THE ASTROPHYSICAL JOURNAL, 434:707–712, 1994 October 20

10 MICRON IMAGING OF UZ TAURI: EVIDENCE FOR CIRCUMSTELLAR DISK CLEARING DUE TO A CLOSE COMPANION STAR

A. M. GHEZ[1,2]
Steward Observatory, University of Arizona, Tucson, AZ 85721; ghez@mira.astro.ucla.edu
J. P. EMERSON
Queen Mary & Westfield College, Mile End Rd., London E1 4NS, UK; jpe@starlink.qmw.ac.uk
J. R. GRAHAM[3] AND M. MEIXNER[4]
Astronomy Department, University of California, Berkeley, CA 94720;
jrg@ucbast.berkeley.edu and meixner@ucbast.berkeley.edu
AND
C. J. SKINNER
Lawrence Livermore National Laboratory, Livermore, CA 94551-9900; skinner@tristan.llnl.gov
Received 1994 March 2; accepted 1994 April 26

ABSTRACT

We present 10 μm images of the multiple T Tauri star system UZ Tau taken with the Berkeley mid-infrared array camera at UKIRT and evidence that UZ Tau E and W are a common proper pair. The mid-infrared emission is resolved for the first time into the two components UZ Tau E and UZ Tau W. The mid-infrared excess deduced for UZ Tau W appears to be much lower than that observed for UZ Tau E. This excess emission is consistent with an optically thin circumstellar disk in the case of UZ Tau W, whereas UZ Tau E's excess is consistent with an optically thick disk. We suggest that the close binary star pair in UZ Tau W is responsible for the observed difference between UZ Tau E and W's mid-infrared excess. In the proposed model, the binary star interacts with the local circumstellar disk environment and clears out much of the material inside its orbital radius ($\sim$50 AU). As a result, the hot dust, observed at mid-infrared wavelengths, in UZ Tau W is suppressed compared to its "wider" companion UZ Tau E. This scenario can also plausibly account for differences observed in UZ Tau E's and UZ Tau W's optical line strengths and profiles.

Subject headings: binaries: visual — circumstellar matter — infrared: stars — stars: individual (UZ Tauri) — stars: pre–main-sequence

1. INTRODUCTION

UZ Tau is one of the many T Tauri systems whose properties suggest that it is surounded by a circumstellar disk. It has an infrared excess (Strom et al. 1989; Skrutskie et al. 1990) as well as strong millimeter and submillimeter continuum emission (e.g., Beckwith et al. 1990; Beckwith & Sargent 1991), which are all thought to originate in a circumstellar disk. UZ Tau's forbidden-line emission, which probes the low-density outer region of a mass outflow, shows only a blueshifted component, which suggests the presence of an opaque disk occulting the receding portion of the wind from the observer (Appenzeller, Jankovics, & Ostreicher 1984; Edwards et al. 1987). Its optical and near-infrared emission is linearly polarized (e.g., Bastien 1985; Tamura & Sato 1989), which is interpreted in terms of scattering by dust located in a circumstellar disk. Although no direct evidence for a disk around UZ Tau exists to date, as in the case for most T Tauri stars (cf. review by Bertout 1989), the wealth of circumstantial evidence strongly supports this hypothesis.

UZ Tau is a multiple star system. Three components have been identified: a "wide" $\sim$3".6 east-west pair (UZ Tau E-W), which was originally detected visually by Joy (1942), and a "close," 0".35, north-south pair (UZ Tau Wa-Wb) that was observed both by lunar occultation (Simon et al. 1992) and speckle imaging (Ghez, Neugebauer, & Matthews 1993). At a distance of 140 pc (Elias 1978) UZ Tau's components are separated by 500 and 50 AU, for E-W and Wa-Wb respectively. In this paper, we will refer to the combination of the close binary star pair simply as UZ Tau W.

Multiplicity is an important property. The presence of unaccounted for companions can severely effect our assumptions, as was clearly demonstrated in the case of the age of T Tauri stars in Taurus by Simon, Ghez, & Leinert (1993). Unseen companions also bias the circumstellar disk properties derived from modeling spectral energy distributions (e.g., Ghez et al. 1991). UZ Tau's companions potentially have two effects. First, the companions contribute emission, which is not included in the standard single star plus circumstellar disk models. Second, the closest pair, separated by less than the size typically assumed for a circumstellar disk, may have a significant, but so far virtually unrecognized, effect on the evolution of the circumstellar disk material.

T Tauri stars' mid-infrared flux is assumed to arise from relatively hot dust located in the inner regions of the circumstellar disk and therefore has played a critical role in the understanding of these disks. In particular, these data points are used to determine the disk's temperature distribution (e.g., Beckwith et al. 1990; Adams, Emerson, & Fuller 1990). However, almost all the mid-infrared data that exists for T Tauri stars comes

[1] Hubble Fellow.
[2] Present Address: Department of Astronomy, University of California Los Angeles, Los Angeles, CA 90024.
[3] Alfred P. Sloan Research Fellow.
[4] Present address: Department of Astronomy, MC 221, University of Illinois, Urbana-Champaign, IL 61801.

from *IRAS*. Given the large beam size of *IRAS* ($\sim 1'$ at 12 μm), the mid-infrared data for multiple star systems are the combination of all the components' flux densities. In the case of UZ Tau, this source confusion is usually ignored and the flux is assigned to only one star (e.g., Beckwith et al. 1990; Strom et al. 1989) or is divided between the components on the basis of the flux ratios observed at shorter wavelengths (e.g., Cohen, Emerson, & Beichman 1989). However, there is no reason, a priori, to believe that this should be true.

The primary purpose of this work is to resolve the mid-infrared emission detected by *IRAS* between UZ Tau E and UZ Tau W, to accurately determine how much each individual component contributes to the total, and to assess how the resolved flux densities fit in the current star plus disk modeling of UZ Tau's spectral energy distribution. In addition, we are interested in seeking observational evidence for any physical effect the close binary star pair in UZ Tau W has had on its local circumstellar disk environment.

2. OBSERVATIONS AND DATA REDUCTION

Observations of UZ Tau [α (1950) = $04^h29^m39^s\!.3$, δ(1950) = $+25°46'13''$, coordinates of the system's optical photocenter taken from Jones & Herbig (1979)] and the reference star α Tau were carried out under photometric conditions at UKIRT[5] Mauna Kea, Hawaii, on 1992 December 8–10 using the Berkeley 10 × 64 Ga:Si mid-infrared array camera (Arens et al. 1987; Keto et al. 1992). This camera mounted on UKIRT has a pixel scale of $0''\!.39$ pixel^{-1}, resulting in a field of view for a single frame of $3''\!.9 \times 25''\!.0$, where the long axis is aligned roughly east-west. The position angle of the chip was measured to be 92° (degrees east from north). This was determined by scanning a star across the chip by moving the telescope in right ascension only. The observations were made through a circular variable filter ($\delta\lambda/\lambda = 0.1$) at wavelengths of 8.5, 9.7, and 12.5 μm. The throw of the chopping secondary was 12″ east at 6.5 Hz and the telescope was nodded 30″ south every 30.8 s (cf. Ball et al. 1992).

In the first half of the chop cycle UZ Tau was located at the center of the eastern half of the chip. During the second half of the chop cycle, the source was centered in the western half of the chip as a result of the 12″ throw of the chopping secondary. In this configuration each nod-chop set contained two exposures of the source and had a total on-source integration time of 25.6 s. Ten nod-chop sets were obtained of the source at each wavelength. The reference source, however, was sufficiently bright that significant flux was detectable beyond the north and south edges of a single frame and was therefore observed with one nod-chop set each at three positions: centered, offset to the north by $1''\!.5$, and offset to the south by $1''\!.5$. Observations of UZ Tau and the flux calibrator α Tau were obtained very close in time and at very similar air masses such that air mass corrections in the flux calibration were negligible.

The exposures of both UZ Tau and α Tau were background subtracted using "double differences" as described in Ball et al. (1992) and flat-fielded by a normalized image of the sky. The double images of the source, a positive and negative one, in each single 10 × 64 reduced frame were separated to produce 20 independent 10 × 32 images of UZ Tau and 6 of α Tau at each wavelength. In each resulting image of UZ Tau only one component was detectable at a significant level. The centroid of this component was used to measure the offsets between the individual frames, which were then combined into a single mosaic. Likewise for each of the three positions of α Tau the frames were co-added. These were then mosaiced together using cross-correlation techniques to align the three positionally offset frames.

[5] The United Kingdom Infrared Telescope is operated by the Royal Observatory, Edinburgh on behalf of the Science and Engineering Research Council of the United Kingdom.

3. RESULTS

Figure 1 shows the images obtained at 8.7, 9.5, and 12.5 μm. UZ Tau is easily resolved at these mid-infrared wavelengths into a double star separated by $3''\!.6 \pm 0''\!.1$ at position angle 275° ± 2°. At each wavelength, UZ Tau E dominates the flux by roughly a factor of 5. During the 9.5 μm measurement UZ Tau was not precisely centered on the chip in the north-south

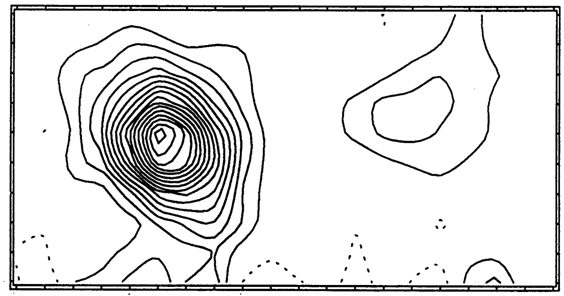

FIG. 1*a*

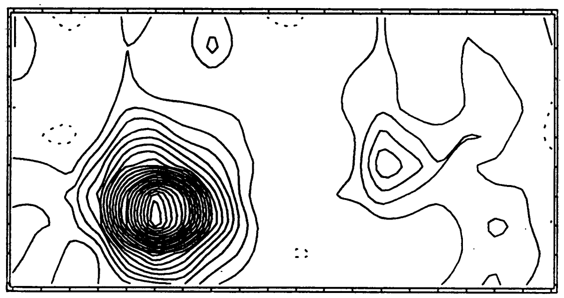

FIG. 1*b*

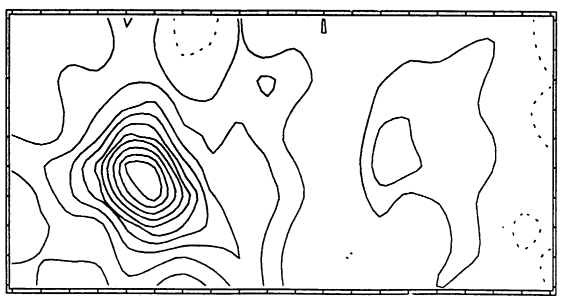

FIG. 1*c*

FIG. 1.—Contour plots of UZ Tau at (*a*) 8.7 μm, (*b*) 9.5 μm, (*c*) 12.5 μm show that UZ Tau E dominates UZ Tau W at mid-infrared wavelengths by roughly a factor of 5. This figure is approximately oriented such that north is up and east is to the left (as discussed in the text the detector axes deviate from this by 2°). The contour levels are separated by 1 σ starting at -1 σ, but skipping the zero level (dotted line used for negative contours).

TABLE 1

MID-INFRARED OBSERVATIONS OF UZ TAURI

λ (μm)	Date (1992) (UT)	Seeing	α Tau[a] (Jy)	UZ Tau E (Jy)	UZ Tau W (Jy)
8.7..........	Dec 8	1″.0	806	0.74 ± 0.03	0.12 ± 0.03
9.5..........	Dec 8	0.9	710	1.06 ± 0.04	0.23 ± 0.04
12.5..........	Dec 9	1.2	433	0.84 ± 0.04	0.16 ± 0.04

[a] Flux density assumed for α Tau.

direction; based on radial averages of UZ Tau E in this image, we estimate that 2% of its flux is lost off the edge. Table 1 summarizes the observations made of UZ Tau and lists the seeing conditions, as measured by the FWHM of α Tau, and the flux density assumed for α Tau at each wavelength. The third companion, located 0″.35 away from UZ Tau Wa, is below the diffraction limit of UKIRT at mid-infrared wavelengths and is therefore unresolved in these observations.

The mid-infrared fluxes of the two components, listed in Table 1, when combined agree with earlier narrow-band measurements of this system made in 1982 December 12 with a 9″ diameter beam (Cohen & Witterborn 1985). These authors concluded that the UZ Tau system shows a definite silicate emission feature. The resolved measurements, plotted in Figure 2, suggest that both UZ Tau E and W independently show silicate emission features. Presumably the measurements made by Cohen & Witterborn were dominated by the light coming from UZ Tau E.

4. DISCUSSION

It is helpful in interpreting these results to put them in context with what else is known or can be determined about

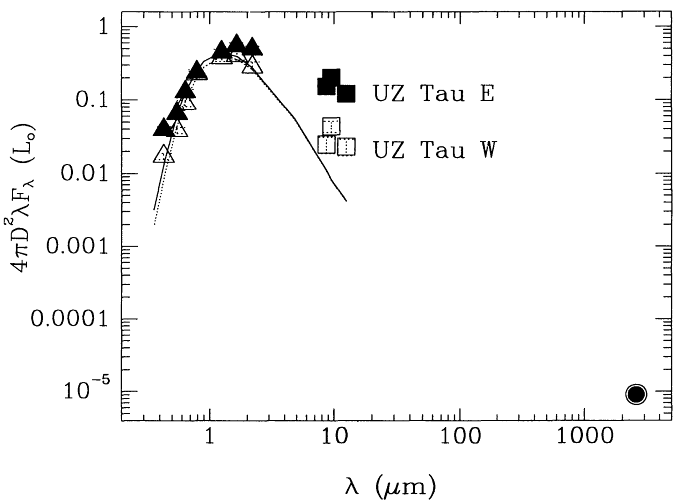

FIG. 2.—Spectral energy distributions of UZ Tau E (*filled circles*) and UZ Tau W (*open circles*). The *photospheric* emission, as estimated from blackbody fits to the RIJ data (solid and dashed lines for the fits to UZ Tau E and UZ Tau W, respectively), at mid-infrared wavelengths for the two stars appears to be similar. The *observed* 10 μm emission for UZ Tau E, however, appears to be much stronger than that of UZ Tau W. This is unlike the situation at 2.6 mm, where the two components contribute equally. We propose that UZ Tau W's binary star system has cleared out the material inside its orbit ($r \leq 50$ AU) leaving the material at larger radii intact. The mid-infrared points (*squares*) are from this work, the visual and near-infrared points (*triangles*) are from Hartigan, Strom, & Strom (1994), and the millimeter points (*circles*) are from Simon & Guilloteau (1992).

the system. In § 4.1 we present data from the literature, which collectively establishes the physical relationship between UZ Tau E and UZ Tau W. Next the stellar components' photospheric contribution to the mid-infrared emission is determined (§ 4.2). In addition, we attempt to establish the stellar components' masses and ages. The primary objective of this last exercise is to examine the ages of these stars with respect to each other as well as the general population of T Tauri stars. In the last section of this discussion (§ 4.3) we present what is known about UZ Tau E's and UZ Tau W's individual circumstellar disks and propose a model, which accounts for both the observed similarities and differences in UZ Tau E and UZ Tau W.

4.1. *Physical Relationship between UZ Tau E and UZ Tau W*

In the past, it has been assumed that UZ Tau E and UZ Tau W are physically bound on the following statistical argument: the density of field stars in the direction of Taurus is sufficiently low such that the probability of these two stars being the result of a chance projection is less than 5×10^{-4} (Reipurth & Zinnecker 1993; Simon et al. 1992). The argument that UZ Tau E and W are physically related is further supported by the similarity of their age and line of sight extinction (see below). However, it can be demonstrated that these two stars are a common proper motion pair and are therefore most likely members of a gravitationally bound binary star system.

The 1992.0 positions of UZ Tau E and UZ Tau W in Simon & Guilloteau's (1992) interferometric map are significantly different from the astrometric position (epoch 1960.0) listed in Jones & Herbig (1979) for the system's photocenter (cross in Simon & Guilloteau's Fig. 1). The observed midpoint is consistent with the photocenter right ascension, but falls ~0″.9 ± 0″.2 south of the photocenter declination (Simon 1993). However, this does not take into account UZ Tau's proper motion, which Jones & Herbig (1979) measured to be $\mu_\alpha \cos\delta = 0''.000$ yr^{-1} and $\mu_\delta = 0''.018$ yr^{-1}. Consequently, over the course of 32 years (1960.0 to 1992.0) UZ Tau's absolute position on the sky should move 0″.54 ± 0″.07 to the south. Within the uncertainties, this accounts for the apparent positional discrepancy for the photocenter. Furthermore, if only one component moved with the above proper motion, the position angle of the system would have changed by ±13° (plus or minus depending on which component moved) in the 48 years since the position angle between UZ Tau E and UZ Tau W was first measured. Table 2 lists all the separation measurements in the literature

TABLE 2

MEASUREMENTS OF THE SEPARATION BETWEEN UZ Tau AND W

Date (UT)	Separation	Position Angle	Observation	Reference
1944.25	3″.68	271°.5	Optical	1
1988.04	3.6 ± 0.2	274	Near-Ir	2
1990.77	3.78 ± 0.07	273 ± 1	Near-Ir	3
1990.90	3.5	275	Optical	4
1986–1992[a]	3.6	275	Optical	5
1992.04	3.9 ± 0.3	270 ± 5	Millimeter	6
1992.94	3.6 ± 0.1	275 ± 2	Mid-Ir	7

NOTE.—Uncertainties in the separation and position angle measurements are not always given in the literature and in those cases are not listed here.

[a] Exact date of observation is not given.

REFERENCES: (1) Joy & Van Biesbroeck 1944; (2) Moneti & Zinnecker 1991; (3) Simon et al. 1992; (4) Hartigan et al. 1944; (5) Reipurth & Zinnecker 1993; (6) Simon 1993; (7) this work.

and the measurement presented in § 3 along with the date and wavelength at which these observations were made. It can clearly be seen from Table 2 that the position angle has not changed by 13° but has remained fairly constant over this time period. *Thus we conclude that UZ Tau E and UZ Tau W are a common proper-motion pair.* This, combined with the similarity of their ages and visual extinction (see § 4.2), suggests that they are gravitationally bound and were formed from the same parent molecular cloud core.

4.2. *Stellar Properties*

To assess the 10 μm photospheric emission of UZ Tau E and UZ Tau W, we used the recent measurements of Hartigan, Strom, & Strom (1994) to fit reddened blackbodies with temperatures fixed by the observed spectral types (M2 for UZ Tau E: M3 for UZ Tau W) to the RIJ data points. It should be noted that the third companion's (UZ Tau Wb) emission is contained in these UZ Tau W measurements. At K (2.2 μm), the only wavelength at which UZ Tau Wb has been observed (Simon et al. 1992; Ghez et al. 1993), the difference between the "contaminated" and "uncontaminated" (with and without UZ Tau Wb) measurements of UZ Tau W is small ($\sim$0.2 mag). Consequently, we assume that UZ Tau Wa dominates the measurements of UZ Tau W made by Hartigan et al. and derive UZ Tau Wa's stellar properties from the blackbody fit. The stellar luminosities, L_*, and visual extinction, A_V, obtained from the blackbody fits are $L_* = 0.94 \pm 0.06$ and $A_V = 1.5 \pm 0.1$ for UZ Tau E and $L_* = 0.83 \pm 0.05$ and $A_V = 1.6 \pm 0.1$ for UZ Tau Wa, which suggests that *the two photospheres are very similar and therefore contribute nearly identical amounts of emission at mid-infrared wavelengths* (see Fig. 2).

The mass and age of UZ Tau E and UZ Tau Wa are estimated from their position in the Hertsprung-Russell (H-R) diagram and theoretical pre–main-sequence evolutionary tracks (D'Antona & Mazzitelli 1994), which gives $M \sim 0.22$ $M_\odot$ and $t \sim 5 \times 10^4$ yr for UZ Tau E and $M \sim 0.19$ $M_\odot$ and $t \sim 3 \times 10^4$ yr for UZ Tau Wa. These values are dependent on evolutionary models and will vary if different evolutionary tracks are used. Hartigan et al. (1994), however, noted that the *relative* masses and ages are fairly model independent. Thus the only points that should be emphasized here are that UZ Tau E and Wa are (1) similar in age, (2) younger than most T Tauri stars (cf. Simon et al. 1993), and (3) roughly the same mass.

Very little is known about UZ Tau Wa's close companion (UZ Tau Wb), and thus it is not possible to go through the sample procedure used to derive UZ Tau E's and UZ Tau Wa's stellar properties. However, for the sake of argument, we use the only known property for UZ Tau Wb, its K magnitude ($K = 9.5$ mag; Simon et al. 1992), to approximate its position in the H-R diagram and estimate its mass and mid-infrared photospheric contribution. This procedure is based on a number of assumptions about UZ Tau Wb: (1) it has the same age ($t \sim 4 \times 10^4$) and therefore lies on the same isochrone as UZ Tau E and UZ Tau Wa, (2) it suffers the same visual extinction found for UZ Tau E and UZ Tau Wa, $A_v \sim 1.5$ mag, and (3) its 2.2 μm flux density is purely photospheric. This defines a unique location in the H-R diagram, $T_{\rm eff} = 3037$ K and $L_* = 0.25$ $L_\odot$. UZ Tau Wb's mid-infrared photospheric emission, estimated from a blackbody with this temperature and luminosity, is down by a factor of $\sim$3 compared to that of UZ Tau E's and UZ Tau Wa's. The mass implied by the UZ Tau Wb's estimated position in the H-R diagram is $\sim$0.12 $M_\odot$. This suggests a mass ratio of $\sim$1.6 for the UZ Tau W binary star system. It should be stressed that this mass estimate depends on a number of assumptions and therefore could be significantly in error.

4.3. *Circumstellar Disk Material*

Mid-infrared measurements of a T Tauri star can be used to ascertain the presence and character of nearby circumstellar material, if the photospheric contribution is known. As discussed in § 4.2, the photospheric emission from the stars UZ Tau E and UZ Tau Wa are quite similar. It is readily apparent from an inspection of Figure 2 that the mid-infrared flux densities for UZ Tau E and W are above the photospheric level, which implies the presence of dust around both stars. In this discussion we assume that the dust is in a flattened disk, given the low visual extinction to both sources and other signatures of disk processes (see below). The apparent silicate emission feature in both UZ Tau E and UZ Tau W suggests the presence of an optically thin dust component. This, however, does not imply that both stars are surrounded by optically thin disks. As Calvet et al. (1992) point out, it is possible for an optically thick disk to produce a silicate emission feature. The presence of an optically thin disk therefore must be ascertained from the strength of the infrared excess. The observed 10 μm (mid-infrared) excess in the two components is quite different; it is much larger in UZ Tau E than in UZ Tau W. To quantify the infrared excesses observed in UZ Tau, we used the parameters ΔK and ΔN, where

$$\Delta K = \log \frac{F(\text{obs})_{2.2\,\mu m}}{F(\text{phot})_{2.2\,\mu m}}\,, \quad \Delta N = \frac{[K(\text{obs}) - N(\text{obs})]}{2.5} + \Delta K\,,$$

constructed by Strom et al. (1989). A "typical" T Tauri star, which is thought to have an optically thick disk at infrared wavelengths, has a $\Delta K \geq 0.2$ dex and $\Delta N \geq 1.2$ dex, whereas a T Tauri star system with optically thin disk has $\Delta K < 0.2$ dex and $\Delta N < 1.2$ dex (Skrutskie et al. 1990). Although broadband N measurements of UZ Tau E and W were not obtained, estimates for the N-band emission were derived by integrating over the narrow-band measurements, $N_{\rm UZ\,Tau\,E} = 4.0$ mag and $N_{\rm UZ\,Tau\,W} = 5.8$ mag. When combined these values agree with earlier measurements of the total system (cf. Rydgren et al. 1984). Using these values in conjunction with Hartigan, Strom, & Strom (1994) K band measurements and the above estimates of the photospheric contribution, we find $\Delta K_{\rm UZ\,Tau\,E} = 0.3$ dex, $\Delta N_{\rm UZ\,Tau\,E} = 1.7$ dex, $\Delta K_{\rm UZ\,Tau\,W} = 0.0$ dex, and $\Delta N_{\rm UZ\,Tau\,W} = 0.9$ dex. *Thus the infrared excesses in UZ Tau E and UZ Tau W appears to be significantly different; not only is this excess much larger in UZ Tau E than in UZ Tau W, but aso UZ Tau E's excess emission is consistent with an optically thick disk, whereas UZ Tau W's is suggestive of an optically thin disk.*

The occurrence of T Tauri stars with optically thin disks at infrared wavelengths has been interpreted as evidence of circumstellar disk evolution, because the fraction of stars with optically thin disks appears to increase with age. In particular, more than half of the T Tauri stars with ages greater than 3×10^6 yr have optically thin disks. It has furthermore been postulated that these disk become optically thin due to the formation of planetesimals (Strom et al. 1989; Skrutskie et al. 1990).

For several reasons it is unlikely that UZ Tau W's optically thin disk results from planetesimals. First, the age of UZ Tau W derived in § 4.2 of $\sim 4 \times 10^4$ yr is quite young compared to the majority of stars that have optically thin disks. Second, UZ Tau W and UZ Tau E, which have similar masses, were born at the same time and from the same parent molecular cloud material (see §§ 4.1 and 4.2). This leaves no apparent reason why grains would start to agglomerate in UZ Tau W's and not UZ Tau E's circumstellar disk.

Clues to the origin of the mid-infrared excess discrepancy can be found in other observed differences between UZ Tau E and UZ Tau W. One significant difference has already been noted: the presence of a nearby companion to UZ Tau W (UZ Tau Wb), separated by a projected linear distance of 50 AU. No such close companions have been detected around UZ Tau E.

Another difference lies in both the strength and profile of the forbidden-line emission. In general, the forbidden lines in T Tauri stars are thought to probe the outer regions (roughly tens of AU) of the winds in these sources and are typically observed to be blueshifted only. This has led researchers to propose that opaque circumstellar disks occult the redshifted portions of the lines (Appenzeller et al. 1984; Edwards et al. 1987). Furthermore, these outflows are currently believed to be powered by disk accretion (e.g., Cabrit & Andre 1991). The observed strength of the forbidden-line emission is significantly smaller in UZ Tau W compared to UZ Tau E, which is reflected in the mass-loss rates derived by Edwards et al. (1987) ($\dot{M}_{\rm UZ\,Tau\,E} = 2 \times 10^{-8}\ M_\odot\ {\rm yr}^{-1}$ and $\dot{M}_{\rm UZ\,Tau\,W} < 2 \times 10^{-9}\ M_\odot\ {\rm yr}^{-1}$). If the outflow is powered by disk accretion, the discrepancy in mass-loss rates between UZ Tau E and UZ Tau W is a consequence of differing disk accretion rates.

The observed line profiles also differ. UZ Tau E, which lacks the redshifted emission, looks like a typical T Tauri star and is assumed to have an obscuring disk. In contrast, Edwards et al. (1987) noted a greater fraction of redshifted [O I] emission in UZ Tau W than UZ Tau E or any other T Tauri star in their sample. They suggest UZ Tau W is being viewed nearly edge-on, such that its circumstellar disk does not completely occult the redshifted emission. It is, however, unlikely that UZ Tau E and W support individual disks with such different orientations for the following reasons: (1) observationally, the similarity of both their low visual extinction and strong millimeter emission (see below) suggest that neither UZ Tau E nor UZ Tau W is being viewed edge-on and (2) theoretically, if UZ Tau E and W formed from the same molecular cloud core as suggested in § 4.1, their disks are expected to be parallel although not necessarily coplanar (e.g., Bonnell et al. 1992). We therefore assume that UZ Tau W is not being viewed edge-on and look for another solution to this apparent discrepancy.

UZ Tau E's and UZ Tau W's circumstellar environments do not appear to differ at all wavelengths. Simon & Guilloteau's (1992) continuum map of UZ Tau show *UZ Tau E and UZ Tau W contributing identical amounts of emission at* 2.6 mm. This suggests that similar amounts of cold dust exist around UZ Tau E and UZ Tau W. Both UZ Tau E and UZ Tau W appear to be unresolved at 3 mm, which given the 2″ beam size in Simon & Guilloteau's map suggests that this dust must be confined to within 280 AU of each source.

To explain UZ Tau E's and W's differences and similarities, we treat them as "twins." We have proved that they are the same age and physically bound and have therefore concluded that they were formed from the same parent molecular cloud core. Thus with the exception of the presence of UZ Tau W's close companion, their initial conditions and subsequent environment were presumably the same. We suggest that any discrepancies in their circumstellar disk evolution are consequences of the additional influence of the close binary star pair in UZ Tau W.

The effect of a binary star in a circumstellar disk has been examined both analytically (e.g., Pringle 1991) and numerically (e.g., Artymowicz et al. 1991; Artymowicz & Lubow 1994). In general, it is expected that after a few dynamical timescales a binary star will create a gap in the circumstellar disk, which effectively separates out three regions in which circumstellar material can reside: a circumbinary disk and two circumstellar disks. Since the circumstellar disks are isolated from the surrounding material they can no longer be fed and will be depleted relatively quickly. Furthermore, the binary star itself may stimulate accelerated accretion in the circumstellar disk through tidal interactions (e.g., Bonnell & Bastien 1992; Ostriker, Shu, & Adams 1992). The exact structure of the surrounding circumbinary disk depends on the binary star's semimajor axis, mass ratio, and eccentricity (Artymowicz & Lubow 1994).

In the case of UZ Tau W's close binary star, no orbital elements have been determined. Taking the mass estimates obtained in § 4.2 and assuming a circular orbit with a semimajor axis of 50 AU (the observed projected separation), we estimate a period of 645 yr. Given the approximate age of this system, $\sim 4 \times 10^4$ yr, sufficient time has passed for a gap to have been formed in this system. Furthermore, assuming that it has been observed near apastron, where the system spends most of its time, and that it is not in a highly eccentric orbit, the inner edge of the circumbinary disk is expected to be at a radius of ~ 100 AU (approximately twice the semimajor axis; see Artymowicz & Lubow 1994). We suggest that the observed difference between UZ Tau E and UZ Tau W are consequences of this gap clearing and that the 2.6 mm emission, which appears to be the same in both sources, arises from regions in the circumbinary disk which are relatively unaffected by the close binary star pair in UZ Tau W.

We can use the observed 2.6 mm flux density of UZ Tau W, $F_\nu = 13$ mJy (Simon & Guilloteau 1992), to check whether or not the assumption that the 2.6 mm emission arises from dust located within the circumbinary disk (i.e., $r \sim 100$ AU) implies a reasonable disk mass. With the assumption of an optically thin disk, long-wavelength flux density places a lower limit on the total disk mass, M_D, via the following relationship:

$$4\pi d^2 F_\nu \geq 4\pi B_\nu(T_{\rm RD}) \kappa_\nu M_D\ ,$$

where B_ν is the Planck function, κ_ν is the opacity, $T_{\rm RD}$ is the outer disk temperature, and d is the distance to the source (e.g., Adams et al. 1990). At 2.6 mm this relationship can be reduced to

$$M_D \leq \frac{F_\nu}{\rm Jy}\left[\exp\left(\frac{5.54\ {\rm K}}{T_{\rm RD}}\right) - 1\right] 8\ M_\odot$$

where we have adopted an opacity per unit mass of all material at 2.5 mm, κ_ν (2.6 mm), of 0.01 cm^2 g^{-1} (cf. Simon & Guilloteau 1992). For dust located 100 AU away from UZ Tau Wa ($L = 0.83\ L_\odot$; § 4.2), we assume an equilibrium temperature of 38 K. This sets a lower limit of 0.02 $M_\odot$ for UZ Tau W's disk mass. This is well within the accepted range of disk masses estimated for T Tauri stars (cf. Beckwith & Sargent 1993).

With the inner ~ 100 AU of its disk cleared, the receding portion of UZ Tau W's wind would be observable without the system being viewed edge-on. This permits UZ Tau E and W to have similar orientations, relieving the apparent discrepancy discussed above (see discussion of outflow). The difference in mid-infrared excess, which arises ~ 1 AU away from the stars, is also easily accounted for by an inner hole in UZ Tau W's disk. Furthermore, it appears unlikely that UZ Tau W will be able to undergo planetary formation, given its youth and the observed disruptive influence of its close companion star.

Although most of the gas and dust appears to have been cleared out of UZ Tau W's inner disk, a low level of accretion with respect to UZ Tau E is still detected. Its signature is observed in the weak outflow detected from forbidden-line emission (e.g., Edwards et al. 1987), its Hα emission (e.g., Hartigan et al. 1994), and the weak but still present mid-infrared excess. It is not, however, possible to determine whether it is both components in the UZ Tau W binary system or only one that is accreting. The individual components could be accreting from their remnant circumstellar disks or the binary star pair could be accreting from the circumbinary disk. In the latter case, it would more likely for the less massive component (UZ Tau Wb) to be the accretor (cf. Artymowicz & Lubow 1994). Only with further high spatial resolution imaging of UZ Tau W either with *Hubble Space Telescope* or with ground-based speckle imaging will we be able to constrain which star or stars are still undergoing accretion in this close binary star pair.

5. CONCLUSIONS

For the first time UZ Tau's mid-infrared emission is resolved into two components, UZ Tau E and UZ Tau W. UZ Tau E is observed to dominate the 10 μm emission by roughly a factor of 5 and has a much larger mid-infrared excess than UZ Tau W. After the mid-infrared photospheric emission, which is similar for the two sources, is accounted for it appears that UZ Tau E's mid-infrared excess is consistent with an optically thick circumstellar disk, whereas UZ Tau W's is suggestive of an optically thin disk.

It is demonstrated that UZ Tau E and W are a common proper motion pair and therefore gravitationally bound. Their physical associations as well as the similarity of their ages and visual extinction suggest that all components in this multiple star system were formed from the same molecular cloud core. UZ Tau E and W, which have similar masses, have therefore experienced identical evolutionary processes and forces with the exception of the addition influence of UZ Tau Wb on its local environment.

We propose that the observed differences in UZ Tau E and W's infrared excess, forbidden-line profile, and mass-loss rate and observed similarities in age and millimeter continuum emission can be explained by an optically thin inner hole in UZ Tau W's disk that has been caused by the resonant interactions between the close binary star pair in UZ Tau W and the circumstellar disk material. In this model, the similar properties, in particular the millimeter emission, are assumed to be properties of the disk that arise in regions outside that expected to be affected by UZ Tau W's close binary star system (i.e., $r > 100$ AU). The properties that differ are believed to reflect the clearing of UZ Tau W's disk by the system's close binary star pair. It is noted that although most of the material inside 100 AU has been depleted, UZ Tau W still appears to be undergoing accretion. The rate of accretion, however, appears to be much slower than that observed in UZ Tau E. An assessment of where and how this accretion is occurring in UZ Tau W cannot currently be made and it awaits further high spatial resolution data of this close binary star pair.

We are grateful for the support of the UKIRT staff, especially telescope operators Thor Wold and Dolores Walther, during the observations, A. M. G. thanks Ian Bonnell, Cathie Clarke, Gary Fuller, and Jim Pringle for many fruitful discussions, and Mike Simon for providing us with information on the details of the 2.6 mm maps of UZ Tau and a thoughtful referee's report. This work benefited from the use of the Simbad database, operated at CDS, Strasbourg, France. Support for A. G.'s research is provided by NASA through grant HF-1031.01-92A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA under contract NAS5-26555. J. P. E. acknowledges travel support from SERC.

REFERENCES

Adams, F. C., Emerson, J. P., & Fuller, G. A. 1990, ApJ, 357, 606
Appenzeller, I., Jankovics, I., & Ostericher, R. 1984, A&A, 141, 108
Artymowicz, P., Clarke, C. J., Lubow, S. H., & Pringle, J. 1991, ApJ, 370, L35
Artymowicz, P., & Lubow, S. H. 1994, ApJ, 421, 651
Arens, J. F., Jernigan, G. J., Peck, M., Dobson, C. A., Kilk, E., Lacy, J., & Gaalema, S. 1987, Appl. Apt., 26, 3846
Ball, R., Arens, J., Jernigan, G., Keto, E., & Meixner, M. 1992, ApJ, 389, 616
Bastien, P. 1985, ApJS, 59, 277
Beckwith, S. V. W., Sargent, A. I., Chini, R. S., & Gusten, R. 1990, AJ, 99, 924
Beckwith, S. V. W., & Sargent, A. I. 1991, ApJ, 381, 250
———. 1993, in Protostars and Planets III, ed. E. H. Levy & J. I. Lunine (Tucson: Univ. of Arizona Press), 521
Bertout, C. 1989, ARA&A, 27, 351
Bonnell, I., Arcoragl, J.-P., Martel, H., & Bastien, P. 1992, ApJ, 400, 579
Bonnell, I., & Bastien, P. 1992, ApJ, 401, L31
Cabrit, S., & Andre, P. 1991, ApJ, 379, L25
Calvet, N., Magris, G. C., Patinao, A., & D'Alessio, P. 1992, Rev. Mexicana Astron. Af., 24, 27
Cohen, M., Emerson, J. P., & Beichman, C. A. 1989, ApJ, 339, 455
Cohen, M., & Witterborn, F. C. 1985, ApJ, 294, 345
D'Antona, F., & Mazzitelli, I. 1994, ApJS, 90, 467
Edwards, S., Cabrit, S., Strom, S. E., Heyer, I., Strom, K. M., & Anderson, E. 1987, ApJ, 321, 473
Elias, J. H. 1978, ApJ, 224, 857
Ghez, A. M., Neugebauer, G., Gorham, P. W., Haniff, C. A., Kulkarni, S. R., Matthews, K., Koresko, C., & Beckwith, S. 1991, AJ, 102, 2066
Ghez, A. M., Neugebauer, G., & Matthews, K. 1993, AJ, 106, 2005
Hartigan, P., Strom, K. M., & Strom, S. E. 1994, ApJ, 426, 961
Jones, B. F., & Gerbig, G. H. 1979, AJ, 84, 1872
Joy, A. H. 1942, PASP, 54, 33
Joy, A. H., & Van Biesbroeck, G. 1944, PASP, 56, 123
Keto, E., Ball, R., Arens, J., Jernigan, G., & Meixner, M. 1992, Int. J. Infrared Millimeter Waves, 13, 1709
Moneti, A., & Zinnecker, H. 1991, A&A, 242, 428
Ostriker, E. C., Shu, F. H., & Adams, F. 1992, ApJ, 399, 192
Pringle, J. E. 1991, MNRAS, 248, 754
Reipurth, B., & Zinnecker, H. 1993, A&A, 278, 81
Rydgren, A. E., Schmelz, J. T., Zak, D. S., & Vrba, F. J. 1984, vol. 25, part I
Simon, M. 1993, private communication
Simon, M., Chen, W. P., Howell, R. R., Benson, J. A., & Slowik, D. 1992, ApJ, 348, 212
Simon, M., Ghez, A. M., & Leinert, Ch. 1993, ApJ, 408, L33
Simon, M., & Guilloteau, S. 1992, ApJ, 397, L47
Skrutskie, M. F., Dutkevitch, D., Strom, S. E., Edwards, S., & Strom, K. 1990, AJ, 99, 1187
Strom, K. M., Strom, S. E., Edwards, S., Cabrit, S., & Skrutskie, M. F. 1989, AJ, 97, 1451
Tamura, M., & Sato, S. 1989, AJ, 98, 1368