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THE TEMPERATURE PROFILE OF T TAURI DISKS

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ABSTRACT

This paper proposes that T Tauri stars are three-component systems, formed by a star, its circumstellar disk and a tenuous, dusty envelope which surrounds both. The dust in the envelope scatters and reemits stellar light in the direction of the disk, which is therefore significantly hotter at large distance from the star than if direct heating alone is considered.

The overall behavior of the disk temperature is very sensitive to the envelope properties. For example, for spherically symmetric envelopes, the whole observed range of spectral indices in the interval 5–100 μm, (4/3 to 0), can be accounted for by models with density in the envelope $\propto r^{-1}$ and values of τ increasing from 0 to $\sim$0.4.

In this context, stellar winds, disk winds, and infall models are discussed. Only disk winds seem able to reproduce the observed flat TTS spectra.

Subject headings: accretion, accretion disks — circumstellar matter — stars: mass loss — stars: pre–main-sequence

1. INTRODUCTION

T Tauri stars (TTS) have spectral energy distributions in the infrared that can be approximately described by power laws with spectral index n ($\nu F_\nu \propto \lambda^{-n}$) varying between 4/3 and 0 (see, for instance, Rucinski 1985; Rydgren & Zak 1987; Beckwith et al. 1990). Various authors have shown that these spectra can be explained as the emission of star/circumstellar disk systems (Rucinski 1985; Adams, Lada, & Shu 1987, 1988; Beckwith et al. 1990).

The star/disk interpretation of TTS requires that the disk temperature profile varies from star to star. In fact, it is easy to prove that, for the large interval of frequencies over which the disk is optically thick, the spectral index n depends only on the temperature profile (Beckwith et al. 1990). If $T \propto r^{-q}$, then $n = (4q - 2)/q$, so that, in order to span the observed range of n, q has to vary between $\frac{3}{4}$ and $\frac{1}{2}$.

Adams et al. (1988) have shown that the temperature profile of *passive* disks, i.e., of disks which have no intrinsic luminosity but intercept and reprocess the radiation of the central star, has the approximate form $T \propto r^{-3/4}$, independent of the stellar and disk parameters. Such disks, supposed to be spatially flat and thin, but optically thick to most wavelengths, intercept and reradiate about 1/4 of the stellar luminosity and are characterized by a spectral index in the infrared $n = 4/3$. The same index $n = 4/3$ characterizes also the spectrum of classical Keplerian accretion disks (Lynden-Bell & Pringle 1974). These so called *active* disks have an intrinsic source of energy, so that they radiate more than $\sim\frac{1}{4}$ of the stellar luminosity, but the shape of the spectral energy distribution cannot be distinguished from that of a *passive* disk. In summary, disk models, both for *passive* and *active* disks, predict a temperature profile $T \propto r^{-3/4}$ (and, therefore, a spectral index $n = 4/3$), which should be the same for all stars. Suggestions for producing flatter temperature profiles have included strongly flared disks (Kenyon & Hartmann 1987), nonviscous mechanisms for mass and momentum transport (Adams et al. 1988) and eccentric gravitational instabilities (Adams, Ruden, & Shu 1989). The real capability of these mechanisms to reproduce the extremely flat spectra observed in some TTS is, however, somewhat controversial (see, for example, Shu 1991; Kenyon & Hartmann 1987).

An important aspect of the above modeling of TTS disks is that the star/disk system is considered to be isolated in vacuum. In reality, there is growing observational evidence of the contrary (Elsasser & Staude 1978; Beckwith et al. 1984; Grasdalen et al. 1984, 1989; Sargent & Beckwith 1987; Bastien & Ménard 1988, 1990; Ohashi, Kawabe, & Umebayashi 1991; Weintraub et al. 1992); indeed, it is not difficult to believe that winds, residual accreting matter, disk evaporation will fill the space above and below the disk plane with *some* matter, gas, and dust. Its amount is likely to be small in optical stars like TTS, but can be much larger in deeply embedded objects. In fact, the star/disk/dust shell morphology has been used to model various young objects (see, for example, Adams et al. 1988; Mathieu, Adams, & Latham 1991), but the contribution of the dust shell to the disk heating, and its effects on the resulting disk spectral energy distribution have been insofar neglected.

The effects of surrounding matter on the disk thermal structure have begun to be investigated only recently. The case of deeply embedded objects has been considered by Butner, Natta, & Evans (1993), who have examined the effects on the disk temperature structure of an extremely optically thick envelope, and found that its contribution to the heating of the outer parts of the disk is significant (see also Keene & Masson 1990). Safier (1993a, b) is currently computing self-consistent spectral energy distributions of star/disk/wind systems, where the wind is centrifugally driven from the surface of the disk by the magnetic field.

In this paper we will discuss a situation, more relevant for the TTS problem, where the amount of dust above and below the disk plane is small. We will adopt for the disk spatial structure the same simplifying assumptions used by Adams et al. (1988) and confine the discussion to cases where the optical depth of the envelope is smaller than unity. Both the results of this paper and Safier's illustrate how even a small amount of dust can affect deeply the disk temperature structure and provide a simple answer to the puzzle of the large variation of n, and, in particular, to the smallest values observed in several TTS.

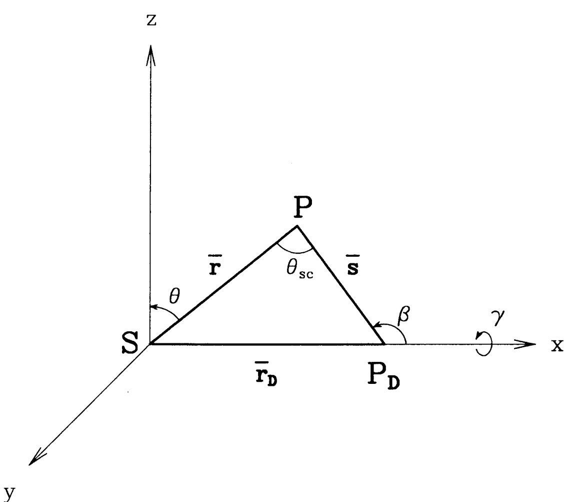

FIG. 1.—Coordinate systems. S marks the position of the star, P is a point in the envelope, P_D a point on the disk surface. The disk lies in the (x-y) plane. The angle β and θ_{sc} are defined in the ($SP_D P$) plane, while θ is in the (x-z) plane.

2. A SCATTERING ENVELOPE OF DUST

Let us consider the simplest case of a spherical envelope of particles which *scatter* the stellar radiation. Let P_D be a point on the disk at distance r_D from the star, whose location is indicated by S, and P a point in the envelope at distance r from S (see Fig. 1). The star has luminosity L_*, temperature T_* and radius r_*. The disk, supposed to be perfectly thin and flat, lays in the (x, y) plane. We found it convenient to adopt a system of spherical coordinates (s, β and γ) centered at P_D; s is the distance between P and P_D, β is the angle between the $\hat{s}$ and $\hat{x}$ directions in the ($SP_D P$) plane and γ is the rotation angle around the x-axis. We indicate with $\hat{s}$, $\hat{r}$, $\hat{x}$, $\hat{y}$, and $\hat{z}$ unit vectors in the s, r, x, y, and z directions, respectively.

For simplicity, we will consider in the following the stellar radiation to be monochromatic. If the envelope optical depth τ at the wavelength of the stellar radiation is much smaller than unity, then the fraction of the stellar luminosity L_* intercepted by a unit volume of matter in P is given by

$$f(P) = \eta \, \frac{N(P)\kappa}{4\pi r^2} \, s^2 ds \, |d \cos \beta| \, d\gamma \, , \tag{1}$$

where η is a coefficient that corrects for the fraction of stellar radiation that is intercepted by the disk before being scattered in the envelope, $N(P)$ is the number density of scatterers at P in cm^{-3}, and κ is the opacity in cm^2 per scatterer. We consider in the following mostly cases where N varies as a power-law function of r

$$N \propto \left(\frac{r}{r_*}\right)^{-\alpha} . \tag{2}$$

The fraction of photons scattered in a unit solid angle in the $\hat{s}$ direction is determined by the phase function $\Phi(\theta_{sc})$, where the angle of scattering θ_{sc} is given by

$$\cos \theta_{sc} = (\hat{r} \cdot \hat{s}) = \frac{r_D \cos \beta + s}{r} . \tag{3}$$

For isotropic scattering, $\Phi(\theta_{sc}) = 1/4\pi$.

Finally, the fraction of L_* intercepted by a unit area centered in P_D, $f(P, P_D)$, is given by

$$f(P, P_D) = f(P)\Phi(\theta_{sc}) \, |\hat{s} \cdot \hat{z}| \, \frac{1}{s^2} . \tag{4}$$

Assuming that the disk is optically thick at all the relevant wavelengths and neglecting the effects of scattering in the disk itself (see Adams & Shu 1985, 1986), the heating rate in P_D due to scattered radiation (in ergs cm^{-2} s^{-1}) can be obtained by integrating equation (4) over the volume of the envelope

$$H_{sc} = \eta \sigma T_*^4 \int_{s_{min}}^{s_{max}} ds \int_0^{\pi} \sin \beta \, d\beta \int_0^{\pi} d\gamma \left(\frac{r_*}{r}\right)^2 N(r)\kappa\Phi(\theta_{sc})(\hat{s} \cdot \hat{z}) \, , \tag{5}$$

where $s_{min} = |r - r_D|$, $s_{max} = r + r_D$ and r can be written as $r^2 = r_D^2 + s^2 + 2r_D s \cos \beta$.

Following Adams et al. (1988), the heating rate due to direct stellar radiation can be written as

$$H_{dir} = \eta_* \frac{\sigma T_*^4}{\pi} \left\{ \arcsin \left(\frac{r_*}{r_D}\right) - \left(\frac{r_*}{r_D}\right) \left[1 - \left(\frac{r_*}{r_D}\right)^2\right]^{1/2} \right\} , \tag{6}$$

where we have neglected the shadowing of the disk due to the finite size of the star. The factor η_* corrects for the fraction of stellar photons that are scattered by the envelope before directly reaching the disk.

The two coefficients η, η_* are always of the order of unity and vary between two extreme cases: if the envelope is much smaller than the disk, $\eta_* \sim (1 - \tau)$, $\eta \sim 1$; if, instead, the envelope is much larger than the disk, or most of the dust is concentrated in its outer part, $\eta_* \sim 1$, $\eta \sim \frac{3}{4}$. The exact values can only be computed in self-consistent calculations; however, this turns out to be not necessary, because the difference between the two extreme cases just discussed is small, and never such to change the results significantly.

Assuming that the disk is isothermal in the vertical direction, the disk temperature T at distance r_D from S can be obtained from the energy balance equation, written as

$$\sigma T^4 = H_{\rm sc} + H_{\rm dir} = \sigma T_{\rm sc}^4 + \sigma T_{\rm dir}^4 . \tag{7}$$

The calculation of the exact value of $H_{\rm sc}$ for each disk radius r_D requires a numerical integration. However, it is easy to gain some insight on the effects of the heating due to the scattered photons from simple physical arguments. A first consideration concerns the disk luminosity L_D. It is immediate to see from equation (5) that $H_{\rm sc}$ is directly proportional to the optical depth τ of the envelope in the radial direction; by increasing τ it is therefore possible to increase the disk luminosity, i.e., the fraction of stellar light which is reprocessed by the disk. For forward-backward symmetric scattering and $\tau \ll 1$, the luminosity of a disk extending to infinity (integrated over the viewing angle) is simply

$$L_D \sim L_*(\tfrac{1}{4}\eta_* + \tfrac{1}{2}\eta\tau) . \tag{8}$$

The dependence of $H_{\rm sc}$ on r_D has two obvious limiting cases: if the density profile of the scattering particles is very steep, then one should recover the dependence $T_{\rm sc} \propto r_D^{-3/4}$, typical of the direct stellar heating, while if the scattering particles are concentrated in the outer part of the envelope (as, for example, when $\alpha < 0$), then $T_{\rm sc} \sim$ constant. In the intermediate cases one can make use of the fact that the major contribution to the heating at r_D comes from the nearest scatterers, that is from grains at radius $r \sim r_D$. In this case, $T_{\rm sc}$ should be a power law function of r_D of the kind

$$T_{\rm sc} \propto r_D^{-(1+\alpha)/4} . \tag{9}$$

Detailed numerical calculations confirm the validity of equation (9) in the range $0.7 \lesssim \alpha \lesssim 1.5$. For $\alpha \gtrsim 1.5$, the dependence of $T_{\rm sc}$ on r_D is less steep than predicted by equation (9); the limit $T_{\rm sc} \propto r_D^{-3/4}$ is reached for $\alpha \sim 3$. For $\alpha \lesssim 0.7$ $T_{\rm sc}$ tends to be steeper than predicted by equation (9).

Unless τ is very large, the direct heating term in equation (7) dominates for small r_D. In fact, in all the cases we have computed, $T(r_D)$ has an inner part where $T \propto r^{-3/4}$, followed by a region of slower decrease. The crossing point between the two regimes depends, of course, on τ, so that the overall behavior of $T(r_D)$ depends on α and τ and may therefore vary from object to object.

The results of numerical calculations confirm to an unexpected degree what we just said. The quantity T is computed solving equation (7) for different values of α and τ. The stellar parameters are fixed ($L_* = 2\ L_\odot$, $T_* = 4500$ K, $r_* = 1.6 \times 10^{11}$ cm) as well as the inner and outer radius of the disk ($r_0 = r_*$, $r_{\rm out} = 100$ AU). The envelope has outer radius $r_{\rm env} = 1000$ AU and inner radius $r_i = 3r_*$. The latter corresponds to a temperature for grains in thermal equilibrium with the stellar radiation field of about 2000 K. We have assumed $\eta_* = 1$, $\eta = \frac{3}{4}$, as the most appropriate values for the set of parameters we have considered. Figure 2 shows the computed temperature profile for a case where $\alpha = 1$, $\tau = 0.2$. One can easily recognize the inner part, where direct heating dominates (*dashed-dotted curve*), and the outer part, where the scattering heating dominates and $T \propto r_D^{-1/2}$, as predicted by equation (9) (*dashed curve*). The two curves cross at about 0.3 AU, where $T \sim 265$ K.

Once T is known in each point of the disk, the monochromatic disk luminosity is obtained at each frequency as

$$L_\nu^D = 4\pi \cos \imath \int_{r_0}^{r_{\rm out}} B_\nu(T)(1 - \exp - \tau_\nu^D) 2\pi r_D \, dr_D , \tag{10}$$

where $\imath$ is the angle with the line-of-sight and τ_ν^D is the optical depth through the disk, which can be obtained, once the monochromatic opacity k_ν^D and the disk surface density Σ are specified, from the relation

$$\tau_\nu^D = \frac{k_\nu^D \Sigma(r_D)}{\cos \imath} . \tag{11}$$

The chosen values of the disk parameters are typical of TTS (Beckwith et al. 1990), namely $\Sigma \propto r_D^{-1.5}$, a disk mass of 0.05 $M_\odot$, $k_\nu^D = 0.1(\nu/10^{12}\ {\rm Hz})\ {\rm g}^{-1}\ {\rm cm}^2$. The adopted viewing angle is $\imath = 60°$. With these values, the disks are optically thick at all wavelengths up to $\sim$1 mm.

Figure 3 shows the resulting spectral energy distribution for various models with different τ and α. Let us consider first models with $\alpha = 1.0$ (see Fig. 3*b*). For $\lambda \gtrsim$ 5–10 μm, the luminosity is much larger than that of a disk heated only by direct stellar light (*dashed curve*); the excess luminosity increases with increasing τ and the spectrum becomes correspondingly flatter in the range $\sim$5–100 μm. For larger values of α (Fig. 3*c* and 3*d*), $H_{\rm sc}$ may still dominate the heating of the outer disk region, but the temperature profile is steep; the excess luminosity, which depends only on τ, is large, but the spectral energy distribution is not flat. For very low values of α (Fig. 3*a*), only the outer parts of the disk are efficiently heated by the scattered radiation ($T_{\rm sc} \propto r_D^{-q}$ with $q < 0.5$), so that the spectral index n is negative and the resulting spectral energy distribution has a double hump shape, with one peak centered at about 1.6 μm, due to the inner disk, and the other in the range 100–200 μm, whose strength depends on τ.

Figure 4 plots the disk luminosity L_D, obtained by integrating the computed spectral energy distribution over frequency. For small α, the computed L_D-values are lower than those predicted by equation (8), because the outer part of the envelope (for which $r > r_{\rm out}$)

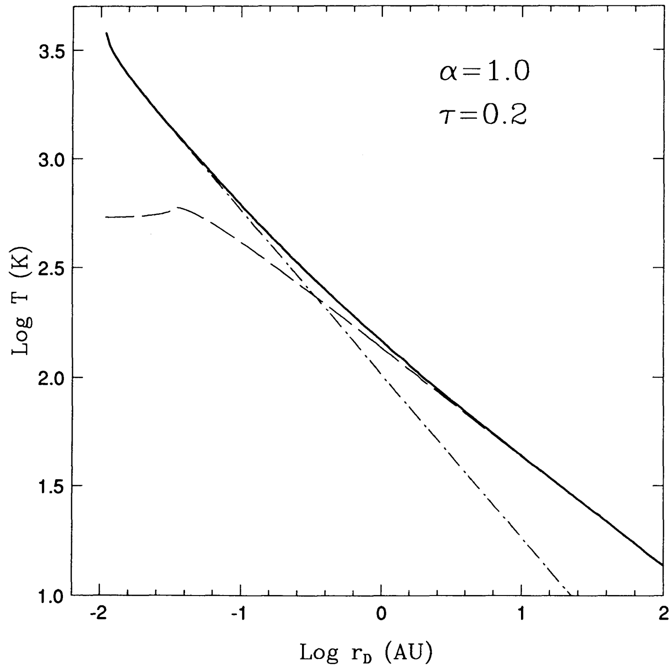

FIG. 2.—Disk temperature as a function of r_D for a model with $\alpha = 1.0$, $\tau = 0.2$. The dashed line shows the contribution of the stellar radiation scattered in the envelope, the dash-dotted line shows the contribution of direct stellar heating, and the solid line shows the resulting temperature.

does not contribute significantly to the disk heating. If $r_{\rm env} \sim r_{\rm out}$, the values predicted by equation (8) are always recovered. If we consider L_D to be the sum of two terms, $L_{\rm dir}$ and $L_{\rm sc}$, corresponding to $H_{\rm dir}$ and $H_{\rm sc}$ in equation (7), then one can have $L_{\rm sc} \gtrsim 1/2 L_{\rm dir}$ already for $\tau \sim 0.3$.

The results shown in Figures 2 and 3 have been obtained for isotropic scattering. However, they hold basically unchanged for any scattering phase function which is forward-backward symmetric; if a degree of asymmetry occurs ($\langle \cos\theta_{\rm sc} \rangle = g > 0$), $H_{\rm sc}$ decreases, for a fixed value of τ, and vanishes in the limit $g \sim 1$. This, however, does not seem to be the case in the visual and near-infrared, where most of the TTS stellar light is radiated ($g \sim 0.3$; Draine & Lee 1984). In practice, a moderate degree of asymmetry can be compensated by increasing τ by a factor $1/(1 - g)$.

3. THE EFFECTS OF THE ENVELOPE THERMAL EMISSION

The same grains that scatter the stellar light also absorb and re-emit it isotropically at longer wavelengths, typically in the infrared.

If the disk is still optically thick in the far infrared, as is probably the case in TTS, then the fraction of the thermal emission of the envelope that is radiated toward the disk will also contribute to its heating, in the same way as the scattered stellar light discussed in § 2, while only the fraction that is radiated forward will escape from the cloud and contribute to the spectral energy distribution of the object.

In this section we will estimate the contribution of the thermal envelope emission to the spectral energy distribution.

Self-consistent calculations of the spectrum of the system star + disk + envelope are still, at present, not available. However, in the case of small optical depth and infinitely extended disks, it is possible to estimate approximately the fraction of L_* that is available for the various components of the system. Let $\tau_{\rm sc}$ be the scattering optical depth in the envelope, $\tau_{\rm abs}$ be the absorption optical depth, and $\tau_{\rm ext} = \tau_{\rm sc} + \tau_{\rm abs}$; assuming, as in § 2, that $\eta = \frac{3}{4}$, $\eta_* = 1$, one finds the following

Fraction of L_* that escapes directly: $\sim \frac{3}{4}(1 - \tau_{\rm ext})$;

Fraction that reaches the disk from the star: $\frac{1}{4}$;

Fraction that reaches the disk from the envelope: $\frac{3}{8}\tau_{\rm ext}$;

Total fraction reprocessed by the disk: $1/4[1 + (3/2)\tau_{\rm ext}]$;

Fraction that escapes after having been scattered by the envelope: $\frac{3}{8}\tau_{\rm sc}$;

Fraction that escapes after having been thermalized in the envelope: $\frac{3}{8}\tau_{\rm abs}$.

The resulting spectral energy distribution will therefore be the sum of three components, each having a different dependence on λ: if we indicate with f_ν^*, f_ν^D and f_ν^E the monochromatic radiation field, normalized to L_*, of the star, of the disk radiation and of the envelope thermal emission, respectively, we have

$$L_\nu = L_*[\tfrac{3}{4}(1 - \tau_{\rm abs} - \tfrac{1}{2}\tau_{\rm sc})f_\nu^* + \tfrac{1}{4}(1 + \tfrac{3}{2}\tau_{\rm ext})f_\nu^D + \tfrac{3}{8}\tau_{\rm abs} f_\nu^E] \,. \quad (12)$$

Figure 5 shows two examples of the resulting spectral energy distribution. They have been computed for $\tau_{\rm abs} = \tau_{\rm sc} = 0.1$ (i.e., assuming a typical albedo of 0.5). The envelope has $\alpha = 1.0$ in Figure 5*a* and $\alpha = 1.5$ in Figure 5*b*. The stellar and disk parameters, as

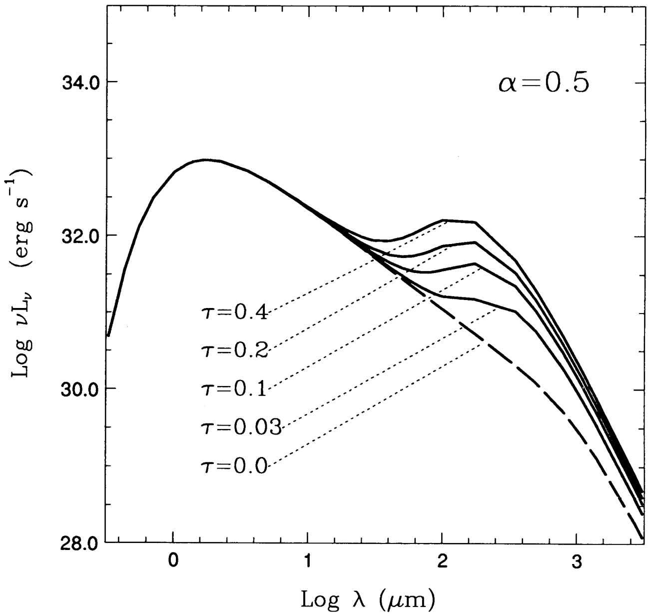

FIG. 3*a*

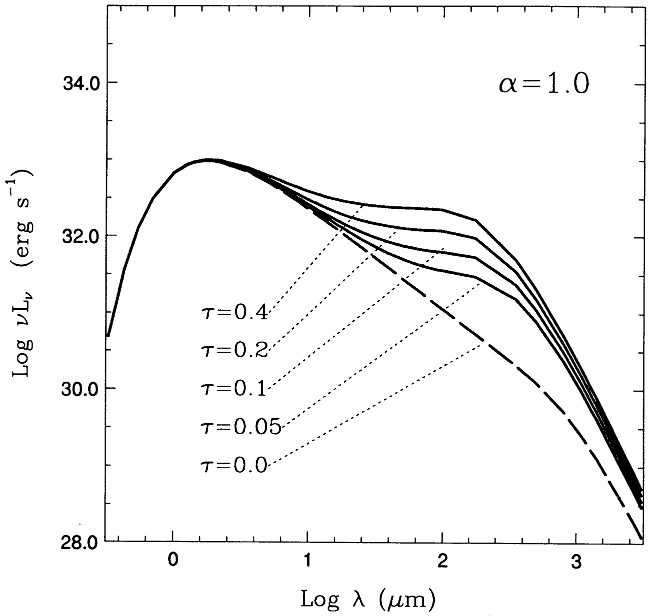

FIG. 3*b*

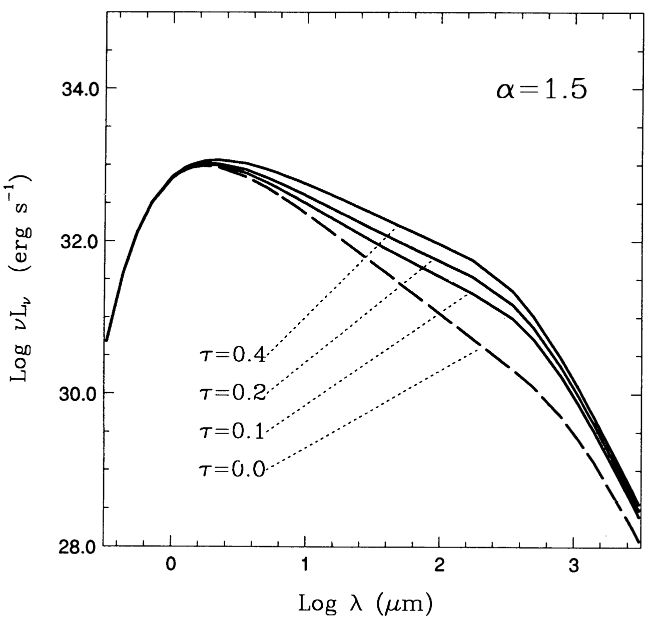

FIG. 3*c*

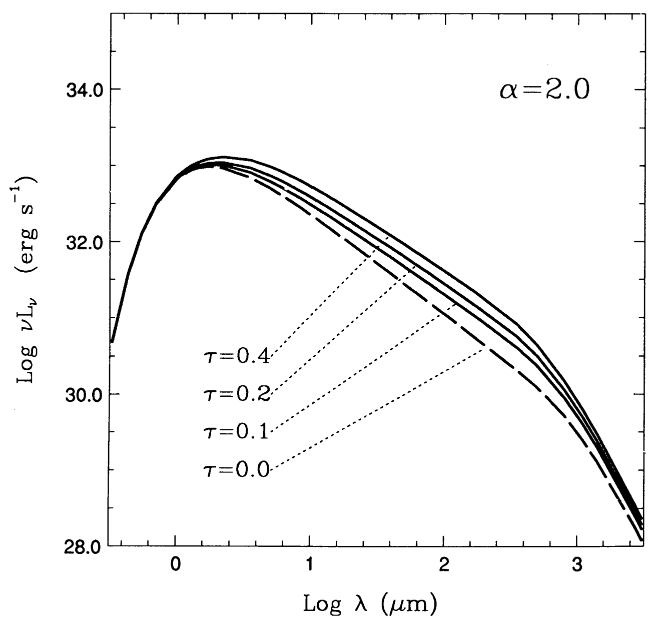

FIG. 3*d*

FIG. 3.—Disk spectral energy distributions for various envelope parameters: (*a*) $\alpha = 0.5$, (*b*) $\alpha = 1.0$, (*c*) $\alpha = 1.5$, and (*d*) $\alpha = 2.0$. Each curve is labeled by the corresponding value of τ. The dashed curve is for $\tau = 0$, i.e., for direct heating only.

well as the inner and outer radii of the envelope are the same as in § 2. The disk spectrum is computed as discussed in § 2, assuming isotropic phase function and $\tau = 0.2$, to take into account also the heating due to the thermal envelope emission. The latter has been computed using the radiation transfer code developed by Egan, Leung, & Spagna (1988; see also Natta et al. 1992), where we have included only the absorption part of the grain cross section. For this calculation, the stellar luminosity has been set equal to $\frac{3}{4}L_*$, to correct for the fraction that goes into direct heating of the disk. A minor inconsistency in the results derives from the fact that, while the radiation transfer code uses for the star a blackbody spectrum at T_*, the disk heating calculations assume in practice a monochromatic stellar radiation, i.e., a constant albedo over the range of frequency where the stellar luminosity is emitted. For TTS, this is in fact quite a good approximation (see Draine & Lee 1984).

The results show that, for the range of τ we consider, the disk emission dominates over the thermal emission of the envelope and determines the overall shape of the observed spectral energy distribution. All the considerations of § 2 hold also when the thermal emission of the envelope is taken into account and should be confirmed, at least qualitatively, when self-consistent calculations of the thermal balance and of the resulting spectral energy distribution will become available.

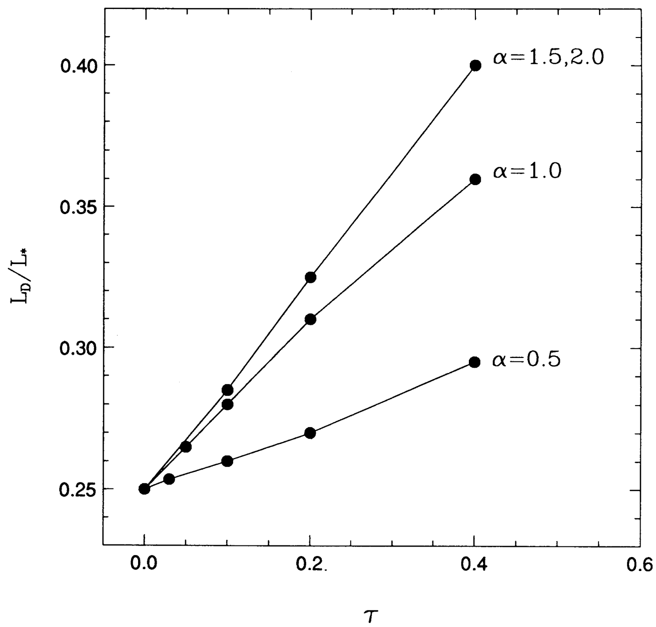

FIG. 4.—Disk luminosity in units of L_* as a function of τ for various values of α

The most interesting consequence of including the thermal envelope emission in the calculations, and one which deserves further consideration, is the appearance in the resulting spectrum of the 10 μm silicate feature in emission, as seen in many TTS (Cohen & Witteborn 1985).

4. THE ORIGIN OF THE ENVELOPE

The discussion developed in the previous sections suggest that tenuous dusty envelopes are a necessary component of TTS systems in order to reproduce the flat spectra of several objects. These envelopes must have relatively shallow density profiles and contain about 10^{-7} $M_\odot$ in a volume of 100 AU centered on the star. Can these properties shed light on the origin of the envelope itself?

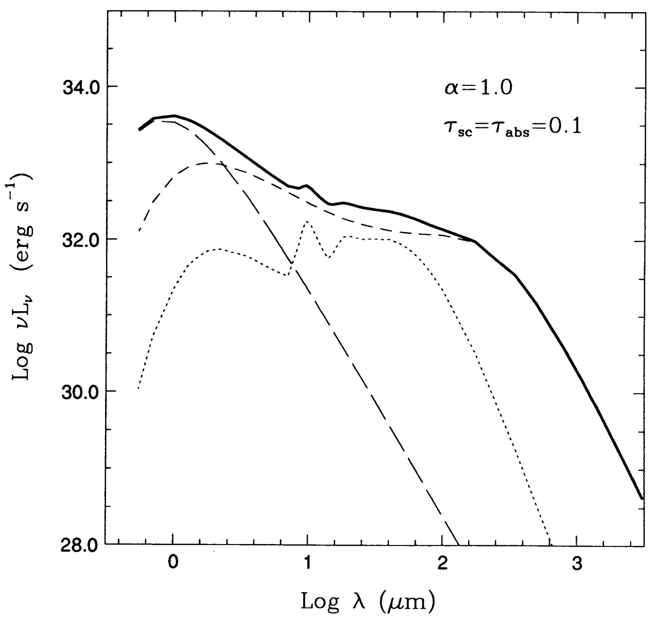

FIG. 5a

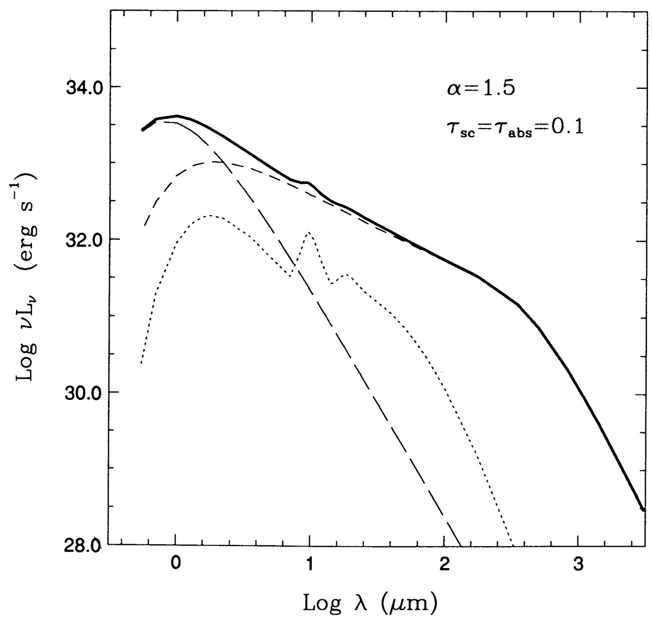

FIG. 5b

FIG. 5.—Spectral energy distribution for models where the thermal emission of the envelope is taken into account. The long-dashed line shows the contribution of stellar radiation (directly transmitted and scattered) to the total, the short-dashed line shows the disk emission, and the dotted line shows the thermal emission of the envelope. The solid line is the total. In (a) the envelope has α = 1.0, τ_{sc} = τ_{abs} = 0.1, in (b) α = 1.5 and the same values of τ.

4.1. *Stellar Wind*

We define for convenience as *stellar wind* any mass outflow which expands radially on scales from a few stellar radii to a few AUs. If not dust-depleted, a stellar wind having a rate of mass loss of $\sim 10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$ provides the required mass; similar mass-loss rates have indeed been derived for the most active TTS (Giovanardi et al. 1991). The main failure of the stellar wind interpretation derives from the fact that in radially expanding winds the density drops fast with r ($\alpha \gtrsim 2$), unless the wind is decelerating on scales of a few stellar radii. With such a steep density profile in the envelope, it is not possible to obtain flat spectral energy distributions for the disk emission.

4.2. *Disk Wind*

A disk origin for the winds in young stellar objects has been proposed by various authors (Pudritz & Norman 1983, 1986; Königl 1989; see also Pudritz et al. 1991) and recently applied by Calvet, Hartmann, & Kenyon (1993) to the interpretation of the spectrum of FU Ori. The properties of disk winds, such as the density and velocity structures, depend on several parameters, among which the magnetic field strength and structure play a fundamental role (Blandford & Payne 1982; Lovelace, Wang, & Sulkanen 1987; Pelletier & Pudritz 1992). In general, when compared to stellar winds, they are characterized by flatter density profiles, at least in the vicinity of the disk plane.

To check the capability of disk winds to reproduce the observed spectral energy distributions, we have adopted the simplified description of the wind properties used by Calvet et al. (1993) and have computed models, along the lines outlined in § 2, for cases where the density at any given point P with cylindrical coordinates (R, z) can be approximately expressed as

$$N = N_0\left(\frac{R}{r_*}\right)^{-a_1+1.5}\left(\frac{z}{r_*}\right)^{-a_2}, \tag{13}$$

where

$$N_0 = \frac{\dot{M}_0}{4\pi r_{\mathrm{iw}}^2}\left(\frac{GM}{r_*}\right)^{-1/2}. \tag{14}$$

In equation (14) r_{iw} is the innermost radius at which the wind is ejected, $\dot{M}_0$, a_1 and a_2 are free parameters. In the self-similar models of Blandford & Payne (1982), it is approximately $a_1 = 2$, $a_2 = 1$ so that the mass-loss rate varies with R as $\dot{M}(R) = \dot{M}_0 \ln(R/r_{\mathrm{iw}})$. Pelletier & Pudritz (1992) have argued that other solutions are possible, and that they have physical meaning as long as $a_2 = 1$, $a_1 \leq 3$. Safier (1993a, b) has argued that winds should have $a_1 + a_2 \sim 3$, so that if $a_2 \sim 1$, then $a_2 \sim 2$.

Tentatively, we have computed three disk wind models, with $a_2 = 1$ and $a_1 = 2$, 1.5 and 1.0, respectively. The other parameters are $r_{\mathrm{iw}} = 3r_*$, and $\dot{M}_0 = 4 \times 10^{-9}$, 6×10^{-10}, and $2 \times 10^{-10}\,M_\odot\,\mathrm{yr}^{-1}$ for $a_1 = 2$, 1.5, and 1, respectively; the values of $\dot{M}_0$ have been chosen so that the resulting disk luminosity due to scattered heating is $L_{\mathrm{sc}} \sim 0.15\,L_\odot$ in all three cases. The star and disk parameters are the same adopted in the spherically symmetric models described in § 2. The calculations indicate that, for $r_D \gtrsim r_{\mathrm{iw}}$, T_{sc} follows a power law with exponent ~ 0.75 for $a_1 = 2$, ~ 0.5 for $a_1 = 1.5$, and ~ 0.4 for $a_1 = 1$. The resulting disk spectral energy distributions are shown in Figure 6. While the $a_1 = 2$ model spectral energy distribution is still steep in the infrared ($n \sim 1$ in the 10–100 μm interval), the $a_1 = 1.5$ spectral energy distribution is quite flat in the same range of wavelengths ($n \sim 0.3$). This last is in fact very similar to the $\alpha = 1.0$, $\tau_{\mathrm{sc}} = 0.2$ spherically symmetric case shown in Figure 3*b*. The $a_1 = 1$ spectral energy distribution shows the double-peaked shape that we find in spherically symmetric models with $\alpha = 0.5$.

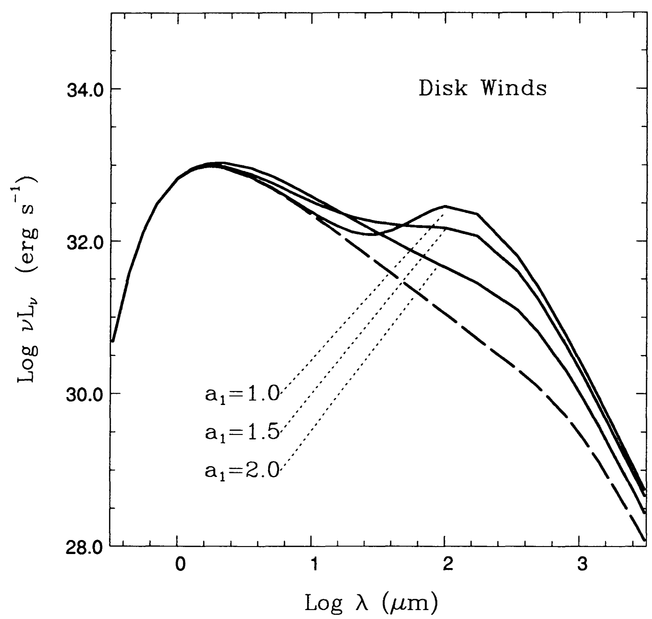

FIG. 6.—Disk spectral energy distributions for three disk wind models. The curves are labeled by the value of the parameter a_1, which characterizes the wind density profile along the disk (see eq. [13]). In all the three models it is $L_{\mathrm{sc}} = 0.15\,L_\odot$. The corresponding mass-loss rates for a disk of 100 AU are 3×10^{-8}, 6×10^{-8}, and $6 \times 10^{-7}\,M_\odot\,\mathrm{yr}^{-1}$ for $a_1 = 2$, 1.5, and 1.0, respectively.

The conclusion that can be derived from these, admittedly oversimplified and preliminary, calculations, is that disk winds can supply the necessary extra amount of heating to the outer parts of the circumstellar disks in TTS systems, provided that $a_1 \sim 1.5$. The required rate of mass loss, integrated over the entire disk surface, is of the order of $5 \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$, consistent with the current estimates of $\dot{M}$ in TTS. An important point for the disk wind hypothesis is that the ejection of matter must involve a large portion of the disk area, extending to at least 10 AU (i.e., $\sim 10^3$ stellar radii), as advocated by Pudritz & Norman (1986) and Königl (1989); if the ejection mechanism becomes inefficient at much smaller radii (Pelletier & Pudritz 1992), then the outer parts of the disk, emitting in the far-infrared, will be much cooler than required by the observations.

In hydromagnetic disk winds, the ejection of matter from the disk surface occurs by converting the gravitational binding energy of the matter accreting onto the star into mechanical energy of the wind. Some fraction of the gravitational energy must be dissipated in the disk; if the required rate of mass-loss implies an accretion rate $\dot{M}_{\mathrm{ac}} \sim 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$ (Basri & Bertout 1989; Hartmann & Kenyon 1990; Pelletier & Pudritz 1991), we can estimate an intrinsic disk luminosity of the order of $0.5\ L_\odot$, i.e., comparable to the luminosity due to reprocessed stellar light. The dissipation of this intrinsic luminosity produces an additional term in equation (7), which has the same dependence on r_D as the direct stellar heating H_{dir} ($\propto r_D^{-3}$), and which can therefore be simply added to it. As long as the intrinsic luminosity is much smaller than L_*, it does not alter significantly the overall shape of the spectrum.

4.3. *Infall*

The last scenario we consider is free-fall collapse of a slowly rotating cloud developed by Ulrich (1976), Cassen & Moosman (1981), and Terebey, Shu, & Cassen (1984). In this context, the envelope is formed by matter which is still accreting onto the disk. Following Cassen & Moosman (1981), we can write the density at any point P of coordinates (r, μ), where $\mu = \cos\theta$ (see Fig. 1), as

$$N = N_0\left(\frac{r}{r_*}\right)^{-1.5}\left(1 + \frac{\mu}{\mu_0}\right)^{-0.5}\left[1 + \frac{r_c}{r}(3\mu_0^2 - 1)\right]^{-1}, \tag{15}$$

where μ_0 is the value of $\cos\theta$ for $r \to \infty$ and r_c is the centrifugal radius. The streamline equation for a particle in the meridian plane relates the quantities μ_0, μ, r, and is given by

$$\mu_0^3 + \left(\frac{r}{r_c} - 1\right)\mu_0 - \left(\frac{r}{r_c}\right)\mu = 0\,. \tag{16}$$

In equation (15) N_0 is defined as

$$N_0 = \frac{\dot{M}_{\mathrm{ac}}}{4\pi\mu_H}(GM_* r_c^3)^{-0.5}\left(\frac{r_*}{r_c}\right)^{-1.5}, \tag{17}$$

with $\mu_H = 1.67 \times 10^{-24}$ g.

As before, the envelope surrounds a star/disk system whose parameters are those of § 2 and $r_c = r_{\mathrm{out}} = 100$ AU.

The calculations show that in these models $T_{\mathrm{sc}} \propto r_D^{-0.25}$ and the disk spectrum has a pronounced double-humped structure, typical of disks surrounded by envelopes with very flat density distributions. Figure 7 shows the disk spectral energy distribution for a model with $\dot{M}_{\mathrm{ac}} = 2 \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$, $L_{\mathrm{sc}} = 0.12\ L_\odot$. By increasing $\dot{M}_{\mathrm{ac}}$, we can enhance the far-infrared peak, but we cannot obtain flat spectral energy distributions over the 10–100 μm wavelength interval.

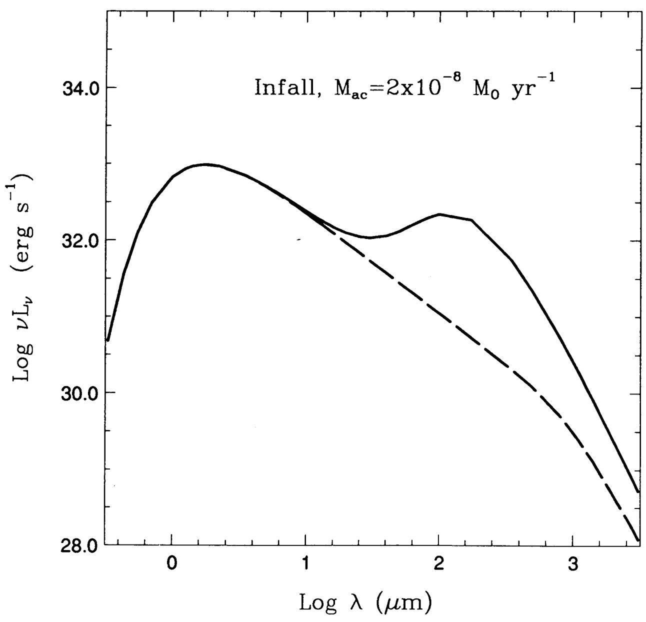

FIG. 7.—Disk spectral energy distribution for an infall model with $M_{\mathrm{ac}} = 2 \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$. The corresponding value of L_{sc} is $0.12\ L_\odot$

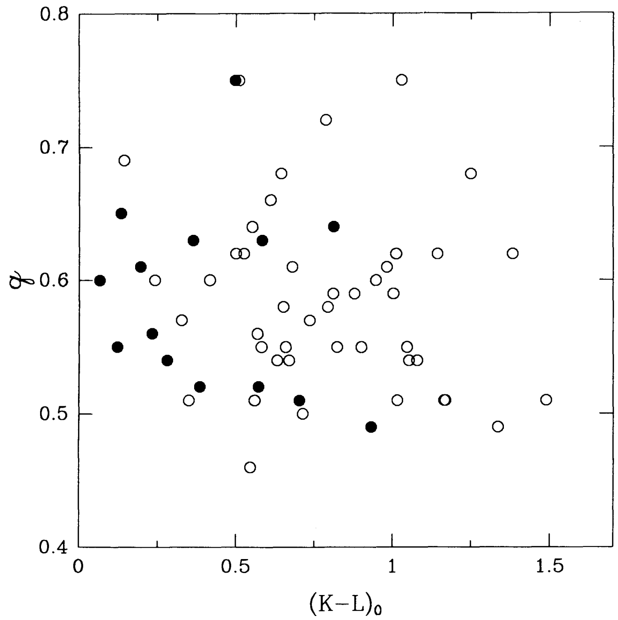

FIG. 8.—Index q, which describes the disk temperature profile, is plotted as a function of the intrinsic color index $(K-L)_0$. The values of q are from Beckwith et al. (1990); K − L are from Cohen & Kuhi (1979), Strom et al. (1989), Hartmann & Kenyon (1990). K − L have been corrected for extinction, using the A_V-values determined by Strom et al. (1989) and standard interstellar extinction curve. Open dots are CTTS, solid dots are WTTS (Strom et al. 1989).

5. CONCLUSIONS

We propose in this paper that TTS are three-component systems, formed by a star, its circumstellar disk and a tenuous ($\tau \ll 1$) envelope of dust. The effect of the envelope is to absorb and scatter part of the stellar radiation back onto the disk, so that the disk luminosity can exceed the value due to direct stellar heating by an amount proportional to the envelope optical depth. The heating due to the scattered light dominates in the outer parts of the disk, so that the resulting temperature profile, and therefore the disk spectral energy distribution, may be much flatter than if only direct heating is considered. Since the overall behavior of $T(r_D)$ is very sensitive to the two parameters α and τ, which describe the density and the optical depth in the envelope, small variations in the properties of the envelope can produce quite different spectral shapes, which will vary from object to object. The whole observed range of the spectral index n (from 4/3 to 0) can be accounted for by models with $N \propto r^{-1}$ and different values of τ. In particular, "flat" spectra in the range 5–100 μm, as observed in several TTS, are easily obtained for $\tau = 0.2$–0.4.

An interesting property of the three-component models is their capability to explain the lack of correlation between the near-infrared colors and the slope of the spectrum at longer wavelengths (see Fig. 8; see also André 1991). In fact, the near-infrared part of the spectral energy distribution is dominated by the emission of the inner disk, heated by direct stellar radiation; the near-infrared colors, therefore, do not depend on the envelope parameters, but only on the stellar colors and on the viewing angle. However, once these are fixed, it is possible to obtain different spectral slopes at longer wavelengths, and cover the whole range of measured values of the index q [$q = 2/(4-n)$; see Beckwith et al. 1990] by changing the envelope properties. Table 1 gives the near-infrared colors and the value of q inferred from the 10/100 μm ratio for various models. The maximum value of the intrinsic K-L index, $(K-L)_0$, is of the order of ~ 1.2. The few TTS in Figure 8 with larger values of $(K-L)_0$ can be objects where the disk does not extend to the stellar surface, but has either a physical or an opacity gap (see also Beckwith et al. 1990; Lada & Adams 1992). Table 1 shows that values of $(K-L)_0$ as large as 1.8 can be obtained in models where the disk is clear at $r_0 = 2.5r_*$.

TABLE 1

INFRARED COLORS

Model	H − K	K − L	q
Star ($T_* = 4500$ K)	0.21	0.16	...
Disk (direct heating only)	0.8	1.1	0.75
Disk ($\alpha = 1.0, \tau = 0.05, r_0 = 1$)	0.8	1.1	0.63
Disk ($\alpha = 1.0, \tau = 0.2, r_0 = 1$)	0.8	1.1	0.56
Disk ($\alpha = 1.0, \tau = 0.4, r_0 = 1$)	0.8	1.1	0.52
Disk ($\alpha = 1.0, \tau = 0.2, r_0 = 1.5$)	1.0	1.4	0.56
Disk ($\alpha = 1.0, \tau = 0.2, r_0 = 2.0$)	1.2	1.6	0.55
Disk ($\alpha = 1.0, \tau = 0.2, r_0 = 2.5$)	1.5	1.8	0.55
Star + disk + envelope ($\alpha = 1.0$, see Fig. 5)	0.6	0.8	0.57
Star + disk + envelope ($\alpha = 1.5$, see Fig. 5)	0.5	0.8	0.66

Two of the objects with large $(K-L)_0$ are the extreme flat spectrum stars HL Tau and DG Tau. In these stars, the disk luminosity appears to dominate over the stellar luminosity at all wavelengths; the model proposed in this paper, which assumes that the only source of energy is the central star, cannot be applied to them. However, based on the results of this paper, we feel that it might be worth it to reconsider the whole issue of TTS accretion, by investigating the effects of an optically thick envelope of dust on both the stellar and the disk spectrum. In fact, all the extreme TTS are classified as having continuum spectral type and have large (although uncertain) visual extinction. Unfortunately, the single scattering approximation used here does not allow a simple extension of the results to larger optical depths. Monte Carlo codes developed to study the polarization properties of the environment of young stellar objects (Whitney & Hartmann 1992; see also Bastien 1991) could be easily modified to include the calculation of the disk heating in a more correct way than we can do.

Is there any physical model for the origin of these envelopes? We have examined stellar and disk hydromagnetic winds as well as models of infall. Disk winds seem able to reproduce the observed TTS spectral energy distributions. Stellar winds have density profiles which are too steep ($\alpha \gtrsim 2$), while, in the collapse of a slowly rotating cloud, too much matter is concentrated at large radii over the plane of the disk, and the resulting disk temperature profile is too flat. In disk wind models such as those proposed by Pelletier & Pudritz (1991), on the contrary, it seems possible to obtain the required balance between the heating of the inner parts of the disk, dominated by direct stellar light and/or by conversion of the accretion luminosity, and that of the outer parts, due to stellar photons scattered by dust in the wind. Infall models, however, deserve further consideration on two grounds. First of all, the single scattering approximation used in our calculations is probaably inadequate to describe the innermost region of the infall, where, at least for some directions, the optical depth is larger than unity. Secondly, several cases of double-peaked spectral energy distributions can be found among Herbig Ae/Be type I stars (Hillenbrand et al. 1992); if our infall calculations will be confirmed, they could provide a very convincing sample of accreting pre–main-sequence stars.

The results presented in this paper have been developed for the particularly simple case of optically visible TTS. However, all the considerations apply also to more obscured pre–main-sequence objects, Herbig Ae/Be stars, and embedded CO outflow sources, such as L1551. In all cases, the disk properties can be heavily affected by the presence of surrounding matter, which should therefore be taken into account in deriving the disk properties from the observations.

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