T TAUER DISK MODEL:
CONFIDENCE LEVELS FOR PARAMETER
ESTIMATION

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Annibal Hetem Jr.
ICET / UNIP (BRASIL)
annibal.hetem.jr@usa.net

Jane Gregorio-Hetem
IAG / USP (BRASIL)
jane@astro.iag.usp.br

Abstract  A simple model to explain the circumstellar structure of T Tauri stars (TTS) by a $\chi^2$ fitting of the observed Spectral Energy Distribution (SED) has been used by us to evaluate the disk and/or envelope contribution to the total luminosity of the system. The assumed structure considers two dust components and the main fitting parameters are: disk and envelope radius, optical depth and angle of view. The method was applied to a selected sample of TTS recently studied by us (Gregorio-Hetem & Hetem 2002). The present work contains a more detailed description of the method to estimate the permissible range of parameters by considering volumes of confidence levels. The $\chi^2$ values are mapped in a projection of the parameter space and the confidence levels are identified. Some results of calculating and plotting out such confidence limits are presented. The main conclusion of this study is that the problem of multiple solutions in the SED fit can be solved by a statistical treatment of the parameter sets and verifying the discrepancies among them when compared with a common solution.
1 Introduction

We have built a model to fit the spectral energy distribution (SED) of young stellar objects (YSOs) in order to reproduce their observed infrared excess and to evaluate the effect in terms of energy contribution in the total emitted flux due the presence of a dust disk and/or an envelope in the circumstellar structure. In our model we assume a system composed by a central star orbited by an optically thick and geometrically thin passive disk, and a spherically symmetric dust envelope around both. For the numerical simulations it is considered the blackbody radiation from each component of the system with different temperature distribution: $T(r) \propto r^{-0.75}$ in the disk, and $T(r) \propto r^{-0.4}$ in the envelope. The best SED fit is obtained by a parameter estimation method based on maximum likelihood statistics and $\chi^2$ tests for the goodness-of-fit.

With this simple model we successfully fitted the SED of 27 IRAS sources showing characteristics of YSOs detected in a survey for T Tauri stars (TTS) in particular for those previously classified as weak-TT (WTT). By evaluating the circumstellar contribution in the total luminosity, the objects were distinguished in different categories of young stars in agreement with an evolutionary sequence. The resulting classification was confirmed by its correlation with other characteristics of the stars as spectral type and intensity of the $H\alpha$ line. We conclude that the assumed system, in which the circumstellar dust is distributed in two different structures (disk and envelope), is a good approximation in fitting with a simple model the SED of YSOs presenting typical IRAS colors of WTTs. In this work we give more details on the discussion of the confidence level for parameter estimation, as proposed by Thamm et al. (1994), which was used in our study of the WTTs sample (Gregorio-Hetem & Hetem 2002).

2 The Model

The contribution of the circumstellar dust in the emitted radiation of young stellar systems is mainly evaluated by means of the infrared excess observed in these objects. The different hypothesis to explain the configuration of the dust distribution around the YSOs, in particular the less massive as the TTS, have conducted two basic lines in building models for the circumstellar structure. In one of them it is assumed that a spherical dust envelope surrounds the central object, and in the other one it is considered the presence of a disk orbiting the star. In principle an envelope or a disk may produce the infrared excess, and the option for one or other model will depend on the evolutionary status of different objects.

A scheme of the adopted circumstellar structure is displayed in Figure 1, showing the central star surrounded by an extended and flat disk and both are enveloped by a thin dust shell. The inner radius of the disk is constrained by an adopted grain destruction temperature and the outer disk radius defines the inner radius of the envelope. The observed data cover the wavelength range of 0.3 - 100 µm (only PDS039 has 1300 mm emission measured by Henning et al. 1993) and the method finds the best fit by varying the following parameters: radius $R_s$ of the star, radius $R_d$ and inclination angle $\theta$ of the disk and radius $R_e$ and optical depth $\tau_\lambda$ of the envelope. The stellar temperature $T_s$, is not a free parameter and could be estimated from the calibration between spectral type and effective
temperature \((T_{\text{eff}})\) proposed by de Jager and Nieuwenhuijzen (1987) for main sequence stars.

The emission from the star and from the disk is attenuated by the opacity of the envelope and the contribution in luminosity of the disk depends on the inclination angle of the system. The flux is calculated by assuming a blackbody emission and different temperature laws for the disk and the envelope.

The total radiation emitted, as a function of wavelength \(\lambda\) will depend on the contributions of each component of the system and can be described by

\[
S(\lambda) = S_s(\lambda) + S_d(\lambda) + S_e(\lambda).
\]

The observed data cover the wavelength range of 0.3-1300 \(\mu\)m and the method searches the best fit by varying the parameters: temperature \(T_s\) and radius \(R_s\) of the star, radius \(R_d\) and inclination angle \(\theta\) of the disk, and radius \(R_e\) and optical thickness \(\tau\) of the envelope. The following sub-sections are dedicated to describe separately the radiation of each component of the system, and the parameter estimation method.

![Model diagram, showing the main geometrical parameters.](image)
2.1 The opacity law

The opacity caused by the grains in the envelope is evaluated as function of its distribution of density, assumed here as $\rho(r) \propto r^{-1.5}$. We estimate the absorption due to the envelope being proportional to its optical thickness, described by: $\tau_\lambda \propto \tau_{\text{lim}} C_{\text{abs}}(\lambda) \rho(r)$, where $\tau_{\text{lim}}$ is one of the model's parameters.

We have adopted the extinction law $C_{\text{abs}}(\lambda)$ obtained by Ossenkopf (1993) from an evolutive model for fluffy aggregates. Among the models proposed by Ossenkopf, we choose the $C_{\text{abs}}(\lambda)$ given by the calculations where the grains evolved during $10^5$ yrs in a medium with $10^5 < n_H < 10^8 \text{ cm}^{-3}$ and $T < 20\text{K}$. The results given by this opacity law are in agreement with those obtained in other works as by Rowan-Robinson (1986) and by Desert, Boulanger & Puget (1990).

When the visual extinction is available, we estimate the optical depth by using the simplified relations between emitted radiation $I_0^0(\lambda)$ and the observed radiation $I_\lambda$ affected by the opacity of a dust cloud, that could be expressed by: $\exp(-\tau_\lambda) = I_\lambda/I_0^0(\lambda)$ and $A_\lambda = -2.5 \log(I_\lambda/I_0^0(\lambda))$. By this way the relation between $\tau_{\text{lim}}$ and $A_V$ can be obtained, and this will decrease the number of free parameters in the fit.

2.2 The contribution of the central star

The star is considered here as a spherical blackbody emitter and the expression for the flux density is given by:

$$S_\lambda(T_s) = \frac{\pi}{d^2} R_s^2 B(\lambda, T_s) e^{-\tau_\lambda}$$

(2)

Several stars of our sample have known spectral type (S.T.), which could be compared with the parameter $T_s$ obtained in the fit, by using the relations between $T_{\text{eff}}$ and S.T. given by Cohen & Kuhi (1979) for young stars.

2.3 The disk contribution

The total thermal radiation of the disk is evaluated by assuming it is composed by several rings emitting each one as a different blackbody with a temperature law from Adams & Shu (1986)

$$T_d = T_s \left(\frac{R_d}{R_s}\right)^{3/4}$$

(3)

It is assumed a holled disk with inner radius defined by: $R_h = R_s (T_g/T_s)^{4/3}$, where we used $T_g = 1500\text{K}$ as the destruction temperature of the grains. The angle of seen $\theta$ represents the amount of energy detected by the observer, being maximized when the system is seen "face-on". As in the case of the star the disk emission is attenuated by the opacity of the envelope and its contribution for the total emitted flux is obtained by integrating the individuals parcels of each ring of the disk, given by:

$$\frac{\delta S_d(\lambda)}{\delta r_d} = \frac{\pi}{d^2} B(\lambda, T_d) r_d e^{-\tau(\lambda)} \cos \theta$$

(4)

In this calculation, the ring radius $r_d$ varies between $R_h$ and $R_g$. 

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2.4 The emission from the dust envelope

Our numerical simulations are based in the radiative transfer model used by Epchtein, Le Bertre & Lépine (1990) to reproduce the infrared data of carbon stars. In their model it is assumed that an spherically symmetric dust envelope surrounds the star with inner radius defined by the energy balance in the dust grains. The envelope is divided in concentric layers, or spherical shells. Each individual shell emits as a blackbody following the temperature law

$$T_e = T_s \left( \frac{2r_e}{R_s} \right)^{-0.4} \tag{5}$$

This temperature distribution is in agreement with the classical models to reproduce the emission of a spherically symmetric distribution of dust, illuminated by a star at the center, which sits in a spherical dust-free cavity (Rowan-Robinson 1980). In our model the circumstellar disk is placed in this cavity and we assume the inner radius of the envelope being coincident with the outer radius of the disk.

The optical depth is evaluated for each shell of the envelope, following the opacity law and the density, as described in Section 3.1. The emission of each shell depends on its own optical depth $\tau(\lambda)$ and also on the absorption of the remaining shells $\tau_{\text{ext}}(\lambda)$. In these cases, the optical depth are estimated in function of the shell radius $r_e$ that varies between $R_d$ and $R_e$. The total flux emitted by the envelope is obtained by integration of the individual contributions:

$$\frac{\delta S_e(\lambda)}{\delta r_e} = \frac{2\pi}{d^2} B(\lambda, T_e) r_e e^{-\tau(\lambda)} \left( 1 - e^{-\tau_{\text{ext}}(\lambda)} \right) \tag{6}$$

3 The Parameter Estimation Method

We used the maximum likelihood statistics in order to perform the n-parameter estimation. The goodness-of-fit function is given by the traditional $\chi^2$ statistic defined by

$$\chi^2(a) = \sum_{j=1}^{N} \left[ \frac{q_j - q(a)}{\sigma_j} \right]^2 \tag{7}$$

where $a$ is the parameter vector in the n-dimensional space, $q_j$ is one of the $N$ observed values, and $\sigma_j$ is the error in the data value $j$. The function $q(a)$ gives the value expected by the model when its parameters are components of $a$. The method supposes that there is an $a_0$ that minimizes $\chi^2$ and its components are the best choice one can find for the parameters.

The described model drives to a non-linear least squares calculation that can be solved using a general unconstrained optimization method. The method searches for a minimum in the goodness-of-fit, that can be done by supplementing a Gauss-Newton algorithm with a univariate search for the updated parameter vector. An advantage of this method is that reliable parameter error estimates are available automatically.
In the neighbors of \( a_0 \) one can take the first terms of the expansion of \( \chi^2(a) \) as a Taylor series

\[
\chi^2(a + \Delta a) \approx \chi^2(a) + D \cdot a + \frac{1}{2} a^T \cdot H \cdot a
\]

where \( D \) is the gradient of \( \chi^2(a) \) in the parameter space and \( H \) is the two dimension matrix with the second derivatives, also called "Hessian matrix", and \( a^T \) is the transpose of the \( a \) matrix. Formal expressions for \( D \) and \( H \) components are

\[
D_i = \frac{\partial \chi^2}{\partial a_i} = -2 \sum_{p=1}^{N} \left[ g_p - q(a) \right] \frac{\partial q}{\sigma_p^2} \frac{\partial q}{\partial a_i}
\]

and

\[
H_{ij} = \frac{\partial^2 \chi^2}{\partial a_i \partial a_j} = L_{ij} + M_{ij}
\]

where

\[
L_{ij} = -2 \sum_{p=1}^{N} \frac{1}{\sigma_p^2} \frac{\partial q}{\partial a_i} \frac{\partial q}{\partial a_j}
\]

and

\[
M_{ij} = -2 \sum_{p=1}^{N} \frac{1}{\sigma_p^2} \left[ g_p - q(a) \right] \frac{\partial^2 q}{\partial a_i \partial a_j}
\]

By introducing \( A \) and \( B \) such that

\[
A_{ij} = -\frac{1}{2} \frac{\partial^2 \chi^2}{\partial a_i \partial a_j}
\]

and

\[
\begin{align*}
\delta a &= k \times B \\
\sum A_{ij} \delta a_i &= B_j
\end{align*}
\]

and

\[
B_i = -\frac{1}{2} \frac{\partial \chi^2}{\partial a_i}
\]

one can set a step for going from a given \( a_n \) to \( a_{n+1} \) using the expression

\[
a_{n+1} = a_n - k \times \nabla \chi^2(a_n)
\]

where the constant \( k \) is related to \( A \) and \( B \) by eq. (14).

The resulting vector \( \delta a \) is the optimized step for minimizing the goodness-of-fit function. By applying successive steps one can get closer to the best result, \( a_0 \). These expressions are applied following the Levenberg-Marquardt method (Press et al. 1992). At the end of the process one obtains the values for the parameters in \( a_0 \) and the last values in the diagonal of \( H^{-1} \) can be used as estimates for the errors in the parameters.
3.1 Solving the problem of ambiguities

The parameter ambiguities were discussed by Thamm et al. (1994) in their study of dust disk parameterized models of YSOs. Fitting the observed spectral energy distribution for these objects leads to a $\chi^2$-fit problem in a topologically complicated multidimensional parameter space. The same problem was discussed by Bouvier & Bertout (1992), who proposed an automatic method to explore the parameter space with a mixed method that considers a $\chi^2$ minimum finding and gradient searches, based on parabolic expansions near local minima.

The adopted strategy is to fit the parameters in four steps. A first fit is done considering only optical band, which is directly affected by $T_s$, $R_s$, and $\tau$. Then, near-IR band is used to determine the disk parameters. A third fit is made with IRAS and millimetric (when available) bands to determine the last parameter, $R_e$. A final fit is done with all data points for the whole set of initial parameters. This procedure enhances the calculation speed since the code is not “trapped” in unwanted minima of the $\chi^2$ function and reduces the number of free parameters (in each step).

We estimate the quality of our fitting procedure by considering confidence levels for the fit parameters. The dependency of two parameters and their confidence limits is demonstrated for PDS118 as an example. Figure 2 presents the contour levels for the $\chi^2=f(T_s, \tau)$ surface, where confidence levels for 68%, 90% and 99% are indicated. A confidence level in this context means the probability to find a solution with parameter values that fall inside the contour. To build such surface, we calculated a number of fitting procedures, each one with a different starting parameter set, obtained randomly. The results where organized in an histogram in order to calculate the confidence levels. One can see that there is a correlation between $T_s$ and $\tau$, due to the deviation of the main axis of the ellipses from the orthogonal axes.

Figure 2. Confidence levels ellipses for $\chi^2=f(T_s, \tau)$ for PDS118, one of the objects in the studied sample.
Figure 3. Detail of surface $\log(\chi^2)=f(R_s, \tau)$ for PDS035, presenting regions where the $\chi^2$ shows a local minimum. The global minimum is inside the deepest region on the left.

Due to the complexities imposed by the expressions and numerical methods (mainly the integrations along disk and envelope radius) the $\chi^2$ function is mostly non-linear nearest the minima. Figure 3 shows a $\log(\chi^2)=f(R_s, \tau)$ surface obtained for the source PDS035. This surface was built by building a set of points in $R_s$ and $\tau$ space and calculating the value of $\chi^2$. Some regions present a mean minimum, and this value varies from a region to another. The region with the smaller minimum is selected the region that contains the final solution, but the exact value of $a_0$ parameters cannot be found. It is of fundamental importance to consider the physical constraints in order to avoid minimum-regions that are too far from an acceptable solution.

So, the confidence levels are the best one can say about the solutions. The “center” of the regions shown in Figures 2 and 3 give the better solution, and the radius of the ellipses is a good approximation to the error bar around it. Of course, Figures 2 and 3 are two dimension examples and the final results have to take in account a number of dimensions corresponding to the number of free parameters.

4 Results of the fit

The fitting method looks for the parameter set $(R_s, R_d, R_e, \tau, \theta)$ providing a solution for the model equations that reproduces the observational data. Actually, the number of free parameters is reduced since the spectral type and the observed $E(B-V)$ give us the estimation of $T_s$, $R_s$, and $\tau$. The initial values of the other parameters are chosen among those typical of young stars ($R_d =100$ A.U.; $R_e =1000$ A.U.; $\theta=45^\circ$), avoiding unwanted minima and speeding up the code significantly. In order to test the variation in goodness-of-fit (gof) due to possible changes in $T_s$, after obtaining the best fit with $T_{\text{eff}}$, we made the calculations setting the temperature as a free parameter. A maximum deviation of 150K was found and in most of the cases, the temperature obtained with the SED fit is quite the same temperature estimated by using the calibration $T_{\text{eff}}$ vs. spectral type. The optical depth was compared to the values derived from the total visual extinction, by using the color excess $E(B-V)$ and adopting $A_v=3.1$ E$(B-V)$ and $A_\lambda=1.086 \, \tau/\lambda$, with $\lambda$ given in $\mu$m. The results of both comparisons are shown in Figure 4 and Figure 5.
Table 1 presents the results obtained for 27 TTs by Gregorio-Hetem & Hetem (2002) showing their identification, the spectral type, star temperature, $T_s$, star radius, $R_s$, disk radius, $R_d$, envelope radius, $R_e$, estimated optical depth, $\tau$, inclination angle, $\theta$, the goodness of fit, and the indexes $U-B$ and $B-V$. The columns 4 to 9 correspond to the results from the SED fit. The observed spectral type and colour indexes were used in the calculation of the first guess for the parameters $T_s$, $R_s$, and $\tau$.

Figure 6 presents plots of the obtained SED fits showing the observational data and the individual contribution from each component.

5 Conclusions

The automatic fitting method described above looks for the parameters set ($R_s$, $R_d$, $R_e$, $\tau$, $\theta$) providing a solution for the model equations that reproduces the observational data. The results obtained with the described model show that it is not necessary to adopt complicated geometries of sophisticated details to successfully fit the SED of YSOs as we are interested in obtain bolometric luminosities.

In order to avoid the problem of multiple solutions in the SED $\chi^2$-fit, a statistical treatment of the parameter must be considered as proposed by Thamm et al. (1994). Physical and astronomical coherence with the model must play an important role in the process to find the minima in the $\chi^2$ function. A comparison with a common solution is useful in order to verify the discrepancies among the several obtained parameter sets. The present method helps to find the better solution when few observational data points are available.

6 References

Figure 4. The stellar temperature obtained by the method \((T_{\text{fit}})\) compared with the effective temperature, estimated by the relation \(T_{\text{eff}} \times \text{spectral type} \ (T_{\text{teo}})\). The dashed lines indicate the error range of \(\pm 150 \text{ K}\).

Figure 5. The optical depth obtained from the method \((\tau_{\text{fit}})\) compared with the optical depth given by \(E(B-V)\) and the visual extinction \((\tau_{\text{teo}})\). The dashed lines indicate the extinction error range of \(\pm 0.5 \text{ mag}\).
Table 1. The 27 sources from the PDS catalog. Besides PDS and IRAS identification are spectral type, star temperature, $T_s$, star radius, $R_s$ disk radius, $R_d$ envelope radius, $R_e$, estimated optical depth, $\tau$, inclination angle, $\theta$ (in degrees), the goodness of fitting, and the indexes $U-B$ and $B-V$ (from Gregorio-Hetem & Hetem 2002).

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Figure 6a. Curves showing individual contribution and total flux for the best fit. Observational data are represented by square symbols. Upper limits are indicated by arrows. The total emitted flux is shown by the gray curve. The red line is used to represent the stellar contribution, green line for the disk contribution and the blue line for the envelope contribution.
Figure 6b. (continued).
Figure 6c. (continued).