Boletim da Sociedade Astronômica Brasileira, **37**, no. 1, 325-326

Circumstellar Emission: Modeling T Tauri Stars

T. D. B. Cotrim[1] & J. Gregorio-Hetem[1]

[1] Instituto de Astronomia, Geofísica e Ciências Atmosféricas da Universidade de São Paulo - IAG/USP
e-mail: `thomaz.dean@usp.br, gregorio-hetem@usp.br`

Abstract. T Tauri stars are low-mass objects ($< 2M_\odot$) in the Pre-Main Sequence phase that often exhibit circumstellar emission due to the presence of dust and gas. Studying this emission through Spectral Energy Distributions (SEDs) is crucial for better understanding the characteristics of these stars, in addition to identifying protoplanetary disks in the early stages of planets formation. This work aims to model the SEDs of T Tauri stars to characterize their circumstellar emission. We implemented a numerical model in Python based on the work of Gregorio-Hetem & Hetem (2002), which considers a system composed by a central star, a disk and a diffuse envelope. We utilized photometric data from 2MASS, PDS, and IRAS catalogs. The results obtained from our code were validated by reproducing synthetic spectra for stars PDS 39, PDS 54 and PDS 70, showing excellent agreement with the literature.

Resumo. Estrelas T Tauri são objetos de baixa massa ($< 2M_\odot$) na Pré-Sequência Principal (PSP) que frequentemente apresentam emissão circunstelar devido à presença de poeira e gás. O estudo dessa emissão através de Distribuições Espectrais de Energia (SEDs) é fundamental para entender melhor as características dessas estrelas, além de identificar discos protoplanetários em seus estágios iniciais da formação de planetas. Este trabalho visa modelar as SEDs de estrelas T Tauri para caracterizar suas estruturas circunstelares. Implementamos um modelo numérico em Python baseado no trabalho de Gregorio-Hetem & Hetem (2002), que considera um sistema composto de uma estrela central, um disco e um envoltório. Utilizamos dados fotométricos dos catálogos 2MASS, PDS e IRAS. Os resultados obtidos pelo nosso código foram validados reproduzindo espectros sintéticos para as estrelas PDS 39, PDS 54 e PDS 70, mostrando excelente concordância com a literatura.

Keywords. Stars: formation – Estrelas: formação – Stars: pre-main sequence

1. Introduction

The study of Pre-Main Sequence (PMS) stars is essential to understand the physical processes that lead to the formation of circumstellar structure, such as planetary systems. Among these objects, T Tauri stars stand out as low-mass targets ($< 2M_\odot$). A defining characteristic of these stars is the presence of circumstellar material, often in the form of protoplanetary disks, such as the well known system PDS 70 (see Figure 1), which hosts forming planets.

The dust in these structures absorbs the stellar radiation and re-emits it at longer wavelengths, creating an excess of infrared emission. This emission distinguishes the SED of a disk-bearing star from photospheric emission (see Figure 2). Therefore, analyzing the SED allows us to infer the geometry and physical properties of the circumstellar environment. In this work, we present the implementation and validation of a Python-based tool designed to model these SEDs the contributions of the star, the disk, and the envelope.

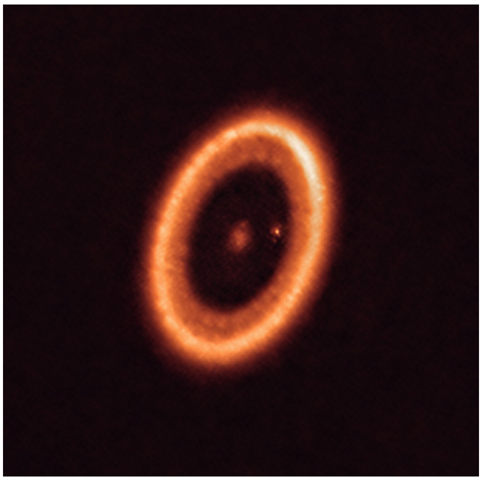

Figure 1. PDS 70 system observed by ALMA, showing the protoplanetary disk structure (ESO, Benisty et al., 2021).

2. The Model and Methodology

To reproduce the observed SEDs, we adopted the model described by Gregorio-Hetem & Hetem (2002). The physical system is conceptualized as a central star surrounded by a diffuse dust envelope, with a geometrically thin and optically thick disk located between them (see Figure 3).

The total flux of the system $S(\lambda)$ is calculated as the sum of the individual contributions:

$$S(\lambda) = S_S(\lambda) + S_d(\lambda) + S_e(\lambda) \tag{1}$$

We implemented the radiative transfer model in Python, calculating the contribution of each component separately. For the central star, the flux is modeled as a blackbody $B(\lambda, T_\mathrm{S})$, defined by the temperature T_S and radius R_S, the distance d, and attenuated by the optical depth $\tau(\lambda)$:

$$S_S(\lambda) = \frac{R_S^2}{d^2}\pi B(\lambda, T_S)e^{-\tau(\lambda)} \tag{2}$$

The disk contribution is integrated over its radius r_{d_i}, considering the temperature profile T_{d_i} and inclination angle θ:

The disk contribution is calculated by summing the emission of several rings with mean radius r_{d_i} and width δr_{d_i}, taking into account the temperature profile T_{d_i} and the inclination angle θ:

$$S_{d_i}(\lambda) = \frac{2r_{d_i}\delta r_{d_i}}{d^2}\pi B(\lambda, T_{d_i})e^{-\tau(\lambda)}\cos\theta \tag{3}$$

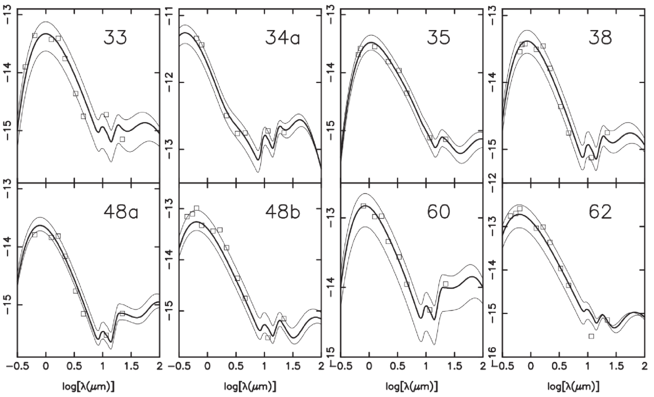

Figure 2. SED of PMS stars. Figure adapted from Fernandes et al., 2015. The points represent the observed data, and the solid line shows the model fit.

For the envelope, we consider the dust re-emission from spherical shells at radius r_{e_i}, given the temperature profile T_{e_i}:

$$S_{e_i}(\lambda) = \frac{r_{e_i}^2}{d^2}\pi B(\lambda, T_{e_i}) e^{-\tau_i(\lambda)} \left[1 - e^{-\tau_{\mathrm{ext}_i}(\lambda)}\right] \tag{4}$$

We used the opacity distribution provided by Ossenkopf (1993) to estimate the optical depth values used in the model and considers the distance d as well.

To validate the code, we utilized photometric data from 2MASS, PDS, and IRAS catalogs. The flux measurements were converted from magnitudes to absolute fluxes (W/m^2) using zero-magnitude fluxes from the Cousins system (Landolt-Börnstein, 1982).

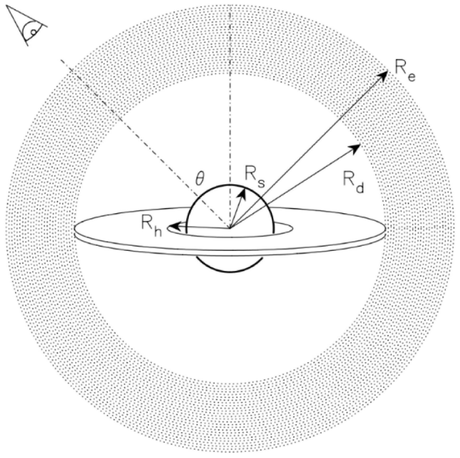

Figure 3. Schematic representation of the model. Components are not to scale. Figure adapted from Gregorio-Hetem & Hetem (2002).

3. Results

The main goal of this work was to validate our Python implementation by reproducing results from the literature. We modeled the SEDs of three well-known T Tauri stars: PDS 39, PDS 54, and PDS 70.

As shown in Figure 4, the synthetic spectra generated by our code (right panels) show a good agreement with the spectra presented in Gregorio-Hetem & Hetem (2002) (left panels). The code successfully separated the contributions: the stellar photosphere dominates the optical/near-infrared, while the disk and envelope dominate the mid and far-infrared.

This agreement confirms that our Python implementation of the physical equations is correct and capable of estimating parameters for these systems. The use of Ossenkopf's opacity tables also proved successful in modeling the dust behavior.

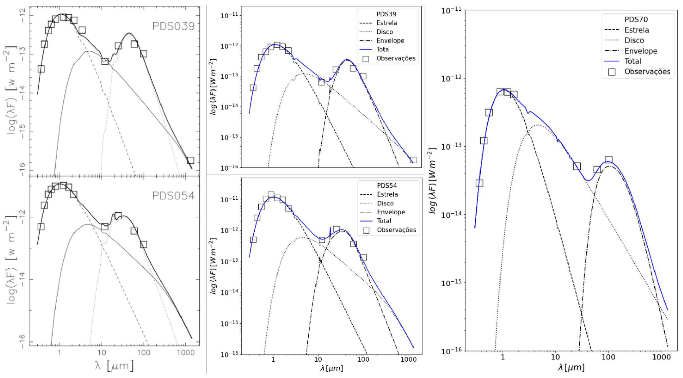

Figure 4. SEDs of stars PDS 39, PDS 54 and PDS70. Synthetic spectrum generated by the model compared with the observed spectrum: on the left, taken from Gregorio-Hetem & Hetem (2002), while the middle and right show the results obtained with the developed code.

4. Future Perspectives

With the code validated, the next steps of this research involve expanding the number of stars analyzed and automating the analysis. We intend to:

1. Implement an automated fitting method (e.g., using a genetic algorithm (GA)) to fit the SEDs and estimate parameters for a larger sample of stars.
2. Use data from the AllWISE catalog to construct color-color diagrams, which will help in identifying new candidates for stars with disks (Koenig & Leisawitz, 2014).
3. Incorporate astrometric and kinematic data from Gaia DR3 (Gaia Collaboration, 2023) to better constrain distances and membership of the target stars.

These advances will allow a more robust statistical study of T Tauri stars and their circumstellar environments.

Acknowledgements. To the Programa Unificado de Bolsas (PUB) for the support, and to the IAG/USP infrastructure.

References

Benisty, M. et al., 2021, ApJL, 916, L2.
Fernandes, B., Gregorio-Hetem, J., Montmerle, T., & Rojas, G., 2015, MNRAS, 448, 119.
Gaia Collaboration, Vallenari, A., Brown, A. G. A., Prusti, T. et al., 2023, A&A, 674, A1.
Gregorio-Hetem, J. & Hetem, A., 2002, MNRAS, 336, 197.
Gregorio-Hetem, J., Lepine, J. R. D., Quast, G. R., Torres, C. A. O., & de La Reza, R., 1992, AJ, 103, 549.
Koenig, X. & Leisawitz, D., 2014, ApJ, 791, 131.
Landolt-Börnstein, 1982, Numerical Data and Functional Relationships in Science and Technology, New Series, Group VI, Vol. 2b, p. 73.
Ossenkopf, V., 1993, A&A, 280, 617.