ~ 50°, i ~ 60°) is similar to those derived from the orbit (PA ~ 28°, i ~ 61°) and the mild asymmetry in the mid-IR emission suggests dynamical interactions between an eccentric binary and the surrounding disk (via resonances or disk warping).

We further test the circumbinary disk hypothesis by analyzing the spectral energy distribution (SED). The SED shows a
large mid-IR bump similar to that seen in “transitional” disks (Calvet et al. 2002; Espaillat et al. 2007). By reddening template Kurucz spectra for B8 V stars, we can fit the near-IR emission with mostly photospheric light (some near-IR emission from hot dust is allowed but not well constrained) assuming \( A_v = 10.95 \) yielding a combined stellar luminosity of \( 400 \, L_\odot \), reasonable for two B8 V stars. Our new proposed SED decomposition for V892 Tau is consistent with emission from the warm inner wall of the circumbinary disk.

Using equation (1) in Isella et al. (2006) the predicted radius for the warm inner wall for the above stellar luminosity (assuming 0.25 \( \mu \)m spherical silicate grains) is 18 AU, consistent with our derived inner hole radius of 17.5 AU based on imaging. Furthermore, we find that the scale height of this wall at 18 AU is \( \sim 1.8 \) AU (Dullemond et al. 2001) which can produce the observed line-of-sight \( A_v \sim 11 \) for the disk inclination of \( \sim 65^\circ \). This latter phenomena may not be widely appreciated; circumbinary (or transitional) disks have warm puffed-up inner walls (the rim scale height is a stronger function of radius than temperature) at large radii that effectively increase the possibility that central stars will be obscured or at least reddened as seen by distant observers. The lack of scattering nebulosity in archival Hubble Space Telescope images independently suggests that the high line-of-sight \( A_v \) is likely from absorption by dust in the outer disk and not infalling envelope material. While a detailed model is beyond the scope of this Letter, a careful study will allow precise constraints of stellar luminosities, dust properties, and circumbinary structure and should be straightforward with today’s 3D Monte Carlo radiative transfer codes (e.g., TORUS; Harries 2000).

5. CONCLUSIONS

We have discovered an extensive circumbinary disk around V892 Tau in the mid-infrared. We also independently confirm the binary nature of the underlying stellar system and our new measurement allows us to fit an astrometric orbit, finding a period \( \sim 14 \) years for system mass of \( \sim 6 \, M_\odot \). Our limited orbital phase coverage and some ambiguity in position angles allow only crude estimates and we strongly urge continued monitoring of this system using near-IR speckle, aperture masking, or adaptive optics.

We have proposed a new SED decomposition with a line-of-sight extinction (\( A_v \sim 11 \)) higher than previously thought, implying a system luminosity \( \sim 400 \, L_\odot \). This result highlights the fact that circumbinary disks (and transitional disks) have much larger opening angles since the puffed-up inner wall causes enhanced extinction of the central stars even at inclinations of 60°.

V892 Tau is another case where high-resolution imaging has motivated a fundamental shift in our understanding of an individual object. As spectral energy distributions are used to discover “transitional” disks implicating planet formation, we must be cognizant of the important role of binarity and the associated circumbinary disks that can mimic signs of planet formation (e.g., Ireland & Kraus 2008). Far from merely being spoilers to planet finders, new circumbinary disks offer fresh laboratories for studying dynamical interactions between gas-rich disks and the massive orbiting bodies embedded within them as well as critical opportunities to calibrate pre–main-sequence tracks.

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