High-resolution Imaging of Circumstellar Gas and Dust in UZ Tauri: Comparing Binary and Single-Star Disk Properties

Eric L. N. Jensen,[1] David W. Koerner,[2] Robert D. Mathieu[1]

ABSTRACT

We present $\lambda = 1.3$ and 3 mm aperture synthesis imaging of the multiple T Tauri system UZ Tauri. UZ Tau is a hierarchical triple composed of a single star, UZ Tau E, 530 AU distant from a 50 AU binary, UZ Tau W. Both dust and gas emission from the close binary are a factor of four lower than from the single star. Since UZ Tau E and W have similar stellar masses, luminosities, and ages, we conclude that the mass of dust and gas associated with UZ Tau W is reduced solely by the influence of a close companion. The disk emission from UZ Tau E is best interpreted as a circumstellar disk similar to those around other single T Tauri stars. In a 1″-resolution aperture synthesis map, $CO(2 \to 1)$ emission is coincident with the continuum peak and elongated with a size of 300 AU (FWHM); a velocity gradient is seen along the long axis, consistent with rotation in a gaseous disk. The emission is elongated at position angle 19°, the same as the PA of previous polarization measurements. A disk model fit to the continuum spectral energy distribution (SED) of UZ Tau E yields a disk mass of 0.06 $M_\odot$. in contrast, no CO emission is detected from UZ Tau W, and its 1.3 mm continuum emission is unresolved in a 1″ (FWHM) beam (corresponding to a 70 AU radius). The small extent of the emission and dynamical considerations imply that the 50 AU binary cannot be surrounded by any appreciable circumbinary disk; its mm-wave emission is from circumstellar disks around one or both components. The mass of the circumstellar material is in the range 0.002--0.04 $M_\odot$ but is very uncertain because of the unknown temperature and surface density distributions of the material. The properties of the UZ Tau E disk are similar to those inferred for the early solar nebula; such a disk could give rise to a planetary system like our own. The properties of the

[1]Univ. of Wisconsin-Madison, Dept. of Astronomy, 475 N. Charter St., Madison, WI 53706. E-mail: jensen@astro.wise.eclu, mathieu@astro.wisc.edu.

[2]169-506, Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109. Formerly at California Institute of Technology, Pasadena, CA 91125. E-mail: davidk@coma.jpl.nasa.gov.

UZ Tau W disk(s) are only marginally consistent with a "minimum mass solar nebula" and demonstrate that the reduced mm-wave flux may be linked to a disparity in the size of disks (and perhaps of planetary systems) around single and binary stars.

Subject headings: stars: individual: UZ Tauri — stars: binary --- circumstellar matter -- planetary systems

1. Introduction

The high detection rate of mm-wave continuum emission from T Tauri stars (Beckwith et al. 1990, henceforth BSCG; Henning & Thamm 1994; André & Montmerle 1994) suggests that circumstellar disks that may give rise to planetary systems are very common (cf. Sargent 1996). Recent, evidence indicates, however, that close binary companions strongly influence the distribution of circumstellar ant] circumbinary material. Millimeter flux from binaries with separations less than $\sim$ 50--100 AU is reduced compared with that of wide binaries or single stars (Jensen et al. 1994, 1996; Osterloh & Beckwith 1995; Dutrey et al. 1996). More than 1/3 of solar-type main-sequence stars have a stellar companion within 100 AU (Duquennoy & Mayor 1991), a typical disk radius (e.g. Sargent 1996), and the frequency of binaries is at least as high for pre-main-sequence stars (Ghez et al. 1993; Leinert et al. 1993; Sirnon et al. 1995; see also Mathieu 1996). Consequently, the effect of companions on the evolution of disks is likely to play a major role in setting the planet formation frequency. Studies of the effect of binaries on mm-wave emission have relied on samples with a range of stellar ages, luminosities, and spectral types. To help reduce possible ambiguity introduced by these factors, we present an aperture synthesis imaging study of the triple system UZ Tauri.

UZ Tau is composed of both a close binary, UZ Tau W (0.''34 projected separation), and a wide companion, UZ Tau E, 3.''8 away (Simon et al. 1995). Assuming a distance of 140 pc to Taurus- s-Auriga (Ken yon et al. 1994), the projected separation of UZ Tau W corresponds to $\sim$ 50 AU which is within a typical circumstellar disk radius. UZ Tau E serves as a "control" single star, coeval with UZ Tau W but sufficiently far removed (530 AU) that its disk should be largely unaffected by its companion (Ghez et al. 1994). The stars in the two systems are quite similar in spectral type, mass, age, and luminosity (Table 1). UZ Tau thus provides an ideal laboratory for studying the effect of companions on disks. Because of the similarity of the properties of E and W, any differences in their disks cannot be attributed to stellar properties but rather directly reflect the influence of multiplicity.

Differences in the circumstellar material of UZ Tau E and W have already been detected at mid-infrared wavelengths. In high-resolution images at $\lambda = 10~\mu$m, Ghez et al. (1994) found that emission from the close binary, UZ Tau W, was a factor of ~ 5 less than that from UZ Tau E. Emission at 10 μm probes relatively hot material near the stars; in typical circumstellar disk models (e.g. BSCG) almost all the 10 μm emission arises from the inner 1 AU of the disk. In contrast, millimeter-wave continuum emission in such models typically arises from a larger disk area and may be predominantly optically thin, probing total disk mass. In addition, emission in optically thick transitions of CO traces the kinematics and outer radius of circumstellar gas. Knowledge of these fundamental properties is critical in order to assess the capacity for such disks to form planetary systems like our own. In this work, we present a high-resolution study of the UZ Tau triple system using $\lambda = 1.3$ and 3 mm continuum and CO(2$\rightarrow$1) line emission.

2. Observations

The Owens Valley millimeter array was used to observe UZ Tau simultaneously in ^{13}CO (1$\rightarrow$0) and $C^{18}O$ (1$\rightarrow$0) line emission and in the 110 GHz continuum ($\lambda = 2.7$ mm) between 1993 January 13 and 1993 June 14. The phase center was the stellar position given in Jones & Herbig (1979): $\alpha(1950) = 04^h29^m39^s26, \delta(1950) = 25~°46'1~3''4$. Four antennas were used, separated by baselines of 15-65 m (5.5-24 kλ at 110 GHz). Cryogenically cooled S1S receivers produced overall system temperatures of 200-400 K. The digital correlator was configured to observe each of the ^{13}CO (1-->0) and $C^{18}O$ (1$\rightarrow$0) lines with a band of Harming-smoothed channels that was 64×125 kHz, yielding spectral resolution of 0.34 km s^{-1}. The band center was $V_{HEL} = 1S.5$ km s^{-1}, the stellar velocity of UZ Tau W (Hartmann et al. 1986). Continuum measurements were made simultaneously in a broadband channel of width 500 MHz. Absolute flux densities were calibrated with measurements of Uranus and Neptune and have an estimated uncertainty of 20%. Gain calibration] was accomplished with periodic observations of 3C120 and 0528+134. The data were calibrated using the Owens Valley MMA software (Scoville et al. 1993).

Continuum emission at 97.8 GHz and 230.5 GHz ($\lambda = 3.1$ and 1.3 mm) and the CO (2$\rightarrow$1) line were observed simultaneously on 1995 March 29 with six antennas. Baselines lengths were 20-206 m (15- 156 kλ at 230 GHz). System temperatures at 230 GHz were ~ 300 K. The digital correlator was configured to observe the CO (2-+1) line with two bands of Hanning smoothed channels, 32×1 MHz and 96×83 kHz, yielding spectral resolutions of 1.30 and 0,11 km s^{-1}, respectively. Two broadband channels, each with 1 GHz bandwidth, were used to observe continuum emission at 97. S and 230.5 GHz simultaneously. The

phase center, central velocity, and calibration methods were identical to those described for observations at 110 GHz.

2.1. Continuum Emission

CLEANed aperture synthesis maps of the 230 GHz and 97.8 GHz continuum emission from UZ Tau were created with IMAGR, a task from the NRAO AIPS software package, and are displayed in Figure 1. The E and W components of UZ Tau are well resolved from tack other at both frequencies. The positions of peak emission from the two sources are $\alpha(1950) = 04^h 29^m 39\overset{s}{.}39$, $\delta(1950) = 25°46'12'.'6$ for UZ Tau E and $\alpha(1950) = 04^h 29^m 39\overset{s}{.}11$, $\delta(1950) = 25°46'12\overset{''}{.}9$ for UZ Tau W. In Figure 1 Q, 230 GHz continuum emission is resolved at the position of UZ Tau E in a synthesized beam with FWHM size $1'.'2 \times 0\overset{''}{.}9$ (170 x 130 AU) at PA 68°. The peak flux density is 91 ± 19 mJy bi^n] and the integrated intensity is 137 ± 28 mJy. Deconvolution of an elliptical Gaussian fit to the UZ Tau E emission yields a source size with FWHM $\sim 1\overset{''}{.}2$, corresponding to a source diameter of 170 AU. While the UZ Tau E source appears to be resolved, the size estimate is uncertain; statistical and systematic errors yield an uncertainty of roughly a beamwidth in the lowest contours. In contrast, the emission from UZ Tau W is unresolved and a factor of four to five lower in flux, with flux density 32 ± 9 mJy. The combined flux density from both components, 169 ± 29 mJy, agrees well with the value of 172 ± 15 mJy measured by BSCG at $\lambda = 1.3$ mm. 'The quoted uncertainty includes rms variations in the map ($1a = 6.5$ mJy bin-*) and a possible 20% error in absolute flux calibration.

In Figure 16, a map of 97.8 GHz emission from UZ Tau reveals unresolved emission at the position of UZ Tau E with flux density 14 ± 3.1 mJy. The synthesized beam has FWHM size $2\overset{''}{.}4 \times 1\overset{''}{.}8$ at PA 72°. Combined with the 230 GHz measurement, the 97.S GHz flux density yields a spectral index $\alpha = d \log(F_\nu)/d \log(v) = 2.7$ for UZ Tau E. No emission is detected at the position of UZ Tau W above the 3σ value of 4.5 mJy. This yields a lower limit of $\alpha > 2.3$ for the UZ Tau W disk, consistent with the value found for UZ Tau E. If the two disks have the same spectral index, a flux of $F_{97.8 \, GHz} = 3.2$ mJy is expected on the basis of extrapolation from the 230 GHz flux with $\alpha = 2.7$.

A CLEANed aperture synthesis map of the 110 GHz continuum emission from UZ Tau was also created with IMAGR. Unresolved emission was detected at the position of UZ Tau with flux 23 ± 6 mJy. Uncertainties are calculated as for 230 GHz, with $1\sigma = 4$ mJy bm^{-1}. The synthesized beam had FWHM size $4\overset{''}{.}6 \times 4'.'3$ at PA 348°, too large to unambiguously separate the E and W components. However, the centroid of the emission is at $\alpha(1950) = 04^h 29^m 39\overset{s}{.}34$, $\delta(1950) = 25°46'13'.'5$. This is $1\overset{''}{.}1$ from the UZ Tau E 230 GHz position and

3"1 from the UZ Tau W position, strongly suggesting that most of the emission is associated with UZ Tau F,. The predicted 110 GHz flux from the 97. S-230 GHz power law agrees with the measured 110 GHz flux to within its uncertainty. A least-squares fit to all three points yields $\alpha = 2.6$ for UZ Tau E. Power-law fits with $\alpha = 2.2$-3.1 are consistent with the data to within the 1σ errors. Dutrey et al. (1996) detected both UZ Tau E and W at 110 GHz; the sum of their E and W fluxes agrees with our 110 GHz flux measurement within the quoted uncertainties. Similarly, scaling by $\nu^{2.7}$, our 97.8 GHz flux for UZ Tau E and limit for UZ Tau W are consistent with their 110 GHz detections of E and W. However, our flux measurements differ from the results of Simon & Guilloteau (1 992), who found equal fluxes for E and W; a similar disagreement was noted by Dutrey et al. (1996).

2,2. Molecular Line Emission

Maps of CO $(2\rightarrow1)$ line emission from UZ Tau are displayed in Figure 2. Molecular gas is detected only at the position of UZ Tau E in a 14.3 km s^{-1} velocity interval, from $V_{HEL} = 11.4$ to 25.7 km s-]. No emission above a 3σ level of 440 mJy is found in 1.3 km s^{-1} channels outside this range. Images of the emission in each channel were CLEANed with IMAGR and reconstituted with a circular beam of 1".2 FWHM to ensure that effects from the 1".2 x 0".9 FWHM synthesized beam did not introduce any artificial elongation in the morphology. Maps of the integrated emission and first moment with respect to velocity were created with AIPS task MOMNT and are displayed as Figure 2a and 2b, respectively. Emission in Figure *2a* is resolved with peak flux 4.8 Jy bm^{-1} km s^{-1} and integrated intensity 10.5 Jy km s^{-1}. A nominal FWHM source size of 2'.'1 x 0'.'9 at PA 19° is obtained by deconvolution of the restoring beam from an elliptical Gaussian fitted to the emission in Figure *2a.* The size across the major axis corresponds to a FWHM diameter of 290 AU; emission is not reliably resolved across the minor axis. A systematic gradient in the velocity across the long axis is apparent in Figure *2b*. A small exception to the gradient is evident to the northeast. This results from exceptionally strong emission in one channel only and may be the result of channel-to-channel noise in the band pass calibration. In the velocity interval over which CO $(2\rightarrow1)$ line emission is detected, no ^{13}CO $(1\rightarrow0)$ or $C^{18}O(1\rightarrow0)$ line emission is found above a 3σ value of 2.0 Jy km s^{-1} in a 4".6 x 4".3 FWHM beam.

3. Modeling

If the mm-wave continuum emission is optically thin, a lower limit to the mass of circumstellar material around each component can be obtained from

$$M_D \approx 10 \times \left(\frac{\lambda}{0.250 \text{ mm}}\right)^\beta \frac{F_\nu d^2 \lambda^2}{2kT_D} \text{ g cm}^{-2} \tag{1}$$

(Hildebrand 1983), where F_ν is the continuum flux at wavelength λ, T_D is the dust temperature, β is the exponent of the dust opacity law $(\kappa_\nu \propto \nu^\beta)$, and d is the distance to the source. Using $d = 140$ pc, $\beta \approx \alpha - 2 = 0.7$ (cf. Beckwith & Sargent 1991), and the component fluxes at 230 GHz, lower limits to the circumstellar dust masses are $M_D \gtrsim$ 0.8-1.7 x $10^2 M_\odot$ for UZ Tau E and $M_D \gtrsim$ 2--4 x $10^3 M_\odot$ for UZ Tau W with $T_D =$ 30-15 K (typical of the dust temperatures in molecular clouds; Hollenbach et al. 199]),

Similarly, the total mass of circumstellar gas can be calculated from the integrated CO $(2 \rightarrow 1)$ emission, $\int S_\nu dv$, using (cf. Scoville et al. 1986)

$$M_{H_2} = 1.42 \times 10^{-10} \frac{(T_x + 0.93)}{e^{-16.76/T_x}} \frac{\tau}{(1 - e^{-\tau})} \frac{d_{kpc}^2}{X(CO)} \int S_\nu dv \quad M_\odot, \tag{2}$$

where T_x is the excitation temperature, τ is the optical depth in the CO line, d_{kpc} is the distance to the source in kpc, $X(CO)$ is the fractional abundance of CO, and $\int S_\nu dv$ is in units of Jy km s^{-1}. For optically thin emission, $\tau/(1 - e^{-\tau}) \approx 1$, and the mass is calculable without *a priori* knowledge of τ. The magnitude of τ in the UZ Tau disks is completely unknown, so we use the optically-thin approximation to determine a lower limit to M_{H_2}. Using the integrated CO (2+1) line flux of 10.5 Jy km s^{-1} and adopting $T_x = 30$ K, $X(CO) = 10^4$, and $d_{kpc} = 0.140$ kpc, we obtain $M_{H_2} \gtrsim 1.5$ x $10^5 M_\odot$ for UZ Tau E.

The above mass estimates were obtained under the assumption that the emission is optically thin and arises from isothermal material. However, given the observed morphology, a disk configuration for the material is more likely. We fit the spectral energy distributions (SEDs) of UZ Tau E and W with a standard model of the emission from a flat, geometrically-thin disk, shown in Figure 3 (Adams et al. 1988; I] SCG). We assumed power-law temperature and surface density distributions, $T(r) = T_1(r/1AU)^{-q}$ and $\Sigma(r) = \Sigma_0(r/r_0)^{-p}$, with $p = 1.5$. The dust emissivity was taken to be $\kappa_\nu = 0.1 \ (\lambda/250 \mu\text{m})^{-\beta}$ cm^2 g^{-1} with $\beta = 1$ (Beckwith & Sargent 1991). The data for UZ Tau E were not well fit by $\beta = 2$, the value typically found for the interstellar medium (Mathis 1990); for UZ Tau W, β is not well constrained because of the presence of only an upper limit at 97.8 GHz. The disk radius for UZ Tau E was taken to be 145 AU, the radius of the CO emission in Figure 2. For UZ Tau W, we adopted half the projected binary separation, $R_{disk} = 25$ AU, as a

reasonable estimate of the circumstellar disk radius (see § 4.2.1). The stellar luminosities, visual extinctions, and spectral types were taken from Ghez et al. (1994). Under these assumptions, the disk mass M_d and temperature parameters T_1 and q were varied to fit data taken from Hartigan et al. (1994) (BVR_cl_cJHK), Ghez et al. (1994) (8.7– 12.5 pm), Weaver & Jones (1992) (IRAS 25-100 pin), and this work (4.8 μm and 1-3 mm).[3] IRAS fluxes were available only for the combined emission from both stars; Figure 3 shows the unresolved IRAS fluxes. For the mode] fit to UZ Tau E, we assumed that the E/W flux ratio at IRAS wavelengths is 5:1, roughly the ratio observed at both 10 μm and 1.3 mm.

The fit for UZ Tau E is reasonably good and yields a disk mass $M_d = 0.063 M_\odot$, with $q = 0.62$ and $T_1 = 147$ K. One source of uncertainty in this disk mass estimate arises from the unknown distribution of IRAS fluxes between E and W. Assigning all of the IRAS flux to UZ Tau E gives it the flattest possible SED and the hottest disk; this yields $M_d = 0.055$ $M_\odot$ as a lower limit to the disk mass in the context of this model.

The SED of UZ Tau W cannot be well-fit with this disk model, The mid-infrared (4.8– 10 μm) flux from UZ 'Tau W falls well below that of an optically-thick reprocessing disk[4] (Figure 3), suggesting that the 4.8-10 μm continuum and silicate emission may be optical] y thin. For a disk with parameter values in the range found for T-Tauri disks, most of the mid-infrared emission arises from within 1 AU of the star in the densest part of the disk (Beckwith & Sargent 1991). If emission from this region is optically thin, no model that fits the mid-infrared emission can also fit the 1.3 mm flux unless the assumption of radially-decreasing surface density is dropped. Because of this and the uncertain IRAS fluxes, the disk mass is poorly constrained. In the context of the continuous-disk model, a reprocessing disk has the lowest mm-wave emission for a given mass and thus gives an *upper* limit on the disk mass. For UZ Tau W, such a disk which reproduces the 1.3 mm flux has a mass of $M_d \approx 0.04 M_\odot$. However, we emphasize that this model does not fit the mid-infrared data and is likely to be inaccurate, Both the millimeter emission and Inid-infrared emission are well-fit by a 25 AU circumstellar disk with a $\sim$ 0.1-0.2 AU optical] y-thin central hole. The fit parameters are $M_d = 0.03 M_\odot, q = 0.73$, and $T_1 = 98$ K if the IRAS flux is partitioned 5:1 between E and W as discussed above, However, there is no *a priori* reason to expect a hole of this size in UZ Tau W; we discuss this issue more in §

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[3] The $\lambda = 4.8 \mu$m points in Figure 3 are based on an image taken at the NASA Infrared Telescope Facility (Mathieu & Carr, unpublished data). The E/W flux ratio of 3.9 $\pm$ 0.4 from the image was used to divide the unresolved UZ Tau E-W photometry of Elias (1 978) between the two components.

[4] We use the term "reprocessing disk" to refer to a disk whose. only source of luminosity is absorbing stellar photons and re-radiating their energy. Such a disk will have $q \rightarrow 0.75$ at large radii if it is optically thick in the optical and near-infrared (e.g., Adams et al. 1988).

4.2.2. Combining the limits from model fitting with the optically thin limit derived above, the disk mass in UZ Tau W is constrained to lie in the range 0.002-0.04 $M_{\odot}$.

4. Discussion

It is evident from Figures 1 and 2 and the discussion above that both the millimeter continuum emission and the disk mass are lower for the close binary UZ Tau W than for the more isolated star UZ Tau E. In this regard, the UZ Tau system is a prime example of the effect, recently discovered in millimeter continuum surveys in which emission from close binaries is found to be significantly reduced relative to single stars or wider binaries (BSCG; Jensen et al. 1994, 1996; Osterloh & Beckwith 1995; Dutrey et al. 1996). A similar reduction of the circumstellar molecular gas (as traced by CO emission) is demonstrated here for the first time. Molecular emission is detected around UZ Tau E, consistent with images of gaseous disks around other single T Tauri stars (Koerner et al. 1993; Koerner & Sargent 1995). In contrast, no molecular gas is detected at the position of UZ Tau W. The importance of these differences is heightened] by the fact that UZ Tau E and W have similar stellar properties (Table 1). The observed contrast is thus not attributable to stellar luminosity, mass, effective temperature, or age, but is likely to be solely the result of multiplicity.

4.1, UZ Tau E

The morphology and velocity structure evident in maps of CO emission from UZ Tau E (Figure 2) are similar to those seen in maps of other single T Tauri stars (Koerner & Sargent 1995). in particular, the CO emission is elongated with a size of a few hundreds of AU and a systematic velocity gradient, parallel to the long axis, 'J'his immediately rules out an interpretation in which infall predominates within a flattened envelope, as observed in the embedded object HL Tauri (Hayashi et al. 1994). Another striking similarity lies in tile fact that the position angle (PA) of the long axis of CO emission is parallel to the polarization angle of optical and infrared emission. The $\lambda = 2\,\mu m$ emission from the UZ Tau (E+W) system is polarized at PA 22° ±12° (Tamura & Sato 1989); other measurements of the polarization PA arc $13^\circ.7 \pm 4^\circ.6\,(\lambda = 5895\,\text{Å}; \text{Bastien 1985})$ and $2^\circ.4 \pm 5^\circ.6\,(\lambda = 7543\,\text{Å}; \text{Bastien 1982})$. In all cases, the PA of the polarization agrees with the PA of elongation of CO emission, 19° ± 2". The same agreement of CO elongation and polarization PA is seen in all of the single T Tauri stars mapped by Koerner & Sargent (1995), Monte Carlo calculations of scattered light from disks and envelopes show that this is diagnostic of flared

disks or flattened envelopes, but not thin disks (Whitney & Hartmann 1992, 1993).[5] A disk or envelope interpretation is confirmed in all instances where the orientation is constrained by imaging of optical jets and/or reflection nebulosity. In no case is the polarization PA found to be parallel to a bipolar outflow. Consequently, even though a compact bipolar outflow along the elongation axis could in principle explain Figure 2, we conclude that a rotating circumstellar disk is by far the most plausible interpretation. Kinematic modeling of spectral line maps with high signal-to-noise and high spatial resolution is required to establish this conclusion with certainty.

The circumstellar mass estimated from a disk model of the SED of UZ Tau E, $M_d = 0.06 M_\odot$, is several times larger than the "minimum mass solar nebula" of 0.01-0.02 $M_\odot$ required to produce our own solar system (Weidenschilling 1977). The lower-limit mass estimated from the CO emission is much less than this, but the disk mass could be greatly underestimated if the CO emission is optically thick. Indeed, a disk with parameters used in the SED model will have a CO optical depth well in excess of 100 throughout (cf. Beckwith & Sargent 1993). In addition, the 2:1 aspect ratio of the CO emission suggests that the disk is closer to edge on, further increasing its optical depth. Given these considerations, there is no justification for concluding that CO (or H_2) is depleted with respect to the dust. It is entirely possible that gas is present in cosmic abundances. If so, the disk around UZ Tau E has sufficiently abundant gas to generate Jovian planets like those in our own solar system. Detection in other isotopes of CO is necessary to determine the CO abundance directly and to settle this issue conclusively. ,

4.2. UZ Tau W

4.2.1. Circumstellar vs. circumbinary disks

The 1.3 mm continuum emission from UZ Tau W is confined to an area 0.''5 in radius. This limits the outer radii of any disks in the system to 70 AU or less and suggests that the UZ Tau W has no circumbinary (as distinct from circumstellar) disk. The inner radius for a stable circumbinary disk is roughly twice the binary semimajor axis for circular orbits and is larger for eccentric binaries (Rudak & Paczyński 1981, Artymowicz & Lubow 1994). If the semimajor axis of UZ Tau W is comparable to or greater than the projected binary separation, any circumbinary disk must lie at radii greater than 100 AU, well outside the

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[5] We note that the flared disk implied by the polarization measurements is inconsistent with our assumption in § 3 that the disk is thin, In the absence of any detailed information about the disk geometry, however, we retain our calculated disk mass as the best estimate from the available data.

observed boundary. If we assume that UZ Tau W has an eccentric orbit, its stars are near apastron, and the orbit is favorably oriented, then the semimajor axis could be less than the current projected separation. However, increasing the eccentricity also increases the allowed inner radius of the circumbinary disk relative to the binary semimajor axis. The result is that no set of orbital elements for UZ Tau W allows a circumbinary disk with an inner radius less than 70 AU. It is possible that UZ Tau W has an extended, low-mass circumbinary disk with mm-wave surface brightness below our detection threshold. However, the total integrated intensity in Figure 1a agrees very well with the flux measured with the IRAM 30 m telescope (BSCG), indicating that little if any extended emission from UZ Tau is undetected in our map. Thus, we conclude that UZ Tau W has little or no circumbinary disk; its millimeter emission arises from circumstellar material around one or both of the binary components.

The presence of circumstellar material with mass $\gtrsim 2 \times 10^{-3} M_\odot$ in UZ Tau W shows that a substantial circumstellar disk can survive the binary formation process and persist up to an age of at least a few $\times 10^4$ yr. The infrared excesses in most young binary systems provide clear evidence that they have circumstellar disks (Mathieu *1994*, Simon & Prato 1995), but in most cases the masses of these disks are unknown because the infrared emission is presumed to be predominantly optically thick and few close binaries are detected at millimeter wavelengths. Jensen et al. (1 996) used IRAS data to place a rough lower limit of $\sim 10^{-5} M_\odot$ on the circumstellar disk masses for typical young binaries with separations of tens of AU. Our measurements of UZ Tau W improve on this limit and thus provide one of the best measurements currently available of the mass of circum*stellar* material in a binary system with a projected separation between 1 and 100 AU. Our measurements of UZ Tau W do not require its circumstellar disk(s) to have lower surface density than that of UZ Tau E or other typical T Tauri stars; the measured millimeter flux is consistent with the disk(s) retaining a high surface density but simply being truncated by the presence of a close companion, in agreement with the conclusions of Dutrey et al. (1996).

Our upper limit on molecular emission from UZ Tau W is consistent with the disk geometry inferred from the continuum emission (circumstellar disks but no circumbinary disk). CO *(2--+1)* emission was not detected above a 2σ value of 1.1 Jy bm^{-1} km s^{-1} across the same velocity interval in which emission was detected from UZ Tau E. Under the assumptions given in § 3, this corresponds to an upper limit of $1.6 \times 10^{-6} M_\odot$ for the total H_2 mass possibly associated with weak optically thin CO emission from a tenuous circumbinary disk. However, this does not take into account possible contributions from small, optically thick circumstellar disks. In the channels with 1,3 km s^{-1} velocity width, no emission peak was detected above a 3σ value of 440 mJy bin^{-1} at the position of UZ Tau W. Under this constraint, the radius of an optically thick disk could be as large as 50 AU

and still go undetected (cf. Koerner & Sargent 1995). Consequently, considerable molecular gas could be confined to one or two circumstellar disks.

4.2.2. An inner hole?

The level of mid-infrared emission from UZ Tau W suggests that the inner disk region may be optically thin (Ghez et al. 1994; § 3). Rascal on 10 μm data, ?'-resolution 3 mm observations (Simon & Guilloteau 1992), and forbidden line profiles (Edwards et al. 1987). Ghez et al. argued that the UZ Tau W system has a central hole cleared by the binary, with the mm-wave emission arising from a circumbinary disk. However, our observations rule out a circumbinary disk; any central hole implied by the reduced mid-infrared flux must lie within a circumstellar disk and cannot be attributed to clearing by the binary companion. Optically-thin infrared emission has been attributed to inner disk clearing by planet formation, but is rarely seen in systems as young as UZ Tau (Skrutskie et al. 1990, Ghez et al. 1994). Inner disk clearing is not more common in binaries than in single stars, at least for binaries wider than $\sim$ 10 AU (Simon & Prato 1995).

The situation is further complicated by the fact that UZ Tau W shows evidence of active accretion and outflow: spectral veiling, strong Hα emission, and variable, occasionally strong [0 I] emission (Cohen & Kuhi 1979, Edwards et al. 1987, Basri & Batalha 1990, Hartmann & Kenyon 1990, Hartigan et al. 1994), Using the stellar parameters in Table 1, the veiling given by Hartmann & Kenyon (1990), and Eqs. 2 and 3 of Hartigan et al. (1995), we derive an accretion rate $\dot{M} \approx 2$ x 10-T $M_\odot$ yr$_1$ for UZ Tau W. The precise value of $\dot{M}$ is uncertain because of the uncertain stellar luminosity of UZ Tau W and the uncertainty about whether one or both components of the binary are accreting. Nevertheless, the fact that UZ Tau W shows spectral veiling and Hα of strengths comparable to those in UZ Tau E and other classical T Tauri stars indicates that accretion is not greatly diminished in this binary system.

The simultaneous presence of strong accretion diagnostics and an apparently optically thin inner disk is problematic. A possible explanation is that material is accreting along magnetic field lines in "accretion colu Inns," and there is a central hole in the disk because disk material is held off from the stellar surface by the stellar magnetic. field (Königl 1991, Shu et al. 1994). The modeled hole size of 0.1- 0.2 AU ($\sim$ 10-20 R.) requires a stellar magnetic field of several kilogauss (cf. Shu et al. 1994 Eq. 2). This field strength is larger than that observed in Zeeman measurements of T Tauri stars (Johnstone & Penston 1986, 1987; Basri et al. 1992; Guenther & Emerson 1996a,b), though few stars have been measured, However, the field inferred for UZ Tau W is a sensitive function of the hole

size and stellar radius; uncertainties in these quantities could reduce the required field to of' order one kilogauss. A strong magnetic field might be expected to result in strong non-thermal radio emission, which is not observed (Bieging et al. 1984),

The forbidden line emission from UZ Tau W may also provide clues about its disk. The [0 I] $\lambda6300$ line profile from UZ Tau W shows a smaller percentage of blue-shifted emission than any other star in the sample of Edwards et al. (1987). This led Edwards et al. to suggest that the system is viewed nearly edge-on; Ghez et al. (1994) interpreted the line profile as evidence for a central hole in the UZ 'l'au W disk. Observations of forbidden line emission from a larger sample of T Tauri stars show that line profiles similar to that of UZ Tau W are seen in a number of other stars (Hartigan et al. 1995). These systems have low-velocity emission, thought to arise from a disk wind, but lack a separate strong, blue-shifted, high-velocity emission component which is thought to arise from a jet near the star. In this picture, the forbidden line emission from UZ Tau W does not require the presence of a central hole. l'bus, another possible scenario is that the mid-infrared emission deficit is caused not by a hole but by changes in the radial opacity and effective temperature profiles of the disk due to the evaporation of different dust grain species at different temperatures. Ross & Yorke (1 993, 1996) showed that such variations could produce a dip in the spectral energy distribution around 10 pm. We note that this mechanism produces low infrared fluxes primarily around 10 pm, whereas the presence of a hole accounts for the observed lower fluxes (near photospheric levels) at shorter infrared wavelengths as well.

While a variety of explanations can at least partially account for the data, we emphasize that none of them explains why there is reduced mid-infrared emission from the binary but not from the single star when their stellar properties are so similar. We conclude simply that any disks in UZ Tau W are predominantly circumstellar, and that they most probably do not have continuous surface density, temperature, and/or opacity profiles from the stellar surfaces to their outer radii. More detailed knowledge of the disk structure awaits further high-resolution observations of the system.

4.3. Summary anti Conclusions

Aperture synthesis maps of UZ Tauri, a pre-main-sequence multiple system, reveal a pronounced difference in the mass and extent of gas and dust around a single star, UZ 'l'au E, and a 50 AU binary, UZ Tau W. Because UZ Tau E and W have similar stellar properties, the observed differences in their disks are likely to be a direct result of multiplicity.

Our observations confirm the existence of a circumstellar disk around UZ Tau E. Compact continuum emission is detected at 97.8, 110, and 230 GHz. Together with mid-infrared and IRAS fluxes, these results can be fitted by a model of a circumstellar disk with radius 145 AU and mass 0.06 $M_\odot$. CO (2-+1) emission is coincident with the continuum peak, elongated with a diameter of 300 AU (FWHM), and oriented at position angle 19°, the same as the polarization angle of optical and infrared emission. A velocity gradient along the long axis is consistent with rotation of a gaseous disk.

in contrast, no CO emission is detected from UZ Tau W; continuum emission, detected only at 230 GHz, is a factor of four to five weaker than in UZ Tau E and unresolved in a 1" FWHM beam (corresponding to a radius of 70 AU). These facts, coupled with dynamical considerations, lead us to conclude that the 50 AU binary cannot be surrounded by any appreciable circumbinary disk. Model fits to the mm-wave and mid-infrared continuum fluxes and optically-thin mass estimates indicate that the circumstellar material has a mass in the range 0.002-0.04 $M_\odot$. This demonstrates that a substantial circum*stellar* disk can survive in a close binary system, at least up to an age of a few x 104 yr. The mm-wave flux from UZ Tau W is consistent with flux reduction due to truncation of the disk(s) by the binary; it does not require reduction in surface density of the remaining circumstellar disk(s).

'l'he properties of the disk around UZ Tau E are similar to those inferred for the early solar nebula. The estimated mass is well above 0.02 $M_\odot$, the minimum mass of a disk of solar composition that could have produced a planetary system like our own (Weidenschilling 1977). The mass of a disk around UZ Tau W could also be as high as the minimum mass solar nebula, but reduced mid-infrared fluxes cast doubt on the appropriateness of fitting its SED with a simple disk model. We find that the mass of the disk(s) in UZ Tau W is at least 30% less than that of the disk around UZ Tau E and could be significantly lower. Furthermore, the radius of any disk in the binary is certainly less than one sixth that of the molecular disk in UZ Tau E (Fig. 2). our observations directly show that reduced mm-wave flux is correlated with a decrease in the extent of dust and molecular gas; modeling the emission indicates a similar decrease in mass. These results suggest that the contrasting properties of the circumstellar material around single and binary stars may eventually be linked to a disparity in the sizes of their disks, and by extension, the sizes of their planetary systems.

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Fig. 1.–- (a) Aperture synthesis map of 230 GHz continuum emission from UZ Tauri. Dashed contours are at --30 and -2σ levels, where 1 $\sigma = 5.5$ mJ y. Solid contour levels are 2σ, 3cr, 4σ, and at 20 intervals thereafter. The FWHM synthesized beam is shown in the lower left corner. (b) Map as in (a) of 97.8 GHz continuum emission from UZ Tauri, with crosses at the positions of peak 230 GHz emission. Contour levels are at 1σ intervals of 1.5 mJy, starting at 2σ. Emission is detected only at UZ 'l'au E, the single star, putting a 3σ upper limit of 4.5 mJy on any 97.8 GHz emission from the closc binary UZ Tau W.

Fig. 2.- (a) Aperture synthesis map of CO $(2\rightarrow1)$ emission from UZ Tau integrated over a 14.3 km s-' velocity width. Contours arc at 1 σ intervals of 580 mJy bm^{-1} km s^{-1}, starting at 2σ. Crosses mark the positions of peak 230 GHz continuum emission from UZ Tau F, and W. Emission at UZ Tau E is resolved along PA 19° with a FWHM size 2″1, corresponding to a disk radius of 145 .4U. (b) First moment velocity map from the CO $(2\rightarrow1)$ emission in (a). Contours arc at 1 km s⁻1 intervals from 14 to 19 km s^{-1}, with darker shades of gray indicating higher velocities. A velocity gradient is evident along the PA of elongation, consistent with the rotational pattern of a circumstellar disk.

Fig. 3---- Spectral energy distribution of UZ Tau, with disk models superimposed. The unresolved IRAS 25, 60, and 100 μm fluxes are shown as half-filled diamonds. The solid lines show the total (star+disk) emission and the dashed lines show the stellar photospheres. For UZ Tau F, the model has $M_d = 0.06$ $M_\odot$, $q = 0.62$, and $T_1 = 147$ K. For UZ Tau W, the model is a reprocessing disk with no intrinsic disk luminosity and $M_d = 0.04$ $M_\odot$; the 4.8 and 10 μm emission falls below this line, suggesting that the 4.S-10 pm emitting region is optically thin. No simple disk model with a continuous surface density distribution fits the UZ Tau W data well. The disk mass of UZ Tau W is uncertain but lies in the range 0.002-0.04 $M_\odot$.

a) 230 GHz Continuum

UZ Tau W

UZ Tau E

b) 97.8 GHz Continuum

RIGHT ASCENSION (1950)

DECLINATION (1950)

a) CO (2 to 1)

b) Mean velocity