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THE TRANSITIONAL PRE–MAIN-SEQUENCE OBJECT DI TAURI: EVIDENCE FOR A SUBSTELLAR COMPANION AND RAPID DISK EVOLUTION

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ABSTRACT

We report mid-IR observations of two young stars found in the Taurus dark cloud, spatially resolving for the first time their 10 μm emission. The weak-emission T Tauri star DI Tau, tentatively identified by Skrutskie et al. on the basis of 12 μm *IRAS* data as an object in the process of dissipating its circumstellar disk, is found to have no infrared excess at a wavelength of 10 μm. The nearby classical T Tauri star DH Tau exhibits excess emission at 10 μm consistent with predictions based on circumstellar disk models. While both objects appear to have the same stellar mass, age, and rotation rate, they differ in two fundamental respects: DH Tau is a single star with an active accretion disk, and DI Tau is a binary system lacking such a disk. The companion to DI Tau has a very low luminosity and is located at a projected distance of ~20 AU from the primary. Assuming the system to be coeval, we derive a mass below the hydrogen burning limit for the companion. We speculate that the formation of a substellar mass companion has led to the rapid evolution of the circumstellar disk that may have surrounded DI Tau.

Subject headings: binaries: close — circumstellar matter — stars: low-mass, brown dwarfs — stars: pre–main-sequence

1. INTRODUCTION

It is generally accepted that circumstellar disks are a common by-product of the star formation process (Beckwith & Sargent 1996). Estimates of the ubiquity of accretion disks around young stars ranges from ~70% in the youngest clusters (Carpenter et al. 1997) to ~50% in the Taurus dark cloud (Kenyon & Hartmann 1995). As young stars age, evidence of active disk accretion diminishes (Hartigan, Edwards, & Ghandour 1995). However, the process by which these disks dissipate remains a mystery. One possibility is that such disks give rise to the formation of planetary systems, though this has yet to be demonstrated. Even the influence of companion stars on the evolution of circumstellar disks is unclear. Combining observations of 2.2 μm excess emission (originating within a few stellar radii) with ground-based 10 μm and *IRAS* observations of mid-IR excesses (originating in the terrestrial planet region from 0.1–2.0 AU) of weak-emission and classical T Tauri stars in Taurus, Skrutskie et al. (1990) estimated the timescale for dissipation of accretion disks around young stars to be less than 10^7 yr. They also identified three stars as "transition objects," thought to be in the process of dissipating an optically thick disk. Based on the small number of these objects, Skrutskie et al. derive a timescale of less than 1×10^6 yr for transition from optically thick accretion disk to optically thin reprocessing disk (see also Wolk & Walter 1996). These timescales are important for constraining the epoch of planet formation and providing insight into the disk dissipation process. For example, calculations by Pollack et al. (1996) require mass surface densities 3–4 times greater than implied by the minimum mass solar nebula for Jupiter to form in less than 10 Myr via runaway accretion. Because of the small sample (~20 objects) observed from the ground at 10 μm, as well as the sensitivity limitations of the *IRAS* satellite at 12 μm, Skrutskie et al. were unable to constrain the lifetime of optically thin circumstellar disks in the terrestrial planet zone.

We have begun a program to determine the frequency of optically thin 10 μm emission among T Tauri stars in the Taurus dark cloud utilizing the current generation of mid-IR detectors with sensitivity limits 10 times better than that of the *IRAS* satellite. We hope to learn whether or not the termination of active disk accretion is also accompanied by rapid clearing of the inner disk. Here we describe initial results obtained for one of the transition objects identified by Skrutskie et al. (1990), DI Tau, which is spatially unresolved from the nearby classical T Tauri star DH Tau in the *IRAS* beam. We present new ground-based 10 μm observations resolving the emission from both stars, construct updated spectral energy distributions (SEDs) for both objects, and reanalyze their stellar and circumstellar disk properties. Our analysis shows that DI Tau does not possess an optically thick circumstellar disk within 0.1 AU of the central star and that its previously known companion, located at a distance of ~20 AU, could very well be a brown dwarf. We speculate that the formation of a very low-mass companion orbiting DI Tau led to the rapid evolution of its inferred circumstellar disk.

2. NEW MID-INFRARED OBSERVATIONS

The data were obtained with the Mid-infrared Array eXpandable (MAX) camera constructed by Infrared Labs for the Max-Planck-Institut für Astronomie. The MAX camera is built around a Rockwell 128 × 128 Si:As BIB array, which provides a field of view 35″ × 35″ when mounted on the 3.8 m United Kingdom Infrared Telescope (UKIRT). Observations were made at UKIRT on 1996 August 26–27 during photometric conditions with diffraction-limited images (FWHM ~ 0″.7) obtained through an *N*-band filter ($\lambda_{\rm eff}$ = 10.16 μm; $\Delta\lambda$ = 5.20 μm). Data were collected while chopping the telescope N-S (12″) at a rate of 2 Hz, and nodding the telescope (12″) every 50 s to correct for nonuniform illumination effects introduced by chopping. Data were reduced according to standard image processing techniques except that no flat-field corrections were applied. Images obtained at each end of the "chop" were subtracted from each other to remove bias, dark current, and thermal background. Co-added images from both "nod" positions

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TABLE 1
STELLAR AND CIRCUMSTELLAR PROPERTIES

Name	T_*[a] (K)	A_V (mag)	$L_*/L_\odot$	$M_*/M_\odot$	τ (yr)	Separation[b] (arcsec)	Period[c] (days)	$(K-L)_0$[d] (mag)	ΔN[e]	$M_D/M_\odot$[f]
DH Tau	3800	1.7	0.54	0.40	8×10^5	NC	7.2	0.60	0.94 ± 0.16	0.011
DI Tau	3800	0.8	0.65	0.38	6×10^5	0.12	7.9	0.16	0.16 ± 0.18	<0.001

[a] Data taken from Cohen & Kuhi 1979 for DH Tau (HBC 38) and DI Tau (HBC 39).
[b] Presence or absence of companions taken from Simon et al. 1995.
[c] Photometric rotation periods taken from Vrba et al. 1989.
[d] Dereddened $(K-L)$ color using A_V listed here; errors ± 0.11 mag.
[e] N-band excess in dex as defined by Skrutskie et al. 1990.
[f] Disk masses taken from Dutrey et al. 1996 for DH Tau and Jensen et al. 1994 for DI Tau.

were averaged and aperture photometry was performed on the final images with a diameter of 3″.12 using a sky annulus of 5″.2–10″.4. Flux calibration was derived by observing standards from the list of Cohen et al. (1992). Both DI and the nearby DH Tau (separation = 15″.1; P.A. = 307°) were observed simultaneously on the array ($T_{\rm int} = 250.0$ s), interspersed with observations of the standard star HR 1370 ($T_{\rm int} = 50.0$ s) at nearly the same air mass ($\Delta X < 0.1$). Comparison of photometry from stellar images appearing on different portions of the array indicates residual uncertainties in the calibration less than $\pm 5\%$. Derived fluxes and associated errors (dominated by the thermal background) are for DH Tau, $F_N = 0.137 \pm 0.005$ Jy (6.26 mag), and for DI Tau, $F_N = 0.030 \pm 0.005$ Jy (7.90 mag). Additional observations were obtained in the Q band ($\lambda_c = 19.91\ \mu$m; $\Delta\lambda = 1.88\ \mu$m) during nonphotometric conditions, yielding a flux ratio of more than 1.7 between DH Tau (detected) and DI Tau (undetected).

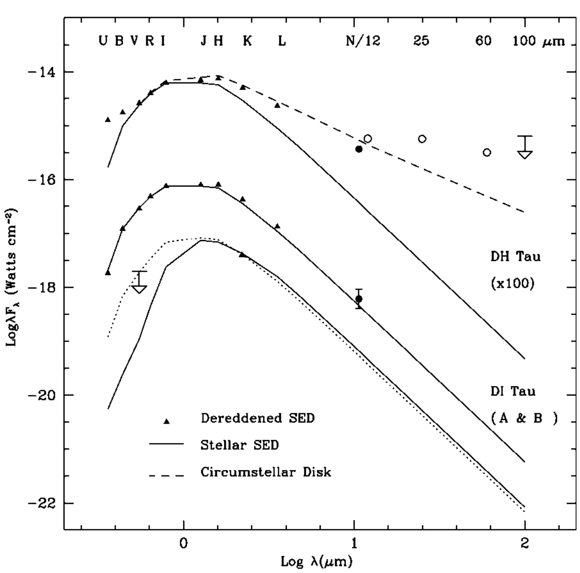

FIG. 1.—Spectral energy distributions for both DH and DI Tau: filled triangles represent simultaneous optical/near-IR data taken from Rydgren & Vrba (1981) and dereddened as described in the text, filled circles represent our new 10 μm observations, and open circles are *IRAS* fluxes from Beckwith et al. (1997). Arrows indicate upper limits. Unless otherwise indicated, the observational errors are smaller than the points. Solid lines are the expected photospheric emission; the dashed line is the emission expected from a face-on reprocessing disk that extends into the stellar surface. While the SED for DH Tau exhibits near- and mid-IR excess emission consistent with an optically thick circumstellar accretion disk, the circumstellar environment of DI Tau A appears to be free of material within 0.1 AU (10 R_*). The SEDs for DI Tau B are shown normalized at 2.2 μm for an intrinsic spectral type of M2 (*dotted line*, corresponding to an absolute upper limit to the V-band flux) and M6 (*solid line*, assuming the primary and secondary are coeval).

3. REVISED SPECTRAL ENERGY DISTRIBUTIONS AND STELLAR PARAMETERS

We combine the new photometry described above with previously published simultaneous optical and infrared data compiled by Rydgren & Vrba (1981) from 0.3 to 3.8 μm to construct updated SEDs for these sources. We adopt the spectral types listed in Cohen & Kuhi (1979) as well as the *IRAS* fluxes recently derived by Beckwith et al. (1997). Because the mid-IR flux of DH Tau dominates that of DI Tau by factors of 4 and 2 at 10 and 20 μm, respectively, we associate the *IRAS* flux with DH Tau. In order to deredden the observed spectral energy distribution, we use the color excess observed in the $(R-I)_c$ index and adopt the reddening law of Rieke & Lebofsky (1985), transformed into the appropriate color system. The stellar contribution is estimated by normalizing the dereddened I-band flux to that expected from a dwarf star of the same spectral type. Key stellar and circumstellar parameters are summarized in Table 1 for both objects.

The dereddened SEDs are shown in Figure 1, along with those expected from stellar photospheric emission and a face-on reprocessing disk model (see, e.g., Hillenbrand et al. 1992). As mentioned above, DI Tau does not exhibit significant infrared excess emission out to a wavelength of 10 μm, while DH Tau shows both ultraviolet and infrared excess emission typical of classical T Tauri stars thought to possess active accretion disks. This is consistent with recently published spectroscopic studies of both stars: Hartigan et al. (1995) place an upper limit on the mass accretion rate of DI Tau at less than $1.5 \times 10^{-8}\ M_\odot\ {\rm yr}^{-1}$ while Valenti, Basri, & Johns (1993) detect significant accretion luminosity in DH Tau. Comparison of the SED with blackbody models of optically thick circumstellar disk emission suggests that if DI Tau does possess a disk, it must be evacuated within at least $10R_*$ (~0.1 AU). DH Tau appears to have a disk that extends to within a few stellar radii (depending on the inclination angle and disk accretion rate adopted; see, e.g., Meyer, Calvet, & Hillenbrand 1997).

Using the effective temperatures and luminosities listed in Table 1, we place the stars in the H-R diagram (Fig. 2) for comparison with the pre–main-sequence (PMS) evolutionary models of D'Antona & Mazzitelli (1994, hereafter DM94) adopting the Alexander opacities and Canuto-Mazzitelli convection prescription. DH Tau and DI Tau are very young (<10^6 yr), low-mass (<1.0 $M_\odot$) PMS objects. From examination of the the properties listed in Table 1, it is clear that DH and DI Tau are quite similar except in two fundamental respects: DH

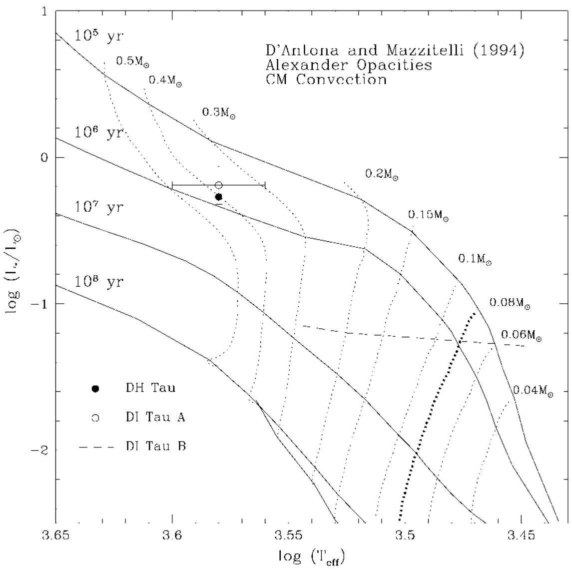

FIG. 2.—The H-R diagram for DH Tau and DI Tau A along with the PMS evolutionary models of DM94. The track corresponding to the hydrogen-burning limit is indicated at 0.08 $M_\odot$. Also shown is the range of effective temperatures and luminosities derived for DI Tau B. The error bars for the point corresponding to DI Tau A indicate an age less than 10^6 yr. If the companion DI Tau B is coeval according to these isochrones, then it must have a spectral type later than M5 and a mass less than 0.08 $M_\odot$.

Tau is a single star with an active accretion disk, and DI Tau is a binary system lacking such a disk.

4. A SUBSTELLAR COMPANION TO DI TAURI?

Both stars were part of the lunar occultation, speckle, and direct imaging survey of Simon et al. (1995) to measure the binary frequency of PMS systems. DH Tau has no companions between 0″.005 and 10″ (1–1400 AU assuming a distance of 140 pc to Taurus). DI Tau A has a companion (hereafter "B") at a projected separation of 0″.12 (16.8 AU) with a K-band flux ratio of 8 ± 1 (Ghez, Neugebauer, & Mathews 1993). The probability of observing a chance projection of a field star with $K < 12.0$ mag at this separation is less than 2×10^{-6}. Recent *HST* observations of DI Tau by Simon, Holfeltz, & Taff (1996) with the Fine Guidance Sensor provide a lower limit to the V-band flux ratio of the system; $\Delta V > 3.3 \pm 0.3$ mag.[2] Because of the systematic uncertainties in the FGS photometry reported in Simon et al. (1996), we adopted the mean magnitude (and range) derived for DI Tau from over a decade of photometric monitoring (see, e.g., Herbst et al. 1994) of $\langle m_V \rangle = 12.85$ ($\delta m_v = 0.14$ mag) resulting in $m_V > 16.2 \pm 0.3$ mag for the companion. Adopting the extinction derived for the primary (with uncertainty of ± 0.5 mag) in the DI Tau system, the *lower limit* to the intrinsic color of the companion is $(V - K)_0 > 4.6 \pm 0.5$ mag, indicating that the companion must have a spectral type of M2 or later. Given this constraint on the effective temperature, the range of associated luminosities for the companion is shown as the dotted line in Figure 2. From the position of DI Tau A in the H-R diagram, its age must be less than 1×10^6 yr. If the system is coeval according to the DM94 tracks, the upper limit on the age of the primary implies a companion mass of less than 0.08 $M_\odot$ (corresponding to a spectral type of M5).[3] Adopting the models of Burrows et al. (1997), an age less than 10^6 yr, and stellar luminosity less than 0.06 $L_\odot$ implies a companion mass less than 0.08 $M_\odot$. How likely is it that that binary is coeval? Hartigan, Strom, & Strom (1994) find that 2/3 of the PMS binaries in their sample (separations between 400 and 6000 AU) are coeval when compared to the evolutionary models of DM94. In cases where an age difference is observed, the lower mass companion always appears younger. Brandner & Zinnecker (1997) find that all binaries in their sample (90–250 AU) are coeval within the observational errors. The lack of infrared excess observed out to 10 μm for the DI Tau system precludes the possibility that the low-luminosity companion detected at 2.2 μm is in a different evolutionary state than the primary (i.e., is an infrared companion). The spectral index ($\lambda F_\lambda \sim \lambda^{-\alpha}$) of the companion must be $\alpha > 4/3$ from 2–10 μm. The luminosity ratio between the two stellar components is greater than 10, one of the highest known among the very young low-mass stars in the Taurus dark cloud. Given that brown dwarf companions have been discovered around low-mass stars in the solar neighborhood (GL 229B, Nakajima et al. 1995; HD 114762, Latham et al. 1989), we consider it reasonable to postulate their existence in the pre–main-sequence; the companion to DI Tau A could very well be a brown dwarf.[4] In fact, DI Tau bears a striking resemblance to what the GL 229 system might have looked like at an age of less than 10^6 yr. This hypothesis could be tested by confirming that DI Tau B has a spectral type later than M5 or by measuring orbital motions through monitoring of the relative positions of the DI Tau system (see, e.g., Ghez et al. 1995).

5. EVIDENCE FOR RAPID DISK EVOLUTION FOR DI TAURI A

In the preceding discussion, we have demonstrated that DI Tau A does not possess an infrared excess indicative of an optically thick inner circumstellar disk and that the previously known companion could be a brown dwarf orbiting at a distance of ~20 AU from the central star. Given the inferred age (~6×10^5 yr), if there was a disk present within 0.1 AU around this star in the past, its lifetime was very short. Arising from the collapse of a rotating cloud core, disks are expected to serve as the main reservoir of angular momentum in young stellar objects, as Jupiter does in our own solar system. Perhaps DI Tau A never had a substantial circumstellar disk, the excess angular momentum being stored in the orbit of the system. Indeed, the DI Tau binary harbors ~100 times the angular momentum of the DH Tau star + disk system even though, separated by only 2100 AU, they presumably formed from the same parent molecular cloud core. Yet DI Tau A is the most slowly rotating star known in the Taurus dark cloud that does not exhibit 10 μm excess emission (Meyer & Beckwith 1997). Can this tell us something about the history of the circumstellar environment? Edwards et al. (1993; see also Bouvier et al. 1993) have presented evidence that stellar angular momentum is regulated by the presence of a circumstellar disk. This explains the slow rotation rates of classical T Tauri stars ($P > 5$ days) compared to the weak-lined T Tauri stars that rotate faster

[2] Although not discussed explicitly in Simon et al. (1996), the simulations presented in Lattanzi et al. (1992) provide an estimate of the error associated with this magnitude difference given the separation of the system (see their Fig. 3).

[3] The uncertainty in the luminosity estimate of DI Tau B is much smaller than that for DI Tau A, where we associated the errors in extinction and distance with the primary.

[4] Ghez et al. (1997) has recently studied several T Tauri binary systems and uncovered three additional candidate brown dwarf companions.

($P < 5$ days). Their discovery finds theoretical support in models of magnetospheric coupling between young stars and circumstellar accretion disks (Königl 1991; Shu et al. 1994; Cameron, Campbell, & Quaintrell 1995). The Kelvin-Helmholtz timescale for a diskless star to spin-up from 8 days to less than 6 days is roughly 1×10^5 yr (Armitage & Clarke 1996). Tidal effects in the DI Tau system are negligible since the semimajor axis is very large compared to the radii of the objects (see, e.g., Rasio et al. 1996). The disk-regulated angular momentum hypothesis implies that, given the rotation rate of DI Tau A ($P = 7.9 \pm 0.5$ days), this star probably had a circumstellar disk in the very recent past.

Could the formation of a very low-mass companion have contributed to the dissipation of a circumstellar disk surrounding DI Tau A? Artymowicz & Lubow (1994) have suggested that gaps in circumstellar disks can be created due to dynamical clearing by a binary companion. The typical distances spanned by these gaps are from half to twice the semimajor axis (10–40 AU for the DI Tau system). An inner accretion disk not fed by an outer disk would dissipate very quickly. For a typical disk mass of 0.02 $M_\odot$ (Osterloh & Beckwith 1995) the amount of material located within 10 AU is ~0.005 $M_\odot$. The lifetime of such an inner disk given a typical disk accretion rate of 10^{-7} $M_\odot$ yr^{-1} (Hartigan et al. 1995) would be less than 50,000 yr. A cold outer disk might still be present, albeit of very low mass ($M_D < 0.001$ $M_\odot$; Jensen, Mathieu, & Fuller 1994). Is it possible that DI Tau A remains locked to a remnant disk located between the inner edge derived here (>0.1 AU) and the tidal truncation radius of ~10 AU? Armitage & Clarke (1996) have suggested this might occur in binary systems with separations between 1 and 8 AU, where material is trapped between the corotation point of the star-disk system ($6R_*$ for DI Tau A) and the inner tidal truncation radius ($0.5 \times$ separation $= 10.0$ AU). This material serves to transfer angular momentum from the central star as it contracts to the orbit of the binary companion, resulting in slower rotation rates for binary stars separated by a few AU compared to single stars or wide binaries. Future observations at wavelengths greater than 50 μm and spatial resolution less than 15″ (e.g., with SOFIA) will be required to set upper limits less than 10^{-4} $M_\odot$ on any remnant material orbiting the DI Tau system.

More recent work by Artymowicz & Lubow (1996) suggests that material from a circumbinary disk could still move across the tidal gap. This material would preferentially accrete onto the lower mass component of the system, tending to drive the mass ratio toward unity. This suggests that if the substellar mass companion formed in the disk of DI Tau A, it did so after the main infall phase had ended, with less than 0.1 $M_\odot$ remaining in the outer disk. Runaway giant planet growth in a proto–planetary disk (see, e.g., Pollack et al. 1997) can probably be ruled out given the formation time of less than 10^6 yr. Perhaps the companion to DI Tau A formed rapidly through gravitational instabilities in a massive circumstellar disk (see, e.g., Boss 1997). A more conventional explanation would be that the DI Tau system simply formed from the fragmentation of a rotating collapsing cloud core (see, e.g., Burkert & Bodenheimer 1996). If DI Tau A had a circumstellar disk, it seems reasonable to conclude that the presence of substellar mass companion at 20 AU contributed to its rapid evolution.

Ghez et al. (1994; see also Jensen, Koerner, & Mathieu 1996) have offered a similar explanation for the differences observed between UZ Tau East (a single star with optically thick disk recently discovered to be a spectroscopic binary!) and UZ Tau West (a binary system with optically thin disk). Is there a connection between binarity and the lifetime of circumstellar disks? Osterloh & Beckwith (1995; see also Jensen et al. 1994) find that young binaries with separations less than 100 AU emit less at mm wavelengths than young single stars and wide binaries. However, Simon & Prato (1995) find no correlation between the presence of companions between 20 and 280 AU and the presence of an inner disk. This finding is confirmed by examining the distribution of $(K - N)$ excesses vs. binary separation (Meyer & Beckwith 1997) including newly discovered CTTS systems with separations less than 1.0 AU (such as UZ Tau East and DQ Tau; Mathieu et al. 1997). Although there is circumstantial evidence in at least two cases that the presence of a very low-mass companion may have influenced the evolution of a circumstellar disk, it remains an open question over what range of separations (and mass ratios) the influence of a binary companion is important.

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