EVIDENCE FOR J- AND H-BAND EXCESS IN CLASSICAL T TAURI STARS AND THE IMPLICATIONS FOR DISK STRUCTURE AND ESTIMATED AGES

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ABSTRACT

We argue that classical T Tauri stars (CTTSs) possess significant nonphotospheric excess in the J and H bands (1.25 and 1.66 μm, respectively). We first show that normalizing the spectral energy distributions (SEDs) of CTTSs to the J-band leads to a poor fit of the optical fluxes (which are systematically overestimated), while normalizing the SEDs to the H-band (0.8 μm) produces a better fit to the optical bands and in many cases reveals the presence of a considerable excess at J and H. Near-infrared spectroscopic veiling measurements from the literature support this result. We find that J- and H-band excesses correlate well with the K-band (2.2 μm) excess and that the J − K and H − K colors of the excess emission are consistent with that of a blackbody at the dust sublimation temperature (~1500–2000 K). We propose that this near-IR excess originates at a hot inner rim, analogous to those suggested to explain the “near-IR bump” in the SEDs of Herbig Ae/Be stars. To test our hypothesis, we use the model presented by Dullemond and coworkers to fit the photometry data between 0.5 and 24 μm of 10 CTTSs associated with the Chamaeleon II molecular cloud. We find that simple models that include luminosities calculated from H-band magnitudes and an inner rim may account for the reported J- and H-band excesses. The models that best fit the data are those in which the inner radius of the disk is larger than expected for a rim in thermal equilibrium with the photospheric radiation field alone. In particular, we find that large inner rims are necessary to account for the mid-infrared fluxes (3.6–8.0 μm) obtained by the Spitzer Space Telescope (Spitzer). The large radius could be explained if, as proposed by D’Alessio and colleagues, the UV radiation from the accretion shock significantly affects the sizes of the inner holes in disks around CTTSs. Finally, we argue that deriving the stellar luminosities of CTTSs by making bolometric corrections to the J-band fluxes, which is the “standard” procedure for obtaining CTTS luminosities, systematically overestimates these luminosities. The overestimated luminosities translate into underestimated ages when the stars are placed in the H-R diagram. Thus, the results presented herein have important implications for the dissipation timescale of inner accretion disks.

Subject headings: infrared: stars — stars: formation — stars: pre–main-sequence

1. INTRODUCTION

Some of the first near-infrared observations of pre–main-sequence (PMS) stars revealed ~2–5 μm fluxes well above predicted photospheric values (e.g., Mendoza 1966, 1968). This near-IR excess was soon recognized as evidence of heated dust in circumstellar disks, well before disks were physically resolved at millimeter wavelengths (e.g., Kitamura et al. 1996) and later in the near-IR by interferometric observations (e.g., Akeson et al. 2004). Over the last few decades, evidence has accumulated supporting the idea that circumstellar disks are the birthplaces of planets, since the disk masses, sizes, and compositions are consistent with the presumed preplanetary solar nebula (e.g., Hillenbrand 2003). For this reason, the study of the structure and evolution of circumstellar disks has become crucial to our understanding of the formation of planetary systems, a field that has been greatly stimulated by the newly discovered exoplanets orbiting nearby main-sequence stars (e.g., Marcy & Butler 1998).

Classical T Tauri stars (CTTSs), which are low-mass PMS stars still accreting circumstellar material, have large ultraviolet (UV), optical, and infrared (IR) excesses that can dominate the photospheric emission at many wavelengths (e.g., Hartigan et al. 1991). These excesses are produced by a variety of mechanisms, all of which are associated with the presence of a disk around the young central source. The current paradigm for the structure of circumstellar disks associated with T Tauri stars (e.g., Hartmann 1998) describes the observed SEDs in terms of the superposition of several components: the star itself, a flared disk, possibly with a hot atmosphere, and magnetoospheric accretion columns through which the circumstellar material is channeled onto the surface of the star. Each component contributes a different percentage of the total flux of the system at different wavelengths, and it is usually difficult to disentangle each contribution, since degeneracies arise among many of the parameters that go into modeling the SEDs (Chiang et al. 2001). The broad wavelength range of the nonphotospheric emission and the frequent presence of significant circumstellar reddening in CTTSs make it difficult to find a wavelength at which to obtain photometry of the star itself from which to estimate the stellar luminosity. The method used most frequently to derive the bolometric luminosity of the stellar photosphere includes applying a bolometric correction to a single-band measurement corrected for extinction (e.g., Kenyon & Hartmann 1995; Hartigan et al. 1994). It is usually argued that the J band, at 1.25 μm, is the best representation of the photospheric emission. The ratio of the radiation from the photosphere to that from the hot accretion shock (UV excess) reaches a maximum here, while the effects of extinction are less important than at shorter wavelengths and the emission from the circumstellar dust is less prominent than at longer IR wavelengths. A detailed discussion supporting this argument can be found in Kenyon & Hartmann (1990). They investigated from a theoretical point of view the change in apparent...
luminosity of K1–M1 CTTSs due to several effects: the occultation of the star by the disk, the accretion and reprocessing luminosity of the disk, and the radiation from the boundary layer between the disk and the stellar photosphere. They conclude that the emission from the hot boundary layer contaminates the photospheric emission at wavelengths ≤0.8 μm, while the disk emission will affect wavelengths ≥2 μm, and therefore that the J and I bands are the best representations of the true stellar fluxes. The same is true for models that replace the boundary layers with magnetospheric accretion columns (Johns-Krull & Valenti 2001; Calvet & Gullbring 1998). Even though the presence of significant J-band excess in CTTSs has been reported in the past (e.g., Folha & Emerson 1999, hereafter FE99), the J-band is still considered to be the best representation of the photospheric emission and is commonly used, without veiling corrections, to calculate the stellar luminosity of CTTSs and to derive their ages.

Here we present additional results that suggest that CTTSs possess significant nonphotospheric excesses in the J and H bands. In § 2 we describe our SED fitting method and show that normalizing the photospheres of CTTSs to the J band leads to a poor fit of the optical fluxes (which are systematically overestimated). We show that normalizing the SEDs to the IC band produces a better fit in the optical bands, BVRIC, and in many cases reveals the presence of considerable J- and H-band excesses. In § 3 we describe near-IR veiling measurements from the literature that provide independent evidence supporting our results, and in § 4 we calculate the $J - K$ and $H - K$ colors of the excess emission, which are consistent with blackbody emission at ~1500–2000 K. In § 5 we fit the photometry data between 0.4 and 24 μm of 10 CTTSs associated with the Chamaeleon II molecular cloud and show that the reported J-band excess can be accounted for by the emission of an inner rim at the dust sublimation temperature. Then, in § 6 we investigate the effects of the J-band excess on estimating stellar ages. Finally, our conclusions are summarized in § 7.

1 IC denotes the I Cousins band at 0.80 μm as defined by Bessel (1979).

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TABLE 1
Chamaeleon II CTTSs from HH92

| Star ID | Spectral Type | $B$ (mag) | $V$ (mag) | $R_{C}$ (mag) | $I_{C}$ (mag) | $J$ (mag) | $H$ (mag) | $K$ (mag) | IRAC-1 (mJy) | IRAC-2 (mJy) | IRAC-3 (mJy) | IRAC-4 (mJy) | MIPS 1 (mJy) |
|--------|-------------|---------|---------|-------------|-------------|---------|---------|---------|------------|-------------|-------------|-------------|-------------|
| Sz 46 | M3 | 17.66 | 16.19 | 14.74 | 13.18 | 11.25 | 10.26 | 9.75 | 8.14 +1 | 6.37 +1 | 5.55 +1 | 5.16 +1 |
| Sz 48 | M1 | 19.17 | 18.05 | 16.17 | 14.36 | 11.44 | 10.10 | 9.45 | 8.63 +1 | 6.87 +1 | 5.97 +1 | 5.58 +1 |
| Sz 50 | M3 | 17.64 | 16.01 | 14.30 | 12.50 | 10.31 | 9.32 | 8.85 | 7.63 +1 | 5.85 +1 | 4.97 +1 | 4.47 +1 |
| Sz 51 | M0 | 15.38 | 14.50 | 13.47 | 12.38 | 10.61 | 9.85 | 9.35 | 8.51 +1 | 6.67 +1 | 5.68 +1 | 4.98 +1 |
| Sz 53 | M1 | 17.85 | 16.59 | 15.20 | 13.66 | 11.73 | 10.58 | 9.92 | 9.39 +1 | 7.73 +1 | 6.31 +1 | 5.28 +1 |
| Sz 54 | K7 | 13.88 | 12.53 | 11.58 | 10.61 | 9.05 | 8.15 | 7.59 | 7.12 +1 | 5.48 +1 | 4.59 +1 | 3.91 +1 |
| Sz 55 | M0 | 18.90 | 17.49 | 15.95 | 14.41 | 12.54 | 11.55 | 10.92 | 9.78 +1 | 7.63 +1 | 6.27 +1 | 5.23 +1 |
| Sz 56 | M4 | 18.53 | 17.08 | 15.41 | 13.47 | 11.49 | 10.78 | 10.41 | 9.32 +1 | 7.44 +1 | 6.03 +1 | 4.97 +1 |
| Sz 57 | M1 | 19.56 | 17.70 | 15.64 | 13.48 | 10.95 | 10.22 | 9.80 | 8.05 +1 | 6.26 +1 | 5.08 +1 | 3.94 +1 |
| Sz 58 | K5 | 17.89 | 16.01 | 14.44 | 13.00 | 10.84 | 9.58 | 8.75 | 7.22 +1 | 5.52 +1 | 4.39 +1 | 3.40 +1 |
| Sz 59 | M0 | 16.37 | 14.80 | 13.42 | 12.08 | 10.51 | 9.26 | 8.83 | 7.98 +1 | 6.02 +1 | 4.78 +1 | 3.82 +1 |
| Sz 60a | M1 | 17.56 | 16.21 | 14.88 | 13.45 | 11.19 | 10.22 | 9.54 | 8.54 +1 | 6.43 +1 | 5.12 +1 | 4.11 +1 |
| Sz 60b | M4 | 18.16 | 16.80 | 15.32 | 13.60 | 11.51 | 9.74 | 9.46 | 8.09 +1 | 6.12 +1 | 5.05 +1 | 4.12 +1 |
| Sz 61 | K4 | 16.77 | 15.13 | 13.69 | 12.38 | 9.88 | 8.76 | 7.94 | 6.94 +1 | 5.12 +1 | 3.97 +1 | 3.08 +1 |
| Sz 62 | M2 | 16.99 | 15.55 | 14.03 | 12.56 | 10.52 | 9.65 | 9.12 | 8.32 +1 | 6.32 +1 | 4.93 +1 | 3.96 +1 | 3.08 +1 |

Notes.—Five of the 20 PMS stars presented in Table 5 of HH92 were excluded from our analysis. Sz 47 and Sz 49 were excluded because they are heavily veiled and their spectral types are very uncertain. IRAS 12496—7650 was excluded because it is a highly embedded Herbig Be/Ae star. Sz 63 and Sz 64 were excluded because of the lack of Spitzer data. Even though the spectral type of Sz 55 is marked as uncertain, this star was kept on the sample because we were able to obtain a reasonable star + disk model to fit the optical, near-IR, and Spitzer data (see Fig. 10).

2. SED FITTING

2.1. J- and H-Band Excesses from SED Fitting

We were motivated to investigate the possibility of significant J- and H-band excesses when trying to estimate the luminosities of a sample of 15 CTTSs in the Chamaeleon II molecular cloud. The sample was taken from Hughes & Hartigan (1992, hereafter HH92), and the goal was to obtain stellar ages by placing the objects in the H–R diagram, following the “standard procedure” (e.g., Kenyon & Hartmann 1995, hereafter KH95). This procedure involves applying a bolometric correction, appropriate to the spectral type of the object, to a single-band measurement corrected for extinction. According to the current paradigm, luminosities obtained from the J band and I band should produce similar results. This is certainly the case, to within ~5%, when the method is applied to weak-lined T Tauri stars (see §§ 2.2 and 6). However, we find that when we apply this method to CTTSs, the luminosities obtained from the J band were systematically higher, by a factor of ~1.35, than those obtained from the IC band.

In order to investigate this discrepancy, we plot the entire SEDs of the stars in the Chamaeleon II sample using broadband photometry and try to separate the photospheric contribution from the rest of the SED. Table 1 lists the fluxes used to construct these SEDs. The BVRIIC photometry and spectral types were taken from HH92, the JHK values come from the Two Micron All Sky Survey (2MASS; Kleinmann 1992), and the mid- and far-IR photometry was obtained as part of the Spitzer Legacy Project “From Molecular Cores to Planet-forming Disks (c2d)” (Evans et al. 2003). A detailed discussion of the Spitzer observations is presented by A. Porras et al. (2006, in preparation) and Young et al. (2005).

As a first step in our SED fitting approach, extinction is estimated from the $R_{C} - I_{C}$ color excess. As discussed in § 1, at least some CTTSs are known to have important nonphotospheric V-band excess emission, and we argue that J- and H-band excesses are also present; therefore, of all the available colors, $R_{C} - I_{C}$ should provide the most reliable measurement of the true photospheric colors of CTTSs. Following the extinction curve provided by the Asiago database of photometric
systems² (Fiorucci & Munari 2003), we adopt \( A_F = 4.76 (R_C - I_C) - (R_C - I_C)_0 \) [for \( R_Y = A_I/E(B-V) = 3.1 \)], where \( R_C - I_C \) is the expected color of a dwarf main-sequence star (from KH95) with the same spectral type as the given Chamaeleon II CTTS. Then, we calculate the extinction factors for all the other bands using the relations listed in Table 2, also derived using the Asiago database of photometric systems. The expected optical and near-IR fluxes are then obtained from the \( I_C \)- or \( J \)-band photometry corrected for extinction and the broadband colors of main-sequence stars taken from KH95. Similarly, the predicted stellar fluxes in the Spitzer bands were obtained from the Spitzer Science Center online tool Stellar Pet,³ which computes the mid- and far-infrared fluxes using Kurucz models (Kurucz 1993) given the \( K \) magnitude and spectral type of the star. Since CTTSs are known to have \( K \)-band excess, we used the predicted \( K \)-band photospheric fluxes calculated as described above as the input for Stellar Pet, rather than the observed \( K \)-band fluxes. Finally, all the optical and near-IR magnitudes are converted to flux densities in units of janskys using the zero points listed in Table 2.

The left column of Figure 1 shows that if the SEDs are normalized to the \( J \) band (i.e., the dereddened \( J \)-band flux is assumed to accurately represent the photospheric flux), the \( BVR_CIC \)-band fluxes are significantly overestimated. Normalizing the SED to the \( I_C \) band, as shown in the right column of Figure 1, leads to a considerably better fit of the optical bands while revealing significant \( J \)- and \( H \)-band excess for many of the sources. This behavior in the SEDs is not consistent with random errors and seems to be systematic. If our SED fitting procedure is correct, then either the \( J \)-band excess is real, or the \( BVR_CIC \)-band fluxes are suppressed. The facts that the \( J \)- and \( H \)-band excesses are accompanied by excesses at longer wavelengths and that in general the observed (extinction-corrected) optical colors match the expected photospheric colors suggest that the \( J \)- and \( H \)-band excesses are real. We note that the accretion shock emission can easily account for the \( B \)- and \( I \)-band excesses seen in some of the SEDs in Figure 1, which are in fact expected (Hartigan et al. 1991).

2.2. Testing the SED Fitting Procedure

In plots such as those in Figure 1, photometric uncertainties (usually around 3% in the optical and the near-IR) are small compared to other sources of error, which include errors in the spectral types, adopted colors, and extinction corrections. To estimate the internal errors in the SED fitting approach, we applied the same procedure to a sample of 71 weak-lined T Tauri stars (WTTSs) associated with the Taurus molecular cloud. Thirty-nine stars of this sample were Taurus WTTSs observed by the Spitzer Space Telescope (SST) as part of the Legacy project c2d (Evans et al. 2003) and are listed in Table 3. The rest of the stars in the sample were WTTSs studied by Strom et al. (1989, hereafter S89) and are listed in Table 4. It is currently believed that the main difference between CTTSs and WTTSs is the presence in CTTSs of an inner accretion disk (Hartmann 1998) and the accompanying phenomena: strong winds and bipolar outflows, near-IR excess, UV excess, strong Hα emission, spectral veiling, etc. All these phenomena are directly connected to the excess radiation at near-IR and shorter wavelengths; therefore, it is reasonable to assume that the fluxes of WTTSs at wavelengths shorter than ∼2 \( \mu m \) are a good representation of the underlying photospheres of CTTSs of the same spectral type. This assumption is not valid at wavelengths longer than ∼2 \( \mu m \), where some WTTSs also possess an IR excess (D. Padgett et al. 2006, in preparation; L. A. Cieza et al. 2006, in preparation). Following the idea that CTTSs and WTTSs have similar photospheres, the difference between the observed SEDs of classical and weak-lined T Tauri stars of the same spectral type can be attributed to a nonphotospheric component in the CTTS fluxes for \( \lambda < 2 \mu m \). Tables 3 and 4 list the broadband photometry and spectral types used to fit the SEDs of our sample of WTTSs. Some of the WTTS SEDs (normalized to the \( I_C \)-band) are shown in Figure 2 as an illustration of the good agreement between expected and extinction-corrected observed fluxes for stars of different spectral types. The solid line indicates the expected photospheric flux (calculated as described in § 2.1, i.e., based on expected broadband colors normalized to the \( I_C \) band) and is not a fit to the extinction-corrected data points. The excellent agreement between the expected and extinction-corrected fluxes gives us confidence in the stellar intrinsic colors and extinction corrections that we use.

The optical photometry for the WTTSs listed in Table 3 comes from L. A. Cieza et al. (2006, in preparation), while the spectral types for these WTTSs were taken from Herbig & Bell (1988) and Wichmann et al. (2000). The optical photometry and spectral types of the WTTSs in Table 4 are taken from S89. For consistency, all the \( JHK \) photometry is from 2MASS. In the case of WTTSs, we find that all bands fit noticeably better than for CTTSs, and normalizing the SEDs to either the \( J \) or \( I_C \) band leads to essentially the same fluxes. Figure 3a shows the \( J \)-band excess for the Taurus WTTSs when the photosphere is normalized to \( I_C \). We define the \( J \)-band excess as \( J_s = J_{\text{obs}}/J_{\text{exp}} - 1 \), where \( J_{\text{obs}} \) and \( J_{\text{exp}} \) are the extinction-corrected observed fluxes and expected fluxes, respectively. The mean and the median of the \( J_s \) distribution for our sample of WTTSs are 0.07 and 0.06, respectively, and the standard deviation is 0.14. This is consistent with WTTSs having no \( J \)-band excess. Given the large number of WTTSs in our sample, we believe that the 6% deviation of the median of the distribution from 0 might reflect a small but measurable difference between the colors of T Tauri stars and those of dwarf main-sequence stars. Such a difference in the colors is not surprising, because T Tauri stars have lower photospheric gravities than dwarf main-sequence stars of the same spectral type. We take this difference in the mean colors into account when we calculate the \( J \)-band excess of CTTSs by folding the offset of the WTTS distribution into our calculations. Thus, for each CTTS the \( J \)-band excess is calculated as \( J_s = J_{\text{obs}}/1.06/J_{\text{exp}} - 1 \). The standard deviation of the distribution of \( J_s \) for WTTSs is a measurement of the errors introduced.

### Table 2

| Band | \( \lambda \) (\( \mu m \)) | \( A_F/A_J \) \((R_Y = 3.1)\) | \( A_F/A_J \) \((R_Y = 5.0)\) | Zero Point \((Jy)\) |
|------|-----------------|-----------------|-----------------|-----------------|
| \( B \)    | 0.44  | 1.31  | 1.20  | 4130  |
| \( V \)    | 0.55  | 1.00  | 1.00  | 3781  |
| \( R_C \)  | 0.65  | 0.79  | 0.84  | 3080  |
| \( I_C \)  | 0.80  | 0.58  | 0.62  | 2550  |
| \( J \)    | 1.25  | 0.26  | 0.26  | 1594  |
| \( H \)    | 1.66  | 0.15  | 0.15  | 1024  |
| \( K \)    | 2.2   | 0.09  | 0.09  | 667   |

Notes.—Extinction curves and optical zero points are from the Asiago database of photometric systems (http://ulisse.pd.astro.it/Astro/ADPS; Fiorucci & Munari 2003). The 2MASS zero points are from the 2MASS All Sky data release web document (http://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec6_4a.html).

² See http://ulisse.pd.astro.it/Astro/ADPS.
³ See http://ssc.spitzer.caltech.edu/tools/starpet.
Fig. 1.—Optical and IR SEDs of six Chamaeleon II CTTSs with the stellar photosphere normalized to the \( J \) band (left column) and to the \( I_c \) band (right column).

In the first case, the \( BVR-I_c \) fluxes are significantly overestimated. Normalizing the SED to the \( I_c \) band leads to a better fit of the optical bands and reveals significant \( J \)- and \( H \)-band excess for many of the sources. The open squares represent observed fluxes, while filled circles denote extinction-corrected fluxes. The solid lines indicate the expected stellar photospheres. Photometric uncertainties (usually around 3% in the optical and the near-IR and 5% in IRAC wavelengths) are small compared to other sources of error, which include errors in the spectral types, the adopted colors, and extinction corrections. We try to quantify these errors in §§ 2.2 and 2.3.
by our SED fitting procedure. These errors include errors in the spectral types, errors in the extinction correction applied, and errors introduced by the photospheric variability of WTTSs (the optical photometry and near-IR photometry correspond to different epochs). We use the standard deviation of the $J_x$ distribution for WTTSs as an estimate of the $1\sigma$ error in our procedure when we calculate the $J$-band excess of CTTSs. However, we caution that the UV excess produced by the accretion shock provides an important additional source of error when our procedure is used to calculate the near-IR excess of CTTSs. First, the optical veiling due to the accretion shock is likely to affect the photospheric colors and the extinctions derived from the observed color excesses. We discuss this problem in § 2.3. Second, the optical veiling introduces a much larger variability in CTTSs than in WTTSs. Since we use optical and near-IR data corresponding to different epochs, the variability of CTTSs will increase the uncertainty in the near-IR excesses derived for individual sources. However, in the context of our procedure, photometric variability should only introduce random errors in the determination of the near-IR excess, and it is equally likely to increase the derived near-IR excess as it is to decrease them. Therefore, given a large enough sample of CTTSs, it should be possible to establish whether or not CTTSs, as a group, present significant $J$- and $H$-band excesses.

To extend our sample of CTTSs, we include in our analysis 44 additional CTTSs associated with the Taurus-Auriga molecular complex. These objects, with $BVR_cJHK_c$ photometry and spectral types also from S89, are listed in Table 5. For consistency with the Chamaeleon II CTTSs, we use the $JHK_c$ photometry from 2MASS. Figure 3b shows the distribution of $J_x$ for the sample of Taurus WTTSs and the combined sample of Taurus CTTSs: the 15 Chamaeleon II objects from HH92 plus the 44 Taurus objects from S89. Defining $1\sigma$ and $J_x$, 48% of the CTTSs have $J_x$-band excesses larger than 1 $\sigma$ larger than 2 $\sigma$, and 66% larger than 3 $\sigma$. The mean $J$-band excess for the sample of CTTSs ($J_x$) is 0.35. Figures 3c and 3d are analogous to Figure 3b, but show the excess in the $H$ and $K$ bands. The statistics of the $J_x$, $H_x$, and $K_x$ distributions for our sample of WTTSs and CTTSs are listed in Table 6. Columns (2), (3), and (4) show the statistics of the distributions of $J_x$, $H_x$, and $K_x$-band excesses for WTTSs. In all cases, the distributions are consistent with WTTSs having no near-IR excess. The standard deviations listed in column (4) are used as an estimate of the $1\sigma$ errors of our procedure. These $1\sigma$ errors are

| Star ID | Spectral Type | $V$ | $R_c$ | $I_c$ | $J$ | $H$ | $K$ |
|---------|---------------|-----|-------|-------|-----|-----|-----|
| FX Tau  | M4            | 13.50 | 12.37 | 10.98 | 9.39 | 8.40 | 7.92 |
| HD 283572 | G2           | 9.05  | 8.56  | 8.07  | 7.41 | 7.01 | 6.87 |
| IW Tau  | K7            | 12.51 | 11.57 | 10.51 | 9.24 | 8.48 | 8.28 |
| Lk 19   | K0            | 10.94 | 10.35 | 9.75  | 8.87 | 8.32 | 8.15 |
| LkCa 4  | K7            | 11.69 | 10.97 | 10.28 | 9.34 | 8.71 | 8.58 |
| LkCa 1  | M4            | 13.73 | 12.63 | 11.05 | 9.64 | 8.87 | 8.62 |
| LkCa 21 | M3            | 13.43 | 12.32 | 10.88 | 9.46 | 8.67 | 8.45 |
| LkCa 3  | M1            | 12.06 | 11.04 | 9.76  | 8.36 | 7.62 | 7.42 |
| LkCa 5  | M2            | 13.54 | 12.54 | 11.29 | 9.97 | 9.29 | 9.05 |
| LkCa 7  | K7            | 12.52 | 11.60 | 10.46 | 9.13 | 8.38 | 8.26 |
| NTTS 032641+2420 | K1 | 12.20 | 11.64 | 11.13 | 10.32 | 9.86 | 9.70 |
| NTTS 040234+2143 | M2 | 14.77 | 13.72 | 12.31 | 10.95 | 10.29 | 10.06 |
| NTTS 041559+1716 | K6 | 12.23 | 11.56 | 10.88 | 10.03 | 9.42 | 9.27 |
| NTTS 042417+1744 | K1 | 10.35 | 9.89  | 9.47  | 8.78 | 8.39 | 8.30 |
| NTTS 042835+1700 | K5 | 12.57 | 11.86 | 11.18 | 10.28 | 9.71 | 9.50 |
| NTTS 042916+1751 | K7 | 12.01 | 11.26 | 10.53 | 9.70 | 9.06 | 8.85 |
| NTTS 042950+1757 | K7 | 13.11 | 12.20 | 11.27 | 10.16 | 9.46 | 9.31 |
| RX J0405.3+2009 | K1 | 10.67 | 9.96  | 9.41  | 8.69 | 8.19 | 8.09 |
| RX J0409.2+1716 | M0 | 13.44 | 12.11 | 11.15 | 9.96 | 9.25 | 9.05 |
| RX J0409.8+2446 | M1 | 13.51 | 12.55 | 11.35 | 10.10 | 9.45 | 9.23 |
| RX J0412.8+1937 | K6 | 12.47 | 11.68 | 10.85 | 9.99 | 9.43 | 9.24 |
| RX J0420.3+3123 | K4 | 12.60 | 11.96 | 11.30 | 10.45 | 9.88 | 9.73 |
| RX J0432.8+1735 | K2 | 13.66 | 12.60 | 11.32 | 10.00 | 9.23 | 9.02 |
| RX J0438.2+202 | K2 | 12.18 | 11.52 | 10.90 | 10.07 | 9.53 | 9.36 |
| RX J0438.6+1546 | K1 | 10.89 | 10.31 | 9.73  | 8.90 | 8.36 | 8.24 |
| RX J0453.8+3322A | K5 | 11.54 | 10.79 | 10.13 | 9.18 | 8.57 | 8.42 |
| RX J0455.8+1556 | G5 | 9.29  | 8.84  | 8.41  | 7.85 | 7.46 | 7.34 |
| RX J0452.5+1730 | K4 | 11.97 | 11.08 | 10.58 | 9.97 | 9.41 | 9.25 |
| RX J0452.8+1621 | K6 | 11.74 | 10.81 | 10.05 | 9.10 | 8.48 | 8.28 |
| RX J0457.2+1524 | K1 | 10.21 | 9.67  | 9.13  | 8.38 | 7.91 | 7.75 |
| RX J0457.5+2014 | K3 | 11.34 | 10.73 | 10.15 | 9.28 | 8.82 | 8.69 |
| RX J0458.7+2046 | K7 | 11.95 | 11.05 | 10.43 | 9.59 | 8.96 | 8.80 |
| RX J0459.7+1430 | K4 | 11.71 | 11.10 | 10.53 | 9.66 | 9.09 | 8.95 |
| UX Tau A | K2 | 11.93 | 11.11 | 10.16 | 8.62 | 7.96 | 7.55 |
| V807 Tau | K7 | 11.44 | 10.56 | 9.58  | 8.15 | 7.36 | 6.96 |
| V836 Tau | K7 | 13.99 | 12.93 | 11.74 | 9.91 | 9.08 | 8.60 |
| V927 Tau | M5 | 14.70 | 13.39 | 11.43 | 9.73 | 9.06 | 8.77 |
| V928 Tau | M0 | 14.04 | 12.77 | 11.33 | 9.54 | 8.43 | 8.11 |
| Wa Tau 1 | K0 | 10.30 | 9.76  | 9.24  | 8.42 | 7.93 | 7.80 |
used to calculate the percentage of CTTSs with excesses larger than 1, 2, and 3 σ (cols. [7], [8], and [9]). The main conclusions that can be drawn from Figures 3b and 3c and Table 6 are that for CTTSs ($K_C > (H_C > (J_C)$ and that these mean excesses are statistically significant in all cases.

Significant $K$-band excesses are expected for CTTSs and have traditionally been used as a diagnostic for the presence of circumstellar disks (e.g., S89). However, $J$- and $H$-band excesses are not expected and are difficult to explain by using current standard models of circumstellar disks around CTTSs (Chiang & Goldreich 1997, 1999). It could be argued that this discrepancy between the near-IR SEDs of CTTSs and WTTSs is due to the fact that, in general, the SEDs of CTTSs were much more strongly corrected for extinction. In that case, an anomalous extinction law could be responsible for the mismatch between the observed and expected fluxes at different wavelengths. However, we find no significant correlation between extinction and $J$- or $H$-band excesses, as illustrated by Figure 4. We have tested the effect of the extinction further by using a different extinction law, characterized by $R_V = 5.0$ (see Table 2), to correct the stellar fluxes. Since the amplitudes of the observed $J$-band excesses are smaller than those of the $H$ band, and since the $J$ band is more affected by extinction, we concentrate our analysis on the result at the $J$ band. From the extinction relations listed in Table 2, we find that $E(J - I_C)_{R_V=5.0} = 0.36A_V$. This implies that in the context of our SED fitting approach, going from an extinction curve with $R_V = 3.1$ to a shallower extinction curve with $R_V = 5.0$ would change the observed $J$-band fluxes by

$$\Delta J = -J_x = E(J - I_C)_{R_V=3.1} - E(J - I_C)_{R_V=5.0} = -0.04A_V.$$ 

Thus, an extinction law characterized by $R_V = 5.0$ could only account for the $J$-band excesses of the handful of objects to the left of the line $I_x/A_V = 0.04$ drawn in Figure 4 (left panel), all of which have insignificant $J$-band excesses ($<1 \sigma$). The same argument applies to the $H$-band excesses. An extinction law characterized by $R_V = 5.0$ could only account for the $H$-band excesses for the objects also to the left of the line $H_x/A_V = 0.04$ drawn in Figure 4 (right panel). Thus, we conclude that our results regarding $J$- and $H$-band excesses are not significantly affected by the choice of extinction law. This very weak dependence of our results on the extinction law is due to two factors. First, since we estimate the extinction from the $R_C - I_C$ color excess, the difference in extinction obtained from the two different extinction laws is less than 5%. Second, in order to estimate $J$-band excesses, we are effectively comparing observed extinction-corrected $J - I_C$ colors to expected $J - I_C$ colors. Since different extinction curves start to converge at these
wavelengths, they predict very similar $J - I_C$ color changes for a given $A_V$.

We have also investigated the propagation of the spectral type uncertainties into the derived near-IR excesses. We find that adopting spectral types that are one subclass later (i.e., lower effective temperatures) than the spectral types tabulated in Tables 1 and 5 for every CTTS in our sample leads to increases of $\sim 0.1$ and $\sim 0.15$ in the calculated mean $J$- and $H$-band excesses, respectively, with respect to the excesses shown in Table 5. Similarly, adopting spectral types that are one subclass earlier (i.e., higher effective temperatures) than those shown in Tables 1 and 5 leads to decreases of $\sim 0.1$ and $\sim 0.15$ in the mean $J$- and $H$-band excesses, respectively. We conclude that unless we have systematically underestimated the stellar temperatures by three spectral type subclasses, the $J$-band excess cannot be attributed to uncertainties in the spectral types. To account for the $H$-band excesses, an even larger systematic error in spectral types is needed.

2.3. Revisiting Initial Assumptions

In order to estimate the $J$, $H$, and $K$-band excesses in §2.2, we implicitly made two assumptions that are necessary to estimate
the extinction and normalize the expected fluxes to a particular band. Namely, we assumed (1) that the observed extinction-corrected $I_C - R_C$ colors of CTTSs correspond to photospheric colors and (2) that the extinction-corrected $I_C$-band fluxes of CTTSs are an accurate representation of the underlying photospheres. Then, we calculated the $J$-, $H$-, and $K$-band excesses by computing the $F_{\text{obs}}/F_{\text{exp}}$ flux ratios, where $F$ stands for the $J$-, $H$-, or $K$-band fluxes. In the context of our procedure, this is equivalent to calculating $I_C - J$, $I_C - H$, and $I_C - K$ color excesses according to $m_{\text{col-exc}} = (I_C - m_{\text{obs}}) - (I_C - m_{\text{exp}})$, where $m$ stands for $J$, $H$, or $K$ magnitudes. If both assumptions 1 and 2 are correct, then the color excess accurately measures the true nonphotospheric excess $m_x$. However, since the emission from the accretion shock and the inner disk will also contribute to the $I_C$- and $R_C$-band total fluxes, these two assumptions are only approximations. In order to test their validity, we take the case of an M0 CTTS, the most common type of star in our sample, with a $J$-band excess equal to the mean $J$-band excess reported in § 2.2 ($r_J = 0.35$) and a $V$-band excess equal to the mean $V$-band excess ($r_V = 0.60$) reported by Gullbring et al.

Fig. 3.—Histograms of the excess at the (a, b) $J$ band, (c) $H$ band, and (d) $K$ band for WTTSs (dotted lines) and CTTSs (solid lines). The excesses shown for CTTSs have been corrected for the median excesses found for WTTSs (col. [3] in Table 6). The distributions shown are consistent with WTTSs having no near-IR excess. Significant excess is seen in all three 2MASS bands for CTTSs.
The table contains data on Taurus CTTSs from S89. It lists HBC ID, Spectral Type, B, V, R_C, I_C, J, H, K, SED, r_J, Spectra, and \( \sigma_r \). The values are for an M0 star with typical J- and V-band veiling of 0.60 and 0.35, respectively. The expected veiling at the I_C and R_C bands is shown in Table 5. Column (4) shows the total change in apparent magnitude due to the veiling produced by the accretion shock (col. [2]) and the rim (col. [3]) emission. The values are for an M0 star with typical J- and V-band veiling. We derived the expected veiling at the I_C and R_C bands shown in Table 7.

### Table 5

| HBC ID | Spectral Type | B | V | R_C | I_C | J | H | K | SED | r_J Spectra | \( \sigma_r \) |
|--------|---------------|---|---|-----|-----|---|---|---|-----|-------------|----------|

### Table 6

| Band | WTTS Mean Excess | WTTS Median Excess | WTTS Standard Deviation \( \equiv 1 \sigma \) | CTTS Mean Excess | CTTS Median Excess | CTTS Excess > 1 \( \sigma \) (%) | CTTS Excess > 2 \( \sigma \) (%) | CTTS Excess > 3 \( \sigma \) (%) |
|------|------------------|-------------------|-----------------------------|-----------------|---------------------|----------------------|----------------------|----------------------|
| J    | 0.07             | 0.06              | 0.14                        | 0.35            | 0.28                | 63                   | 48                   | 32                   |
| H    | 0.06             | 0.03              | 0.18                        | 0.69            | 0.54                | 78                   | 64                   | 52                   |
| K    | 0.10             | 0.06              | 0.24                        | 1.45            | 1.10                | 79                   | 74                   | 67                   |

\( \sigma_r \) stands for lower limit.
find that the $R_C$ and $I_C$ bands contain a nonphotospheric contribution of 28% and 19%, respectively. Since we normalized the photosphere to the $I_C$ band, a zero color excess, $m_{\text{col-excess}} = 0$, for a given band would actually imply $m_x = r_{I_C} = 0.19$ (i.e., it seems that we underestimate the $J$-, $H$-, and $K$-band excesses by 0.19). However, there is another effect that compensates for the fact that we ignore the veiling at $I_C$. Since $r_{I_C} = 0.19$ and $r_{R_C} = 0.28$, the $I_C - R_C$ colors of the stellar photosphere appear bluer by 0.09 mag, and we underestimate the extinction $A_{I_C}$ by 0.43 mag. If the extinction is underestimated, then the shortest wavelengths of the SED are undercompensated with respect to the longer wavelengths, and an artificial color excess is produced. Using the extinction relations from Table 2, we convert the underestimated extinctions into the apparent color excesses shown in Table 8. Column (2) lists the amount by which the extinction is underestimated due to the change in $R_C - I_C$ colors produced by the veiling listed in Table 7. Column (3) shows the amount by which the color excess is overestimated due to the underestimated extinctions, $\Delta_l (l_C - m)_l$. Column (4) shows the net effect of ignoring both $r_{I_C}$ and $r_{R_C}$ on the apparent excesses at the $BVR_{I_C}HK$ bands (for an M0 star with $r_V = 0.60$ and $r_J = 0.35$). For the $J$, $H$, and $K$ bands, the end result is that $m_x \approx m_{\text{col-excess}}$ to within 5%, which was the original assumption.

In addition, we find that the change in the apparent $I_C$ magnitude due to the veiling, $\Delta m_{I_C}$, is well compensated by the underestimation of extinction in that band, $\Delta A_{I_C}$. In fact, $\Delta A_K - \Delta m_{I_C} \sim 0.05$ mag, which implies that assuming no $I_C$ and $R_C$ excess only affects the apparent luminosity by $\sim 5%$.

Column (4) in Table 8 also shows that, in this example, we underestimate the $R_C$- and $I_C$-band excesses by exactly the same amount as the assumed veiling (0.28 and 0.19 mag, respectively). Similarly, we underestimated the $V$ excess by 0.37 mag, which is equivalent to underestimating the veiling by 0.4. Since the assumed $V$-band veiling was 0.6, this means that the SED fitting approach will typically reveal only $\sim 30$% of the $V$-band excess due to the accretion shock. This compensating effect of the veiling is well compensated by the underestimation of extinction.

![Fig. 4.—Extinction ($A_V$) vs. $J$-band excess (left) and $H$-band excess (right). No significant correlation is seen in the figures. A shallower extinction curve with $R_V = 5.0$ can only account for the IR excess for the objects left of the shown solid lines.](image)

Table 7: Expected Veiling

| Band (1) | Veiling (Accretion Shock) (2) | Veiling (Inner Rim) (3) | $\Delta A_{I_C}$ (mag) (4) |
|----------|-------------------------------|-------------------------|---------------------------|
| $R_C$    | 0.50$r_V$                     | 0.05$r_J$               | 0.28                      |
| $I_C$    | 0.23$r_V$                     | 0.15$r_J$               | 0.19                      |

Table 8: Apparent Color Excesses

| Band (1) | $\Delta A_{I_C}$ (mag) (2) | $\Delta (I_C - m)_{I_C}$ (mag) (3) | $\Delta$Excess$^a$ (mag) (4) |
|----------|-----------------------------|-----------------------------------|-----------------------------|
| $B$      | 0.56                        | -0.31                             | -0.50                       |
| $V$      | 0.43                        | -0.18                             | -0.37                       |
| $R_C$    | 0.34                        | -0.09                             | -0.28                       |
| $I_C$    | 0.25                        | 0.00                              | -0.19                       |
| $J$      | 0.11                        | 0.14                              | -0.05                       |
| $H$      | 0.06                        | 0.19                              | 0.00                        |
| $K$      | 0.04                        | 0.21                              | +0.02                       |

$^a$ $\Delta$Excess = $\Delta(l_C - m)_{I_C}$, where $\Delta m_{I_C} = 0.19$.4 The superposition of two different sources of excess emission, one hotter and one cooler than the stellar photosphere, provides a simple explanation for the observations showing that the veiling in CTTs “flattens out” in the red part of their optical spectra (e.g., Basri & Batalha 1990; White & Hillenbrand 2004).
the underestimated extinction on the optical excess explains why the optical SEDs shown in the right panel of Figure 1 match the expected photospheres so well, even though excess emission is likely to be present at all wavelengths.

This interplay between the UV excess and the apparent extinction prevents us from obtaining the $I$-band or $B$-band excess from the SED and improving the fit recursively by taking into account the effect of the veiling on the apparent colors.

2.4. Comparison with Previous Works

We arrive at the conclusion that CTTSs possess significant $J$- and $H$-band excesses by analyzing photometric data that are available in the literature. Thus, we were motivated to compare our procedure and assumptions against those found in the original papers from which most of the data were taken (i.e., S89 and HH92). We also compare our procedure with that followed by Meyer et al. (1997, hereafter M97), who present a detailed analysis of the near-IR colors of CTTSs.

S89 present SEDs for 16 of the T Tauri stars in our Tables 4 and 5. Their SEDs are normalized to the $R$-band, and as a photospheric model they use SEDs of dwarf stars of a spectral type corresponding to that of the T Tauri stars. Even though the presence of significant $J$- and $H$-band excesses is not heavily emphasized by S89, these excesses are clearly seen in most of their SEDs. In fact, S89 mention that in some cases the spectral energy distribution of the excess emission can be characterized as blackbody emission at a temperature of $T \approx 2000$–$2500$ K and suggest that the most likely origin of this emission is the inner edge of the disk at the dust sublimation temperature. This conclusion is one of the main results presented herein (see § 4.2), but it has been for the most part neglected by subsequent literature. Possibly, the large uncertainties in their procedure and the high temperatures derived from the excess emission prevented S89 from making a stronger case for the presence of significant $J$- and $H$-band excesses. Several factors may have contributed to a larger uncertainty in the SED fitting procedure used by S89 when compared to our procedure. First, S89 calculate the extinction from the $V - R$ color excess, which is more sensitive to the veiling produced by the accretion shock luminosity and to the extinction law than is the $R - I_c$ color excess we use. Second, they use intrinsic colors from Johnson (1966), which are on the Johnson system, not on the Cousins system, as the observations they report. The transformation between photometric systems introduces an additional source of error. Finally, S89 use $J$, $H$, and $K$-band photometry compiled from the literature, while we use the 2MASS catalog, which provides a more uniform data set.

HH92 present SEDs for all the objects shown in Figure 1. They normalize the SEDs to the $R$ band (i.e., they assume zero $J$-band excess, as we do for the SEDs shown in the right column of Fig. 1). However, their SEDs do not show the clear systematic underestimation of the optical fluxes seen in our SEDs when they are normalized to the $J$ band. It is likely that the systematic underestimation of the optical fluxes is masked by the large uncertainties in their procedure. HH92 calculate the extinction, as we do, from the $R - I_c$ color excess of the objects but do not specify the extinction law used. They adopt intrinsic colors taken from Bessel (1979), who only reports intrinsic colors for a very limited set of spectral types (i.e., F5, G0, G6, K2, K4, K7, and M2); therefore, they probably had to interpolate in order to obtain intrinsic colors for stars of intermediate spectral types. In addition, and more importantly, they use a blackbody curve as the stellar model, which provides only a very rough approximation of the photospheric fluxes.

M97 follow a procedure very similar to ours in order to calculate the near-IR excess of CTTSs. However, they made the crucial assumption that the nonphotospheric contribution to the $J$-band flux comes exclusively from tail of the UV excess produced by the accretion shock (i.e., there is no contribution from the disk). With this assumption, they estimate that the $J$-band veiling is 10% of the $V$-band veiling and calculate the $J$-band excess from the $V$-band veiling values provided by Hartigan et al. (1995). They find that the mean of the $J$-band veiling calculated in this way is $\langle J_\nu \rangle \approx 0.6$. M97 analyze the same sample of CTTSs reported by S89 (Table 4 in this paper), but they use the original near-IR fluxes provided by S89 rather than the 2MASS fluxes used by us. They calculate the extinction from the $R_C - I_c$ color excess and use extinction corrections identical to ours [i.e., $E(R_C - I_c) = 0.214 \lambda(R), E(J - H) = 0.114 \lambda(R)$, and $E(H - K) = 0.064 \lambda(R)$]. However, M97 adopt intrinsic colors from Bessel (1979), which has the limitations mentioned above. With this assumption that $\langle J_\nu \rangle \approx 0.6$, they estimate the $H$- and $K$-band excesses from the $J - H$ and $J - K$ color excesses. M97 find median $H$- and $K$-band excesses of 0.2 and 0.6, respectively, but caution that the reported values are only lower limits because of the assumption of zero $J$-band excess. In fact, they state that if they normalize the photospheres to the $I_c$ band, the calculated mean $J$-band excess becomes 0.23. In § 2.2 we found median $J$, $H$, and $K$-band excesses of 0.28, 0.54, and 1.1, respectively, for our combined sample of Chamaeleon II and Taurus CTTSs. We conclude that once the M97 excesses are corrected for the assumption of zero $J$-band excess (by adding $\langle J_\nu \rangle \approx 0.25$ to the $(H_\nu)$ and $(K_\nu)$ excesses), their values agree well with our calculated $J$, $H$, and $K$-band excesses. K-band veiling measurements from the literature support larger $K$-band excess values than the 0.6 reported by M97 (closer to our 1.45 calculated mean value). FE99 obtain a mean $K$-band veiling $\langle r_K \rangle \approx 1.3$ for a sample of 30 Taurus CTTSs, and Dopmann & Jaffe (2003) calculate $\langle r_K \rangle \approx 2.0$ for a sample of 10 Ophiuchus CTTSs, while Muzerolle et al. (2003) find $\langle r_K \rangle \approx 1.2$ for a sample of nine Taurus CTTSs. In § 3 we discuss more spectroscopic veiling measurements that support our conclusion that classical T Tauri stars present significant $J$- and $H$-band excesses.

3. SPECTROSCOPIC EVIDENCE FOR J-BAND EXCESS

In order to test our results from § 2 indicating the presence of significant $J$- and $H$-band excesses, we analyze a subsample of the CTTSs in the Taurus-Auriga complex with spectroscopic $J$-band veiling measurements available in the literature. These measurements provide a test that is independent of any assumptions regarding reddening, extinction, or broadband colors. The spectral veiling $r_\lambda$ is defined as the ratio of any nonphotospheric flux to the photospheric flux at a given wavelength $\lambda$. This excess flux is usually estimated by comparing the equivalent widths of the lines of the program objects to those of unveiled stars used as templates or to synthetic models. Perhaps because $J$- and $H$-band excesses are not expected, we find no $H$-band veiling measurements of CTTSs in the literature and only a few works reporting $J$-band measurements. However, FE99 report $J$-band veiling measurements for 45 CTTSs, 33 of which have $BVRC_{IJK}$ photometry from S89. This data set provides a sample to test directly our results from previous sections. The FE99 veiling measurements, listed in Table 5 as “$r_\lambda$ Spectra,” were obtained from high-resolution spectra ($R \approx 20,500$) around the Pa/β line (1.28215 μm) using main-sequence dwarfs of similar spectral types as templates. Also listed in Table 5 are the $J$-band excesses calculated using our SED fitting approach ($J_\nu$ SED). The tabulated $J_\nu$ SED values, defined as in § 2.2, can be directly
compared with the veiling values obtained by FE99. Figure 5 shows the $J$-band excesses obtained by the two different methods. Since the data points cluster on the top right quadrant of the figure, both methods show clear evidence of $J$-band excess for CTTSs as a group. We note that the average and range of the $J$-band excesses measured by these two different methods are in good agreement, even though the agreement for individual objects is relatively poor. The spectroscopic and photometric data correspond to different epochs, however, and variability might be responsible for some of the scatter. Comparison of the $J$-band magnitudes reported by S89 and those from 2MASS shows an average difference of ~0.2 mag and a maximum deviation of up to a factor of 2 in flux, but no systematic variation. In addition, the 1 σ error bars shown for $J_x$(SED) correspond to the standard deviation of the $J_x$ in WTTSs listed in Table 6 and do not include the errors introduced by the interplay between the UV excess and the apparent extinction discussed in § 2.3. These errors are difficult to quantify, but are likely to weaken the expected correlation between $J_x$(SED) and $J_x$(spectroscopy).

Other, somewhat less direct, but still compelling, evidence for $J$-band excess is presented by Doppmann & Jaffe (2003). They obtained $K$-band veiling measurements of 10 CTTSs associated with the $\rho$ Ophiuchus dark cloud from high-resolution spectra ($R = 50,000$) centered around 2.207 μm. In this case, the veiling is obtained using spectral synthesis models as templates. They compare stellar luminosities from dereddened $K$-band...
magnitudes corrected for veiling against luminosities derived from dereddened \( J \)-band magnitudes assuming zero \( J \)-band veiling. They find that the \( J \)-band luminosities are systematically higher by a factor of \( \sim 2 \). This implies an average \( J \)-band veiling of \( \sim 1 \), which is higher than the average \( J \)-band veiling of \( \sim 0.6 \) found by FE99 for the Taurus CTTSs and the average \( J \)-band excesses of \( \sim 0.4 \) from the SED fitting obtained in this work for the CTTSs in Taurus and Chamaeleon II. However, the CTTSs in the Dopmann & Jaffe \( \rho \) Oph sample were selected based on their large \( K \)-band luminosities. Since \( K \)-band excess usually dominates the photosphere (they found \( K_x = 2.0 \)), the sample is probably biased toward large \( K \)-band and \( J \)-band excesses.

SED fitting and spectral veiling measurements independently provide compelling, but not conclusive, evidence for the existence of \( J \)-band excesses in CTTSs. The combination of these two independent lines of evidence, however, provides a very strong case for the presence of significant nonphotospheric \( J \)- and \( H \)-band excesses in CTTSs. The existence of a \( J \)-band excess has important implications for the study of the structure and evolution of CTTS disks and should be investigated further.

4. THE PHYSICAL ORIGIN OF THE NEAR-IR EXCESS

4.1. \( J \)- and \( H \)-Band Excess versus \( K \)-Band and \( V \)-Band Excesses

In order to explore the nature of the \( J \)- and \( H \)-band excesses, we investigate their correlation with the two known sources of nonphotospheric radiation: the accretion shock and the disk emission. If the \( J \)- and \( H \)-band excesses are related to the accretion shock, they should correlate with optical veiling, \( r_{J} \), as measured by spectral veiling (i.e., \( r_{J} \sim 0.1 r_{V} \) for late K and early M stars). Figure 6 shows our \( J \)-band excess measurements versus the \( r_{J} \) from Gullbring et al. (1998). We do not find any strong correlation with this small data set, but clearly \( r_{J} \geq 0.1 r_{V} \), instead of \( r_{J} \sim 0.1 r_{V} \), as would be expected if both originated directly at the accretion shock (Hartigan et al. 1995).

In addition, the emission from the accretion shock should be negligible at the \( H \) band, but we find that \( \langle H_x \rangle > \langle J_x \rangle \). Thus, we discard this explanation.

If the \( J \)- and \( H \)-band excesses come from the circumstellar disk itself, one might expect them to correlate with the excess at longer wavelengths. Figure 7 shows our calculated \( K \)-band excess versus \( J \)- and \( H \)-band excesses (left and right panels, respectively) for both the Chamaeleon II and Taurus CTTSs from Tables 1 and 5. The Spearman’s ranks of these correlations are 0.65 and 0.92 with probabilities of being drawn from a random distribution of \( 1.5 \times 10^{-8} \) and \( 6.3 \times 10^{-26} \), respectively. These are robust correlations, and they strongly suggest that the \( J \)-, \( H \)-, and \( K \)-band excesses have a common source.

4.2. The Color Temperature of the Near-IR Excess

If \( J \)-, \( H \)-, and \( K \)-band excesses have a common source, and this source is optically thick, then its characteristic temperature can be estimated from the \( J \) – \( K \) and \( H \) – \( K \) colors of the excesses, or equivalently the ratio of the \( J \) to \( K \) and \( H \) to \( K \) excess fluxes. Our SED fitting approach allows a straightforward calculation of the \( J \) – \( K \) and \( H \) – \( K \) colors of the excess. Following the discussion in § 2.2, we obtain \( J_{\text{EXC}} \approx J_{\text{obs}} - 1.06 J_{\text{exp}} \), \( H_{\text{EXC}} \approx H_{\text{obs}} - 1.03 H_{\text{exp}} \), and \( K_{\text{EXC}} \approx K_{\text{obs}} - 1.06 K_{\text{exp}} \), where \( J_{\text{EXC}}, H_{\text{EXC}}, \) and \( K_{\text{EXC}} \) are the absolute \( J \)-, \( H \)-, and \( K \)-band excesses \( \text{fluxes} \) in \( J \), as opposed to the dimensionless excess \( J_x, H_x, \) and \( K_x \) discussed so far. Figure 8 shows \( J_{\text{EXC}} \) versus \( K_{\text{EXC}} \) and \( H_{\text{EXC}} \) versus \( K_{\text{EXC}} \) in units of flux of the expected stellar photospheres at 2.2 \( \mu \)m. The flux ratios \( J_{\text{EXC}}/K_{\text{EXC}} \) and \( H_{\text{EXC}}/K_{\text{EXC}} \) shown in Figure 8 are both consistent with blackbody emission at a relatively narrow range of temperatures, \( T \sim 1750 \pm 250 \) K.

The right panel of Figure 8 reveals a tighter correlation than the left panel. This is expected, however, because the percentage error in \( J_{\text{EXC}} \) is about twice the percentage error in \( H_{\text{EXC}} \). The 1 \( \sigma \) error bars shown in the top left of both panels correspond to the standard deviations of WTTSs listed in Table 6. For the reasons discussed in § 2.3, the actual error bars are probably larger, suggesting that uncertainties in our procedure are responsible for a significant fraction of the scatter in the observed excesses.

Depending on the density and composition, the sublimation temperature of dust grains is also \( \sim 1500\,–\,2000 \) K (e.g., Pollack et al. 1994). Thus, we argue that the near-infrared excess of \( \tau \) Tauri stars is produced at the inner edge of the disk whose temperature is set by the dust sublimation temperature.

4.3. The Color Temperature of the IRAC Excesses

Following the procedure outlined in § 4.2, we obtain the color temperature of the mid-IR excess of the CTTSs from the Chamaeleon II sample (Table 1) by computing the ratios of the flux excesses at the IRAC-1 \( ^{5} \) (3.6 \( \mu \)m) and IRAC-3 bands (5.8 \( \mu \)m) (A. Porras et al. 2006, in preparation). At these wavelengths, the excess emission largely dominates over the photospheric emission, and the uncertainties in the expected fluxes are likely to dominate the errors in deriving color temperatures. Figure 9 shows that the color temperatures of the IRAC excess are \( T \sim 1400 \pm 200 \) K. This temperature is similar to the blackbody temperature derived by Muzerolle et al. (2003; \( T \sim 1400 \) K), in which they used high-resolution spectroscopy of three spectral regions between 2.1 and 4.8 \( \mu \)m to probe the shape of the excess emission of nine CTTSs. These temperatures are significantly lower than those obtained from the near-IR colors of the

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5 The Infrared Array Camera on the Spitzer Space Telescope.
Fig. 7.—K-band excess vs. J-band excess (left) and H-band excess (right). The K-band excess correlates strongly with both J- and H-band excesses. The 1 σ error bars shown at the top left corners of the panels correspond to the standard deviations of WTTSs listed in Table 6. The Spearman’s ranks of these correlations are 0.65 and 0.92, with probabilities of being drawn from a random distribution of $1.5 \times 10^{-4}$ and $6.3 \times 10^{-26}$, respectively. These robust correlations suggest that the J-, H-, and K-band excesses have a common source.

Fig. 8.—K-band excess flux vs. J-band excess flux (left) and H-band excess flux (right) in units of the expected photosphere at 2.2 μm. The flux ratios shown are consistent with blackbody emission at a relatively narrow range of temperatures, $T \sim 1750 \pm 250$ K. The lines shown correspond to blackbodies at 1500, 1750, and 2000 K. The 1 σ error bars shown at the top left corners of the panels correspond to the standard deviations of WTTSs listed in Table 6. For reasons discussed in § 2.3, the actual error bars are probably larger (see text).
excess ($T \sim 1750 \pm 250$ K). We discuss a possible explanation for this difference in § 4.4.

4.4. The Inner Disks of PMS Stars

Herbig Ae/Be stars (Herbig 1960) are pre-main-sequence intermediate-mass (mass $\geq 2 M_\odot$) stars analogous to CTTSs (mass $< 2 M_\odot$). The mid- and far-IR regions of the SEDs of Herbig Ae/Be stars are well fitted by standard models of passive flared disks (e.g., Chiang & Goldreich 1997, 1999); however, these models fail to explain the near-IR excess, known as the “near-IR bump,” observed in most Herbig Ae/Be stars. According to these simple models, the disk flares outward at large radii due to the vertical hydrostatic equilibrium but is physically thin near the star. Thus, the grazing angle of the incident radiation is small at small radii, and the inner disk is heated very inefficiently and extends to a few stellar radii before reaching the dust sublimation temperature. When the vertical structure of the inner disk is taken into account (Natta et al. 2001; Dullemond et al. 2001), the very inner edge of the disk, which becomes an inner rim (Isella & Natta 2005) show that when the dependence of the dust sublimation temperature on gas density is taken into account, the inner rim becomes rounded, and its surface has a vertical temperature gradient that is several hundreds of kelvins wide. Such an inner rim would present a hotter color temperature at shorter wavelengths and a cooler color temperature at longer wavelengths, and could help to explain the discrepancy between the color temperatures we derived from the 2MASS and IRAC observations ($\S$ 4.2 and 4.3, respectively).

5. DISK MODELING AND IMPLICATION OF THE NEAR-IR EXCESS FOR DISK STRUCTURE

In order to quantify the contribution from the inner rim to the total flux at different wavelengths, we model the SEDs of 10 CTTSs from the Chamaeleon II sample (Table 1) using the disk model presented by Dullemond et al. (2001). The model is based on the flared disk model of Chiang & Goldreich (1997, 1999) and includes a disk with three distinct components: a cool disk interior, a warm surface layer, and a hot inner rim located at the dust sublimation radius. The main parameters of the models are listed in Table 9. For all models, we assume a single dust sublimation temperature of 1400 K, corresponding to the typical color temperature of the IRAC excess found in § 4.3. To estimate the stellar effective temperatures ($T_{\text{eff}}$), we adopt the spectral type–$T_{\text{eff}}$ relations from KH95. The stellar luminosities are obtained from the extinction-corrected $L_C$-band (0.8 $\mu m$) magnitudes and the bolometric corrections, appropriate for the spectral type, from Hartigan et al. (1994). Following HH92, we adopted a distance of 200 pc for all the objects. Finally, the stellar masses are estimated using the evolutionary tracks presented by Siess et al. (2000). For our objects, we find that Siess et al. models yield masses that are intermediate between those derived from the models by D’Antona & Mazzitelli (1994, 1998)$^6$ and those obtained from the models by Baraffe et al. (1998). The photospheric luminosity of the star, the stellar mass, and the dust sublimation temperature determine the radius and scale height of the rim. This predicted inner rim is labeled “Inner rim A” on the disk models in Figure 10. We find that the models for most of the stars systematically underestimate the near- and mid-IR excesses. However, a good fit can be obtained simply by scaling the contribution from the predicted inner rim by a factor

\begin{table}[h]
\centering
\caption{Parameters of the Models}
\begin{tabular}{lcccccc}
\hline
Star ID & $L_*$ ($L_\odot$) & $T_{\text{eff}}$ (K) & $M_*$ ($M_\odot$) & $R_{\text{inn}}$ (AU) & $\Omega^a$ & $R_{\text{inn}}$ (AU) \\
\hline
Sz 47 & 0.19 & 3470 & 0.35 & 0.05 & 4.1 & 0.07 \\
Sz 51 & 0.35 & 3850 & 0.60 & 0.05 & 5.8 & 0.10 \\
Sz 53 & 0.26 & 3720 & 0.50 & 0.04 & 3.5 & 0.07 \\
Sz 55 & 0.18 & 3850 & 0.60 & 0.04 & 1 & 0.04 \\
Sz 56 & 0.23 & 3370 & 0.30 & 0.04 & 1 & 0.04 \\
Sz 57 & 0.40 & 3370 & 0.30 & 0.05 & 1 & 0.05 \\
Sz 58 & 0.51 & 4350 & 0.60 & 0.05 & 6.0 & 0.10 \\
Sz 59 & 0.41 & 3850 & 0.40 & 0.06 & 6.7 & 0.13 \\
Sz 61 & 1.66 & 4590 & 1.40 & 0.11 & 4.5 & 0.20 \\
Sz 62 & 0.42 & 3580 & 0.40 & 0.05 & 3.6 & 0.08 \\
\hline
\end{tabular}
\label{tab:models}
\end{table}

\footnotetext{6}{Available at http://www.mporzio.astro.it/~dantona/prems.html.}
Fig. 10.—Disk models for 10 Chamaeleon II CTTSs. The solid blue line (“Total SED A”) corresponds to the total SED when the inner rim is irradiated only by the photosphere of the central star (rim A). The solid red line (“Total SED B”) corresponds to the total SED when the emission from the inner rim is scaled by the factor $\Omega$ listed in Table 9 (rim B). According to the models, the near- and mid-IR SED of the CTTSs is largely dominated by the emission from the inner rim at the dust sublimation temperature $T \sim 1750 \pm 250$ K. In addition, in most cases the area of the inner rim is larger than expected for a rim in thermal equilibrium with the stellar radiation field alone. Thus, an additional source of energy is needed. We argue that as proposed by D’Alessio et al. (2004), the UV radiation from the accretion shock significantly affects the sizes of the inner holes in disks around CTTSs, increasing the area of the inner rim.
that ranges from ~1 to ~7. This “scaled-up” rim is labeled as “Inner rim B” in Figure 10. We interpret this result as an indication that the area of the inner rim is larger, by a factor of \( \Omega \), than predicted by the models, i.e., \( \Omega = A_{\text{rim}}/A_{\text{rim,A}} \), where \( A_{\text{rim}} \) is the area of the rim. Since \( A_{\text{rim}} \) \( \propto H_{\text{rim}}^2 \), and according to our adopted model \( R_{\text{rim}} \propto H_{\text{rim}}^{\frac{1}{2}} \), where \( R_{\text{rim}} \) and \( H_{\text{rim}} \) are the radius and the scale height of the rim, then \( A_{\text{rim}} \propto R_{\text{rim}}^2 \). Thus, the radius of the inner rim B can be calculated as \( R_{\text{rim}} B = R_{\text{rim}} A \Omega^2 \).

The masses of the disk models shown in Figure 10 were adjusted to try to match the observed 24 \( \mu \)m fluxes. The adopted disk masses range from \( 5 \times 10^{-2} \) to \( 5 \times 10^{-4} M_\odot \). In all cases, the outer disk radius was set to 400 AU, and the disk’s surface density \( \Sigma \) is given by \( \Sigma(R)(g \text{ cm}^{-2}) = 2 \times 10^4 (R/AU)^{-2} \). Since our simple approach of scaling the inner rim does not take into account the effects of the modifications in the inner disk on the disk structure at larger radii, we do not try to constrain the physical parameters of the outer disks. However, we keep the outer disk models in the SED shown in Figure 10 only to show that the 2MASS and IRAC fluxes are completely dominated by the emission from the inner rim with very minor contributions from the rest of the disk.

The fact that the energy irradiated (i.e., the area under the curve in Fig. 10) by rim B is larger than that irradiated by rim A suggests that the inner rim is powered by more than the stellar photosphere. We argue that the most likely “source of missing energy” is the UV emission from the accretion shock produced as material from the star is channeled onto the stellar surface. The accretion shock emission has already been recognized by D’Alessio et al. (2004) as an important heating source of the inner disks of CTTSs. Unfortunately, as discussed in § 2.3, it is very difficult to estimate the UV excess from the SED alone, and it needs to be obtained independently, e.g., from UV spectroscopy. However, most accretion luminosity estimates based on optical spectroscopy involve an extinction correction. Gullbring et al. (1998) estimate accretion luminosities for a sample of CTTSs from UV spectroscopy and compare their results with those presented by Hartigan et al. (1995) for the same sample of stars, following a similar method. The accretion luminosities derived by these two groups systematically differ by up to an order of magnitude. According to Gullbring et al. (1998), most of the discrepancy can be traced back to a large systematic difference in the extinction corrections. The large variability typical of the UV excess makes it even harder to obtain an accurate estimate of the accretion luminosity unless the observations involved in the analysis are made simultaneously. An estimate of the UV excess is necessary to test whether the energy from the accretion shock luminosity is enough to account for the observed mid-IR excesses seen in the Chamaeleon II objects; however, for the reasons mentioned above, we leave such a test for future work.

We note that the degeneracy between the UV excess and the extinction can eventually be disentangled by measuring the veiling at the wavelengths corresponding to the \( BVR_{\text{I}_C} \) band passes using high-resolution spectroscopy from 0.4 to 0.9 \( \mu \)m and obtaining simultaneous optical photometry. With that information, the \( R_C - I_C \) colors can be corrected for veiling in order to estimate the extinction more accurately, and the UV excess can be estimated directly from the \( B \)-band veiling or the \( U \) photometry corrected for extinction. We plan to follow that procedure in a follow-up paper in order to study self-consistently the effect of the UV excess on the SEDs of CTTSs at near-IR and Spitzer wavelengths. However, even without the veiling information from spectroscopy, we do find indirect evidence that supports the idea that the UV excess significantly affects the sizes of the inner holes in disks around CTTSs. First, if the inner rim is larger than expected because it is significantly powered by accretion shock luminosity, a correlation between the \( K \)-band excess and the accretion luminosity is expected. For a subsample of the Taurus CTTSs, we use the accretion luminosities, derived from UV photometry and spectroscopy, from Muzerolle et al. (1998) to investigate the correlation between \( K \)-band excesses and accretion luminosity. This correlation is evident in Figure 11, which also shows that for some CTTSs, accretion shock luminosity can dominate the stellar luminosity. The Spearman’s rank of the correlation between \( K \)-band excesses and accretion luminosity is 0.81 with a probability of being drawn from a random distribution of \( 1.01 \times 10^{-6} \). A similar correlation between accretion luminosity and \( K \)-band excesses has been reported by Muzerolle et al. (2003) for a smaller sample of CTTSs. In addition, D’Alessio et al. (2004) demonstrate that including the UV radiation in the circumstellar disk models can significantly increase the size of the inner hole. In particular, they find that when the UV excess is included, the dust sublimation radius of the “continuum star” DG Tau (0.2 AU) is ~3 times larger than the radius inferred from neglecting the UV excess emission (0.07 AU) and is in good agreement with the inner radius derived from \( K \)-band interferometric observation of DG Tau (Colavita et al. 2003). For our objects, \( R_{\text{rim}} B/R_{\text{rim}} A \leq 2 \); thus, we conclude that the UV excess from the accretion shock could in principle account for the sizes of all the inner rims reported herein.

We were motivated to investigate the possibility of large inner rims in CTTSs while trying to find an explanation for the \( J \)- and \( H \)-band excesses calculated in § 2. However, we emphasize that our results from the IRAC bands, which suggest the presence of large inner rims, are independent of any assumptions made about the presence of \( J \)- or \( H \)-band excesses. In § 2.2 we found that the \( J \)-band excess is at the \( \sim 35 \% \) level. Using the \( J \) band to obtain the photospheric luminosity, rather than the \( I_C \) band, increases the expected IRAC fluxes only by \( \sim 35 \% \). But in

![Fig. 11.—Accretion luminosity \( (L_{\text{ac}}) \) vs. \( K \)-band excess. The plot shows that \( K \)-band excess correlates well with accretion shock luminosity. The Spearman’s rank of the correlation is 0.81 with a probability of being drawn from a random distribution of \( 1.01 \times 10^{-6} \). The figure also shows that for some CTTSs, the accretion luminosity can dominate the stellar luminosity.](image-url)
some cases, at IRAC wavelengths the flux discrepancy between disk models with small inner rims heated only by the stellar photosphere and the observations is an order of magnitude larger than the $J$-band excess. This discrepancy between the models and the observed IRAC fluxes is well beyond any observational errors and uncertainties in the expected photospheric fluxes. We have followed the same procedure described in § 2.1 to calculate the IRAC excesses of a large sample of WTTSs (L. A. Cieza et al. 2006, in preparation). For WTTSs showing no IR excess, the expected photospheric fluxes agree with the observed fluxes to within $\sim$5%. Since the existence of large inner rims in CTTSs is also supported by interferometric observations (Colavita et al. 2003), and its presence could account for both the IRAC and 2MASS excesses, it is tempting to conclude that the $J$- and $H$-band excesses calculated in § 2.2 are mainly, even if not exclusively, produced by the tail of the inner disk emission.

6. IMPLICATIONS OF THE $J$-BAND EXCESS FOR STELLAR AGES AND DISK EVOLUTION

The presence of significant $J$-band and $H$-band excess has important implications not only for the structure of circumstellar disks, but also for estimations of stellar ages. Since CTTSs are usually placed in the H-R diagram using luminosities derived from the $J$ band (e.g., KH95; Hartigan et al. 1994), a systematic error in the $J$-band luminosities translates into a systematic error in the derived ages. In order to investigate the effect of the $J$-band excess on the derived luminosities and ages, we calculate the luminosities of our entire sample of CTTSs and WTTSs from the extinction-corrected $I_c$- and $J$-band magnitudes and bolometric corrections appropriate for the spectral types from Hartigan et al. (1994), and then compare the results. We adopted distances of 140 and 200 pc for objects in Taurus and Chamaeleon II, respectively (Kenyon et al. 1994; HH92). For our sample of 59 CTTSs (Tables 1 and 5), we find that luminosities derived from the $J$ band are systematically higher by a factor of $\sim$1.35 on average with respect to luminosities obtained from the $I_c$ band. However, for WTTSs we find no systematic difference between the two methods. This systematic difference in the luminosities obtained for CTTSs is a direct consequence of the $J - I_c$ color excesses reported in § 2.2; therefore, the uncertainties in the $J$-band excess determination propagate directly into the uncertainties in the luminosity difference between luminosities derived from the $I_c$ band and those derived from the $J$ band. In § 2.3 we conclude that these color excesses are a good measurement of the nonphotospheric $J$-band contributions (i.e., $J_x \approx J_{\text{col-ex}}$). Thus, we believe that the photospheric luminosities obtained from the $I_c$ band are more accurate than those obtained from the $J$ band. As discussed in § 5, if optical spectroscopic veiling measurements were available, this conclusion could be tested by combining photometry and spectroscopic veiling measurements at the $R_c$ and $I_c$ bands. The extinction can then be obtained from the veiling-corrected $R_c - I_c$ colors, and the $I_c$ fluxes can be corrected for extinction and veiling independently rather than assuming that the effects cancel each other.

If the luminosities obtained from the $I_c$ band are in fact more accurate than those obtained from the $J$ band as a general rule, then the luminosities of CTTSs have been systematically overestimated by most studies. Since low-mass PMS stars (mass $< 1 M_\odot$) contract roughly at constant temperature, overestimated luminosities translate into underestimated ages when the stars are placed in the H-R diagram. This effect is shown in Figure 12, which plots the ages of CTTSs and WTTSs obtained from $I_c$-band luminosities versus those obtained from $J$-band luminosities for three different sets of evolutionary tracks. We find that in general, models by D’Antona & Mazzitelli (1998; Fig. 12a) yield younger ages, models by Baraffe et al. (1998; Fig. 12c) yield older ages, and models by Siess et al. (2000; Fig. 12b) yield intermediate ages. In all cases, CTTSs appear systematically younger when the ages are derived from the $J$-band luminosities instead of the $I_c$-band luminosities. Since WTTSs have no $J$-band excess, no systematic effect is seen for their ages, and using $J$-band or $I_c$ luminosities yields essentially the same age. In Figure 13 we plot the age distribution of CTTSs and WTTSs when the stellar luminosities are estimated from the $J$ band (left) and from the $I_c$ band (right) using the models from Siess et al. (2000). The mean, median, and standard deviation of the logarithmic age distribution (in millions of years) are 0.32, 0.27, and 0.35, respectively, when the ages are derived from $J$-band luminosities and 0.50, 0.47, and 0.37, respectively, when the ages are derived from $I_c$-band luminosities.

The right panel of Figure 13 shows that when the ages are derived from the $I_c$ band, the overlap of the age distribution of CTTSs and WTTSs increases significantly with respect to the age distributions obtained from the $J$-band luminosities. Most WTTSs are likely to be evolutionary descendants of CTTSs, since all low-mass PMS stars are likely to go through a CTTS...
phase, even if this phase is short. Strong winds and star-disk interactions are the main mechanisms through which PMS stars are believed to dissipate angular momentum; therefore, without a T Tauri phase it becomes very difficult to explain the angular momentum evolution of young stellar objects (Rebull et al. 2004). If WTTSs are in fact evolutionary descendents of CTTSs, a large overlap in their age distributions implies a wide distribution in the duration of the CTTS stage. In this context, the right panel of Figure 13 suggests that the inner accretion disk, the presence of which defines the CTTS phase, dissipates on a timescale that ranges from 1 to 10 Myr.

The diversity in the dissipation timescale of the inner accretion disks might be related to the presence of substellar companions or to the formation of giant planets within the disks. The presence of planets is usually invoked to account for the large inner holes (~1–10 AU wide) inferred from the SEDs of several WTTSs and CTTSs (e.g., Calvet et al. 2002; D’Alessio et al. 2005). Mid- and far-IR properties of a statistically significant sample of young WTTSs (i.e., coeval with CTTSs) are needed to test this idea. Spitzer observations will soon reveal the fraction of WTTSs with (nonaccreting) circumstellar disks as a function of age, which will help to constrain the dissipation timescale of the planet-forming region of the disk.

7. SUMMARY AND CONCLUSIONS

1. In § 2 we showed that CTTSs present significant J- and H-band color excesses in addition to the well-studied K-band excess. We interpreted these color excesses as evidence for non-photospheric emission.

2. In §§ 4.2 and 4.3 we estimated the color temperature of the excess emission at 2MASS and IRAC wavelengths, respectively. We found that the color temperature of the excess emission is $T \sim 1750 \pm 250$ K at 2MASS wavelengths and $T \sim 1400 \pm 200$ K at IRAC wavelengths. We suggested that this emission originates at an inner rim that is physically narrow but has a gradient of temperatures several hundreds of degrees wide.

3. In § 5 we modeled the SEDs of 10 CTTSs from 0.4 to 24 μm and found that the 2MASS and IRAC fluxes are dominated by the emission from the inner rim. The models that best fit the data are those in which the inner radius of the disk is larger than expected for a rim in thermal equilibrium with the stellar radiation field alone. We found that the K-band excess correlates with accretion luminosity. As proposed by D’Alessio et al. (2004), the UV radiation from the accretion shock could explain the larger than expected inner holes.

4. Finally, in § 6 we calculated stellar luminosities from the $I_C$ and $J$ bands and used these luminosities to estimate stellar ages from three different sets of evolutionary tracks. We argued that normalizing the luminosity of CTTSs to the $J$ band systematically overestimates their luminosities. These overestimated luminosities translate into underestimated ages when the stars are placed in the H-R diagram. When the ages are derived from $I_C$-band luminosities, CTTSs and WTTSs show a larger age overlap with respect to ages derived from the $J$ band. If WTTSs are descendants of CTTSs, then this large overlap implies a wide diversity in the duration of the CTTS phase.

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Fig. 13.—Age distribution of CTTSs and WTTSs when the ages are estimated from J-band luminosities (left) and when the ages are derived using $I_C$-band luminosities (right). The ages correspond to the models by Siess et al. (2000). We suggest that when J-band luminosities are used, the J-band excess displaces the mean age of CTTSs to a younger value.
