RevMexAA (Serie de Conferencias), **1**, 209-215 (1995)

THE EFFECT OF THE ENVIRONMENT ON THE TEMPERATURE PROFILE OF CIRCUMSTELLAR DISKS

Antonella Natta
Osservatorio di Arcetri, Largo Fermi 5, 50125, Firenze, Italy

RESUMEN

Los discos alrededor de estrellas jóvenes forman parte de sistemas complejos que incluyen a la estrella, al propio disco y a cierta cantidad de materia circunestelar situada tanto por encima como por debajo del plano del disco. La cantidad de esta materia es muy grande en objetos jóvenes muy oscurecidos, y no tan grande, pero no despreciable, en estrellas T Tauri visibles en el óptico. En este trabajo se revisa la influencia de esa materia circunestelar en las propiedades de los discos, como son el perfil de temperatura y la distribución espectral de energía resultante, tanto para estrellas T Tauri como para los objetos jóvenes muy oscurecidos.

ABSTRACT

Disks around young stars are part of complex systems, which include the star, the disk itself, and a certain amount of circumstellar matter, above and below the disk plane. The amount of this matter is very large in embedded young stellar objects, much smaller, but not alltogether negligible, in optically visible T Tauri stars. This talk reviews the effect of circumstellar matter on the disk properties, namely the temperature profile and the resulting spectral energy distribution, both for T Tauri stars and for embedded objects.

Key words: **STARS: CIRCUMSTELLAR MATTER — ISM: DUST, EXTINCTION — STARS: PRE-MAIN-SEQUENCE**

1. INTRODUCTION

Most studies of the temperature profile of circumstellar disks of T Tauri stars (TTS) and of their spectral energy distribution (SED) have considered the star+disk system to be isolated in vacuum (see, for example, Adams, Lada, & Shu 1987, 1988; Beckwith et al. 1990; Thamm, Steinacker, & Henning 1994). In this case, the temperature of both *passive* or *reprocessing* disks (i.e., disks heated by the intercepted stellar radiation only; Adams & Shu 1986) and *active* or *accretion* disks (i.e., disks where accretion energy is transformed into heat by viscous dissipation; Lynden-Bell & Pringle 1974) should have the approximate form $T \propto R^{-3/4}$, where R is the distance from the star. As a consequence, the shape of the SED should be the same for all stars, at least at wavelengths longer than few microns, where the stellar contribution is negligible. This prediction is at odds with the observed wide variety of spectral shapes. In particular, the large majority of TTS have SED which are flatter than model predictions, as if the outer parts of the disk were always warmer than expected from a $T \propto R^{-3/4}$ law (Adams et al. 1988; Beckwith et al. 1990; Osterloh & Beckwith 1994). Suggestions for producing flatter temperature profiles have included strongly flared disks (Kenyon & Hartmann 1987), non-viscous mechanisms for mass and momentum transport (Adams et al. 1988), and eccentric gravitational instabilities (Adams, Ruden, & Shu 1989).

All this work however has neglected the effect that circumstellar dust, located above and below the plane of the disk, may have on the temperature profile of the disk itself. There is growing observational evidence for the existence of significant amount of dust in the immediate environment not only of embedded objects, but also of TTS; indeed, winds, residual infalling matter, disk evaporation are likely to bring dust into the vicinity of the central star+disk system (Terebey, Shu, & Cassen 1984; Safier 1993).

This talk reviews the results of calculations in which a dusty envelope is added to the star+disk system. The result is in all cases a net heating of the outer parts of the disk above the $T \propto R^{-3/4}$ predictions. The resulting temperature profile depends not on the intrinsic properties of the disk, but on the amount and distribution of the dust in its surroundings, so that the surprising variety of spectral shapes observed in the disks of young stellar objects reflects, in fact, variations of their environment. I will discuss first the case of TTS, where the amount of dust in the immediate environment of the disk must be small ($A_V \ll 1$). Both *passive* and *accretion* disks will be considered. I will then briefly discuss the case of embedded objects, where the circumstellar disk is enclosed by a very thick shell of dust. Some of the results presented here have been published elsewhere in greater detail (Natta 1993; Butner, Natta, & Evans 1994).

2. T TAURI STARS

2.1. Passive Disks

Let us consider the simplest case of a star+disk system embedded in a tenuous spherical envelope of particles which scatter the stellar radiation. The envelope has radial optical depth τ ; the spatial distribution of the scatterers is a power-law function of the distance from the star with exponent α. The effect of the envelope is to deflect onto the disk plane a fraction $\sim tau/2$ of the stellar radiation not directly intercepted by the disk (assuming spherically isotropic scattering). The heating rate for a point on the disk surface at distance R from the star is approximately $H_{sc} \sim R^{-(1+\alpha)}$. Near the star, the heating due to directly intercepted stellar light dominates and $T \propto R^{-3/4}$; at larger distances, the heating due to scattered stellar light prevails, $T \propto R^{-(1+\alpha)/4}$ and the decrease of T with R can be rather slow, depending on the value of α. The temperature at which the slope of $T(R)$ changes depends on τ and α. For α=1, it is T_{cross}=375 K for τ=0.4, 210 K for τ=0.2, 85 K for τ=0.05, respectively.

The resulting SEDs are all markedly flatter than that of a standard passive disk at wavelength longer than 5~10 μm. Their shape depends, as the temperature profile, on the two envelope parameters τ and α; smaller

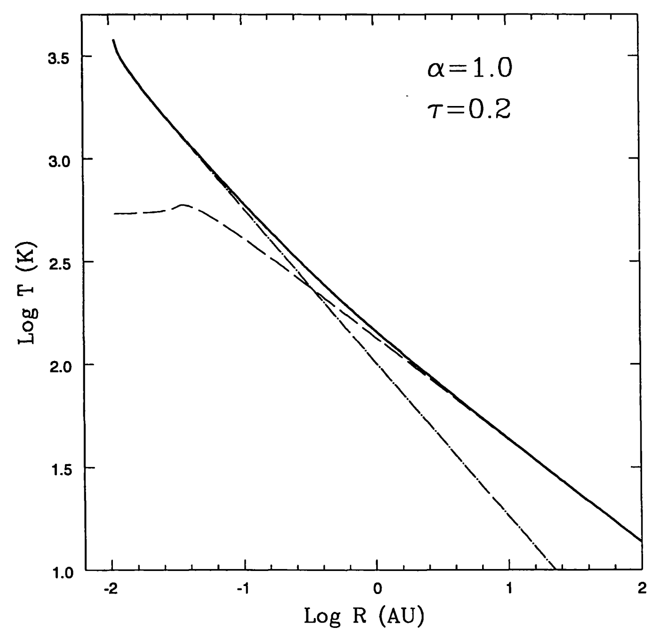

Fig. 1.— Disk temperature as a function of R for a model with α=1, τ=0.2. The star has $L_\star$=2 $L_\odot$, $T_\star$=4500 K, radius $R_\star$=1.6×10^{11} cm; the disk has inner radius R_0=$R_\star$, outer radius R_{out}=100 AU and mass M_D=0.05$M_\odot$; the envelope has an inner radius R_i=3$R_\star$, outer radius R_{env}=1000 AU. The dashed line shows the contribution of the scattered stellar radiation, the dash-dotted line that of stellar radiation directly intercepted by the disk, the solid line the resulting temperature.

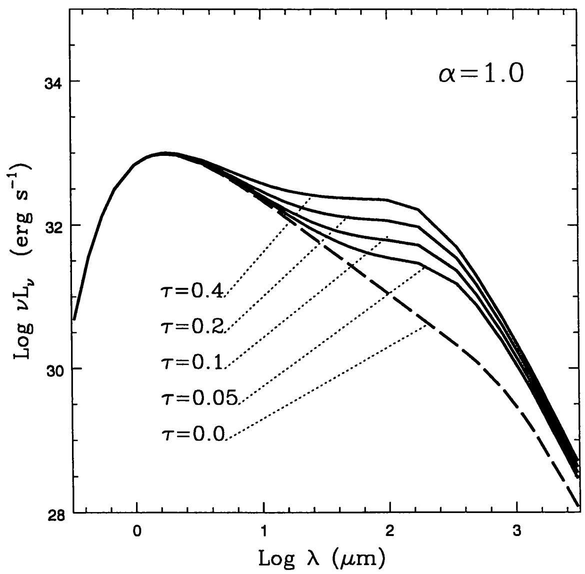

Fig. 2.— Disk SED for models where the envelope has α=1 and different values of τ, as labelled. The other parameters are as in Fig. 1. The dashed line shows the SED of the same disk when there is no envelope, that is when $T \propto R^{-3/4}$.

values of α give origin to flatter SEDs, higher values of τ extend the flatter portion of the SED to shorter wavelengths. In this context, it is important to point out that for values of τ larger than ~0.5, the *thermal* emission of the grains in the envelope will start to contribute significantly to the observed SED, at least in some wavelength interval.

Fig. 1 and 2 shows examples of the temperature profile and SEDs obtained by Natta (1993) using the single scattering approximation and an exact integration of the thermal balance equation. These results have been confirmed by the results obtained by B. Whitney (private communication) with a Monte-Carlo code developed to compute images in scattered light of star+disk+envelope systems (Whitney & Hartmann 1992, 1993), which allowed to extend our investigations to higher optical depth cases, as well as by the elegant analytical approximation illustrated by Cantó, D'Alessio, & Lizano (1995) in these Proceedings.

2.2. Active Disks

The picture we have just outlined does not change much if we consider an accretion disk, instead of a passive one. In this case, T_{cross} depends, in addition to τ and α, also on the ratio of the accretion over the stellar radiative luminosity, L_{acc}/L_{star}. If L_{acc}/L_{star}increases, T_{cross} decreases, i.e., the deviation of the temperature profile from the standard $T \propto R^{-3/4}$ law occurs further out in the disk, and the flattening of the SED at longer wavelengths. As L_{acc}/L_{star}increases further, T_{cross} reaches an asymptotic value, easily understood if we consider that ~1/2 L_{acc} is radiated near the star, either in a boundary layer or in hot spots on the stellar surface caused by accreting columns of gas. This radiation is, in turn, scattered by the envelope onto the disk plane and contributes to its heating roughly as photospheric stellar radiation.

Fig. 3 shows the behaviour of T_{cross} as a function of L_{acc}/L_{star}. The corresponding values of η, defined as the ratio of νF_ν between 10 and 100 μm are also shown, together with the corresponding value of q, the temperature power-law exponent, computed as $q = 2/(4-\log\eta)$. These values of q can, in practice, be compared directly to the q values computed by Beckwith et al. (1990) by fitting TTS SEDs with single power-law $T \propto R^{-q}$. Standard disks have q=0.75, η ~20: one can easily see that the effect of the heating due to scattered light is not negligible also for very large values of L_{acc}/L_{star}.

In summary, both for passive and accretion disks, a small amount of dust located above and below the plane of the disk can have dramatic effects on the disk temperature profiles and on the SED. Small variations of

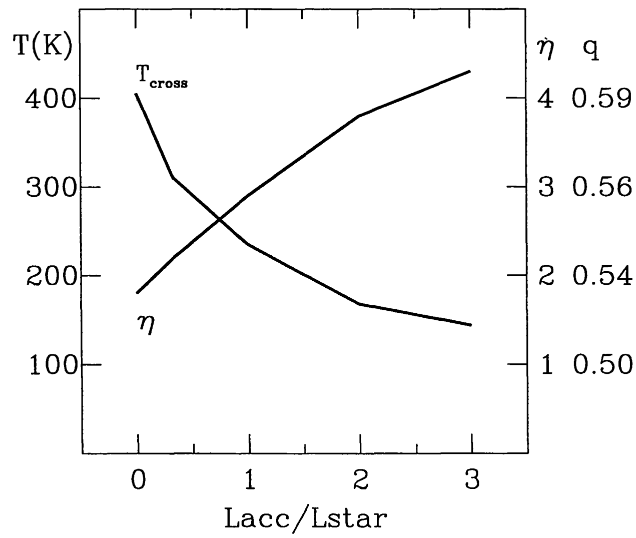

Fig. 3.— The figure plots T_{cross} and $\eta = \nu F_\nu(10\mu m)/\nu F_\nu(100\mu m)$ as a function of the ratio L_{acc}/L_{star}. The scale for T_{cross} is given on the left-hand side of the figure, that for η on the right-hand side, which reports also the corresponding values of q. The results refer to models with the same bolometric luminosity $L_{bol}=L_{acc}+L_\star=2$ $L_\odot$; the disk has $R_0=R_\star$, $R_{out}=80$ AU ; $M_D=0.07M_\odot$; the envelope has $\alpha=1$, $\tau=0.4$, $R_i=2R_\star$, $R_{env}=80$ AU.

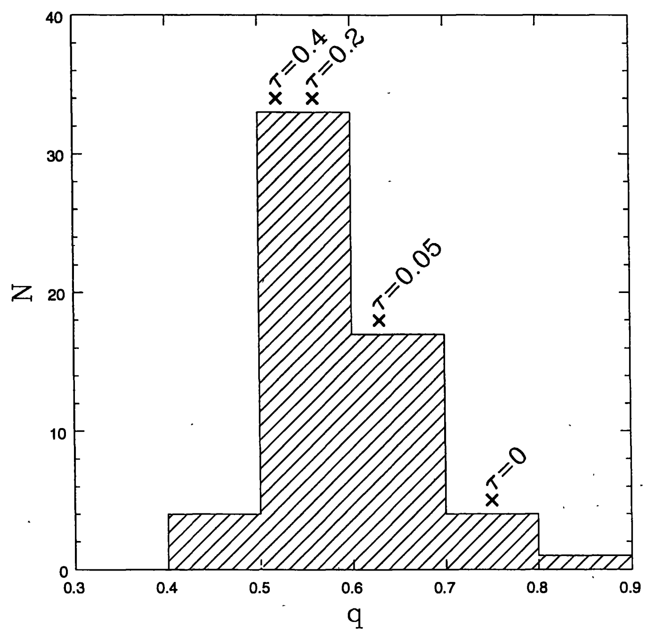

Fig. 4.— Histogram of the values of q for TTS in the Taurus-Auriga cloud. The asterisks indicate the values of q predicted by models with $\alpha=1$ and different values of τ, as labelled. Other model parameters as in Fig. 1

the properties of the dust envelope can well account for the observed range of spectral shapes, as illustrated in Fig. 4, which shows an histogram of the q values derived by Beckwith et al.(1990) for the Taurus-Auriga cloud. I have marked with asterisks the values of q computed from star+disk+envelope models, all having $\alpha=1$ but increasing values of τ. The full observed range is easily encompassed by the models, with the only exception of those few stars with $q \leq 0.5$, for which infalling matter may still have large optical depth in most directions and dominate the observed SED (Calvet et al. 1994).

3. EMBEDDED OBJECTS

The last example of the effects of the environment on the disk properties refers to the case of a very embedded object, which we approximate as a star+disk surrounded by a shell of dust with $A_V \sim 100$ mag. For simplicity, the inner radius of the shell R_i coincides with the outer radius of the disk.

Such a situation cannot be described in a self-consistent way with any of the radiation transfer code currently available. However, one may make an estimate of the results by considering, as pointed out by Keene & Masson (1990) in their work on L1551 that, if the shell was effectively a black-body at temperature T_{shell}, then the disk could not be cooler than T_{shell}. In real cases, T_{shell} will be much lower than the dust temperature at the inner edge of the shell, as assumed by Keene and Masson. We have tried to estimate it by using a

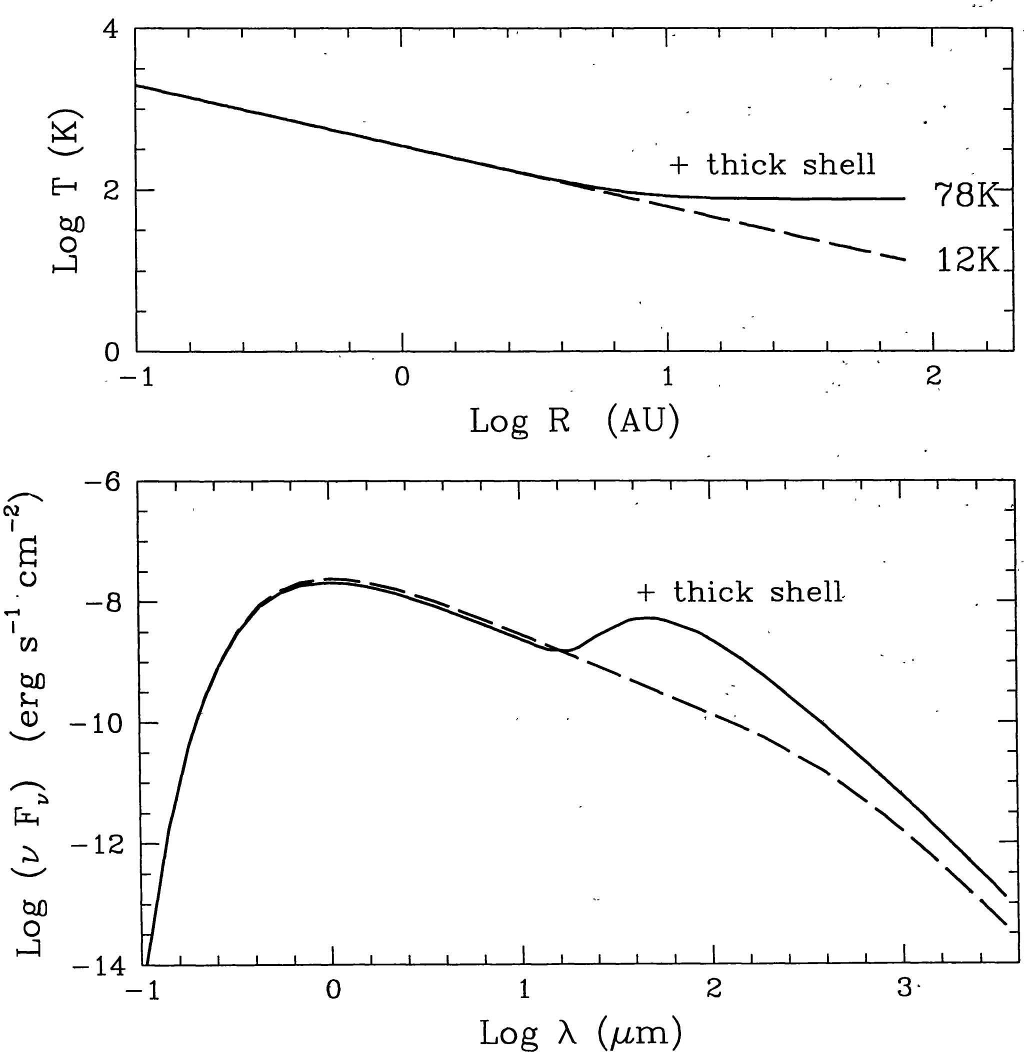

Fig. 5.— The top panel shows the temperature profile and the lower panel the disk SED when the effect of the thick dust shell surrounding the disk is considered (solid line), and when it is not (dashed line). In both cases it is L_{bol}=30 $L_\odot$, L_{acc}=20$L_\odot$; the disk has R_0=0.03AU, R_{out}=80 AU , M_D=0.07$M_\odot$; the shell has α=1.5, R_i=80 AU, A_V=110 mag.

radiation transfer code which calculates the spectrum of the radiation emitted by the shell in the direction of the central star (and of the disk), F_ν^{in}. We then compute an effective temperature T_{shell} as:

$$T^4_{shell} = \frac{1}{\sigma 4\pi R_i^2} \int F_\nu^{in} d\nu \tag{1}$$

where σ is the Stefan-Boltzmann constant. The disk heating rate at a given distance R from the star is then given by the expression:

$$H = H_{star} + H_{visc} + H_{shell} \tag{2}$$

where $H_{shell}=\sigma T^4_{shell}$.

Since in its turn the disk contributes to the heating of the shell, the bolometric luminosity of the system is conserved by using a simple iteration scheme. The procedure is described in more details in Butner et al. (1994) and Natta & Butner (1995).

The results of this procedure are shown for a specific case, whose parameters are specified in the figure caption, in Fig. 5, which plots in the top panel the disk temperature profile and in the lower panel the disk SED. However, one should not be deceived by the plots of Fig. 5. It is important to remember that in the case of embedded objects, the observed SED is dominated by the shell emission, and the effects of the shell on the disk temperature profile can only be appreciated when millimeter wavelengths measurements with interferometric spatial resolution are available. Only in this case is the disk emission directly measurable. Compared to the predictions of models where the effect of the shell is ignored, Fig. 5 shows that the disk emits more flux (for fixed L_{bol}). In fact, its behaviour at long wavelengths is very similar to that of a disk with the same L_{bol} and an anomalous temperature profile $T \propto R^{-0.5}$.

4. CONCLUSIONS

Disks around young stars are part of complex systems, which include the star, the disk itself, and a certain amount of circumstellar matter, above and below the disk plane. This circumstellar dust affects deeply the temperature profile of the disk by making its outer parts hotter than the standard $T \propto R^{-3/4}$ relation predicts. As a consequence, the disk spectral energy distribution is also altered, in the sense that it is flatter than in the standard case.

This talk reviews results concerning TTS, where the amount of circumstellar dust is likely to be very small. The results of model calculations for both passive disks and accretion disks show that even envelopes of low optical depth (τ <0.2∼0.4) have a significant effect on the SEDs. In particular, it is possible to account for the observed great variety of spectral shapes by changing not the disk physics but the properties of their environment. In other words, all TTS disks could look the same, if we were to see them *naked*!

The situation is similar for embedded objects. The effect of a thick shell of dust surrounding the star+disk system is, as in the TTS case, of heating the disk outer parts significantly above the temperature predicted by standard disk models. In embedded objects, the disk SED is accessible only to millimetric observations with very high spatial resolution. It is important for a quantitative interpretation of such observations to note that, in these systems, the ratio of the millimeter disk flux to L_{bol} can be much higher than predicted by standard models.

REFERENCES

Adams, F. C., & Shu, F. H. 1986, ApJ, 308, 836
Adams, F. C., Lada, C. J., & Shu, F. H. 1987, ApJ, 213, 788
Adams, F. C., Lada, C. J., & Shu, F. H. 1988, ApJ, 326, 865
Adams, F. C., Ruden, S. P., & Shu, F. H. 1989, ApJ, 347, 959
Beckwith, S., Sargent, A. I., Chini, R. S., & Güsten, R. 1990, AJ, 99, 924
Butner, H. M., Natta, A., & Evans, N. J. II 1994, ApJ, 420, 326
Calvet, N., Hartmann, L. Kenyon, S. J., & Whitney, B. A. 1994, ApJ, 434, 330
Cantó, J., D'Alessio, P., & Lizano, S. 1995, in Disks, Outflows and Star Formation, ed. S. Lizano & J. M. Torrelles, RevMexAASC, 1, 217
Keene, J., & Masson, C. R. 1990, ApJ, 355, 635
Kenyon, S. J., & Hartmann, L. 1987, ApJ, 323, 714
Lynden-Bell, D., & Pringle, J. E. 1974, MNRAS, 168, 603

Natta, A. 1993, ApJ, 412, 761
Natta, A., & Butner, H. M. 1995, in preparation
Osterloh, M., & Beckwith, S. V. W. 1995, ApJ, in press
Safier, P. 1993, ApJ, 408, 115
Terebey, S., Shu, F. H., & Cassen, P. 1984, ApJ, 286, 529
Thamm, E., Steinacker, J., & Henning, T. 1994, AA, 287, 493
Whitney, B. A., & Hartmann, L. 1992, ApJ, 395, 529
Whitney, B. A., & Hartmann, L. 1993, ApJ, 402, 605