The Transitional PMS Object DI Tauri: Evidence for a Sub-stellar 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 \(\mu\)m emission. The weak–emission T Tauri star DI Tau, tentatively identified by Skrutskie \textit{et al}. (1990) on the basis of 12 \(\mu\)m 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 \(\mu\)m. The nearby classical T Tauri star DH Tau exhibits excess emission at 10 \(\mu\)m 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 \(\sim 20\) A.U. from the primary. Assuming the system to be co–eval, we derive a mass below the hydrogen burning limit for the companion. We speculate that the formation of a sub–stellar mass companion has led to the rapid evolution of the circumstellar disk that may have surrounded DI Tau.

\textit{Subject headings:} binaries: close — circumstellar matter — stars: low–mass, brown dwarfs, pre–main sequence

1. Introduction

It is generally accepted that circumstellar disks are a common by–product of the star formation process (Beckwith and Sargent, 1996). Estimates of the ubiquity of accretion disks around young stars ranges from \(\sim 70\%\) in the youngest clusters (Carpenter \textit{et al}., 1997) to \(\sim 50\%\) in the Taurus dark cloud (Kenyon and Hartmann, 1995). As young stars

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age, evidence of active disk accretion diminishes (Hartigan, Edwards, and 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 $\mu$m excess emission (originating within a few stellar radii) with ground–based 10 $\mu$m and IRAS observations of mid–IR excesses (originating in the terrestrial planet region from 0.1-2.0 A.U.) 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 $< 10^7$ yrs. 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 $< 1 \times 10^6$ yr for transition from optically–thick accretion disk to optically–thin re-processing disk (see also Wolk and 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. (1997) require mass surface densities 3–4 times greater than implied by the minimum mass solar nebula for Jupiter to form in $< 10$ Myr via runaway accretion. Because of the small sample (~20 objects) observed from the ground at 10 $\mu$m, as well as the sensitivity limitations of the IRAS satellite at 12 $\mu$m, 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 $\mu$m emission among T Tauri stars in the Taurus dark cloud utilizing the current generation of mid–IR detectors with sensitivity limits $\times 10$ 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 $\mu$m observations resolving the emission from both stars, construct updated spectral energy distributions (SEDs) for both objects, and re–analyze their stellar and circumstellar disk properties. Our analysis shows that DI Tau does not possess an optically–thick circumstellar disk within 0.1 A.U. of the central star and that its previously known companion, located at a distance of $\sim 20$ A.U., could very well be a brown dwarf. We speculate that the formation of a very low mass companion orbiting DI Tauri 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 3.8m United Kingdom Infrared Telescope (UKIRT). Observations were made at UKIRT on August 26–27, 1996 during photometric conditions with diffraction–limited images (FWHM ∼ 0.7”) obtained through an N–band filter (λ_{eff} = 10.16μm; Δλ = 5.20μm). Data were collected while chopping the telescope N–S (12”) at a rate of 2 Hz, and nodding the telescope (12”) every 50 seconds to correct for non–uniform 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 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 (sep = 15.1”; PA = 307°) were observed simultaneously on the array (T_{int} = 250.0s), interspersed with observations of the standard star HR1370 (T_{int} = 50.0s) at nearly the same airmass (∆X < 0.1). Comparison of photometry from stellar images appearing on different portions of the array indicates residual uncertainties in the calibration less than ±5%. Derived fluxes and associated errors (dominated by the thermal background) are: DH Tau F_N = 0.137 ± 0.005 Jy (6.26") and DI Tau F_N = 0.030 ± 0.005 Jy (7.90"). Additional observations were obtained in the Q–band (λ_c = 19.91μm; Δλ = 1.88μm) during non–photometric conditions yielding a flux ratio of > 1.7 between DH Tau (detected) and DI Tau (undetected).

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 and Vrba (1981) from 0.3–3.8 μm to construct updated SEDs for these sources. We adopt the spectral types listed in Cohen and 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 four and two at 10 and 20 μm respectively, we associate the IRAS flux with DH Tau. In order to de-redden the observed spectral energy distribution, we use the color excess observed in the (R–I)_c index and adopt the reddening law of Rieke and 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 de-reddened SEDs are shown in Figure 1 along with those expected from stellar photospheric emission and a face–on re-processing disk model (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, Edwards, and Ghandor (1995) place an upper–limit on the mass accretion rate of DI Tau at $< 1.5 \times 10^{-8} M_\odot yr^{-1}$ while Valenti, Basri, and 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 $10 R_*$ ($\sim 0.1$ A.U.). DH Tau appears to have a disk which extends to within a few stellar radii (depending on the inclination angle and disk accretion rate adopted; e.g. Meyer et al., 1997).

Using the effective temperatures and luminosities listed in Table 1, we place the stars in the H–R diagram (Figure 2) for comparison with the PMS evolutionary models of D’Antona and Mazzitelli (1994; hereafter DM94) adopting the Alexander opacities and Canuto–Mazzitelli convection prescription. DH Tau and DI Tau are very young ($< 10^6$ yrs), low–mass ($< 1.0 M_\odot$) PMS objects. From examining the properties listed in Table 1, it is clear that DH and DI Tau are quite similar except 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.

4. A Sub-stellar 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 pre–main sequence systems. DH Tau has no companions between 0.005-10” (1–1400 A.U. assuming a distance of 140 pc to Taurus). DI Tau A has a companion (hereafter referred to as B) at a projected separation of 0.12” (16.8 A.U.) with a K–band flux ratio of 8 ± 1 (Ghez et al., 1993). The probability of observing a chance projection of a field star with $K < 12.0^m$ at this separation is $< 2 \times 10^{-6}$. Recent HST observations of DI Tau by Simon et al. (1996) with the Fine Guidance Sensor
provide a lower limit to the $V$–band flux ratio of the system; $\Delta V > 3.3^m \pm 0.3^m$. 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 Tauri from over a decade of photometric monitoring (e.g. Herbst et al., 1994) of $< m_V >= 12.85$ ($\delta m_v = 0.14^m$) resulting in $m_V > 16.2^m \pm 0.3$ for the companion. Adopting the extinction derived for the primary (with uncertainty of $\pm 0.5^m$) in the DI Tau system, the lower limit to the intrinsic color of the companion is $(V - K)_o > 4.6^m \pm 0.5$ 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 $< 1 \times 10^6$ yr. If the system is co–eval according to the DM94 tracks, the upper–limit on the age of the primary implies a companion mass of $< 0.08 M_\odot$ (corresponding to a spectral type of M5). Adopting the models of Burrows et al. (1997), an age $< 10^6$ yrs, and stellar luminosity $< 0.06 L_\odot$ implies a companion mass $< 0.08 M_\odot$. How likely is it that binary is co–eval? Hartigan, Strom, and Strom (1994) find that $2/3$ of the PMS binaries in their sample (separations between 400–6000 AU) are co–eval when compared to the evolutionary models of DM94. In cases where an age difference is observed, the lower mass companion always appears younger. Brandner and Zinnecker (1997) find that all binaries in their sample (90–250 AU) are co–eval within the observational errors. The lack of infrared excess observed out to 10 $\mu m$ for the DI Tau system precludes the possibility that the low luminosity companion detected at 2.2 $\mu m$ 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 $\mu m$. The luminosity ratio between the two stellar components is $> 10$, 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 (GL229B, Nakajima et al., 1995; HD114762, 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. In fact DI Tau bears a striking resemblance to what the GL229 system might have looked like at an age of $< 10^6$ yrs. This hypothesis could be tested by confirming that DI Tau B has a spectral type later than M5, or measuring orbital

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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 Figure 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.
motions through monitoring of the relative positions of the DI Tau system (e.g. Ghez et al., 1995).

5. Evidence for Rapid Disk Evolution for DI Tau 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 $\sim 20$ A.U. from the central star. Given the inferred age ($\sim 6 \times 10^5$ yrs), 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 $\sim 100$ 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 and 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 which rotate faster ($P < 5$ 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, et al., 1995). The Kelvin–Helmholtz timescale for a disk-less star to spin-up from 8 days to $< 6$ days is is roughly $1 \times 10^5$ yrs (Armitage and Clark, 1996). Tidal effects in the DI Tau system are negligible since the the semi-major axis is very large compared to the radii of the objects (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 and 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 semi-major axis (10–40 A.U. 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
and Beckwith, 1995) the amount of material located within 10 A.U. is \( \sim 0.005 M_\odot \). The lifetime of such an inner-disk given a typical disk accretion rate of \( 10^{-7} M_\odot yr^{-1} \) (Hartigan, Edwards, and Ghandour; 1995) would be < 50,000 yrs. A cold outer disk might still be present albeit of very low mass \( (M_D < 0.001 M_\odot; \text{Jensen et al., 1994}) \). 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 \( \sim 10 AU \)? Armitage and Clarke (1996) have suggested this might occur in binary systems with separations between 1–8 AU, where material is trapped between the co-rotation point of the star-disk system \( (6R_\star \text{ for DI Tau A}) \) and the inner tidal truncation radius \( (0.5 \times \text{sep} = 10.0 AU) \). 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 > 50\(\mu\)m and spatial resolution < 15" (e.g. with SOFIA) will be required to set upper limits < \( 10^{-4} M_\odot \) on any remnant material orbiting the DI Tau system.

More recent work by Artymowicz and 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 towards unity. This suggests that if the sub-stellar mass companion formed in the disk of DI Tau A, it did so after the main infall phase had ended, with < \( 0.1 M_\odot \) remaining in the outer disk. Run-away giant planet growth in a proto-planetary disk (e.g. Pollack et al., 1997) can probably be ruled out given the formation time of < \( 10^6 \) yrs. Perhaps the companion to DI Tau A formed rapidly through gravitational instabilities in a massive circumstellar disk (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 (e.g. Burkert and Bodenheimer, 1997). If DI Tau A had a circumstellar disk, it seems reasonable to conclude that the presence of sub-stellar mass companion at 20 A.U. contributed to its rapid evolution.

Ghez et al. (1994; see also Jensen et al., 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 and Beckwith (1995; see also Jensen, Mathieu, and Fuller, 1994) find that young binaries with separations < 100 A.U. emit less at mm-wavelengths than young single stars and wide binaries. However, Simon and Prato (1995) find no correlation between the presence of companions between 20–280 A.U. and the presence of an inner-disk. This finding is confirmed by examining the distribution of \( (K - N) \) excesses vs. binary separation (Meyer and Beckwith, 1997) including newly discovered CTTS systems with separations
< 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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Table 1: Stellar and Circumstellar Properties

| Name   | $T_\ast K$ | $A_V$ | $L_\ast/L_\odot$ | $M_\ast/M_\odot$ | $\tau$ (yrs) | Sep. | Per. | $(K - L)_0^4$ | $\Delta N^5$ | $M_D/M_\odot^6$ |
|--------|------------|-------|------------------|------------------|--------------|------|------|---------------|-------------|----------------|
| DH Tau | 3800       | 1.7$m$| 0.54             | 0.40             | $8 \times 10^5$ | NC   | 7.2d | 0.60$m$       | 0.94 ± 0.16 | 0.011          |
| DI Tau | 3800       | 0.8$m$| 0.65             | 0.38             | $6 \times 10^5$ | 0.12" | 7.9d | 0.16$m$       | 0.16 ± 0.18 | < 0.001        |

1 Data taken from Cohen and Kuhi (1979) for DH Tau (HBC # 38) and DI Tau (HBC # 39).
2 Presence or absence of companions taken from Simon et al. (1995).
3 Photometric rotation periods taken from Vrba et al. (1989).
4 De-reddened $(K - L)$ color using $A_V$ listed here; errors ±0.11$m$.
5 N–band excess in dex as defined by Skrutskie et al. (1990).
6 Disk masses taken from Dutrey et al. (1996) for DH Tau and Jensen et al. (1994) for DI Tau.
Fig. 1.— Spectral energy distributions for both DH and DI Tauri: The filled–triangles represent simultaneous optical/near–IR data taken from Rydgren and Vrba (1979) and dereddened as described in the text, the filled–circles represent our new 10 $\mu$m observations, and the 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. The solid lines are the expected photospheric emission; the dashed–line is the emission expected from a face–on re–processing disk which 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 ($10 R_\ast$). The SEDs for DI Tau B are shown normalized at 2.2 $\mu$m 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 co–eval).
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⊙. 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 < 10⁶ yrs. If the companion DI Tau B is co–eval according to these isochrones, then it must have a spectral type > M5 and a mass < 0.08M⊙.