Modeling Dust Absorption in Circumstellar Envelopes of Hot Stars

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Resumen / Presentamos una extensión de un código existente para modelar envolturas circumestelares de gas y polvo en estrellas calientes de tipo B, así como en otros objetos con envolturas complejas. Incorporamos una descripción más detallada de la absorción debida al polvo basada en la teoría de Mie, que permite explorar explícitamente la dependencia con el tamaño del grano, la densidad de columna de polvo y la composición del material. Este enfoque nos permite separar la contribución de distintos tamaños de grano y diferentes distribuciones de densidad al continuo emergente de la estrella. El objetivo final es lograr una caracterización físicamente consistente de los procesos de interacción radiativa en entornos ricos en polvo, mejorando la capacidad predictiva del modelo para reproducir observables en longitudes de onda del infrarrojo, óptico y ultravioleta cercano.

Abstract / We present an extension of an existing code developed to model circumstellar gas and dust envelopes around hot stars, including B stars and related systems with complex environments. The new version introduces an improved description of dust absorption based on the Mie theory, explicitly accounts for grain size, dust column density, and particle composition. This framework enables us to isolate the contributions of different grain size profiles and density distributions to the emerging stellar continuum, in particular under steady-state outflow conditions. Our goal is to obtain a physically consistent treatment of radiative interaction processes in dusty environments, thereby increasing the predictive power of the model across the infrared, optical, and near-ultraviolet ranges.

Keywords / stars: circumstellar matter — infrared: stars — ISM: dust, extinction — stars: emission-line, B[e]

1. Introduction

Circumstellar envelopes of some hot stars, especially B-type systems with dusty environments (such as B[e] supergiants and Herbig Be stars), contain both ionized gas and warm dust, and produce continuum and line emission that cannot be reproduced by a single stellar photosphere. These systems frequently show stratified outflows and dense equatorial structures, in some cases of binary origin, which reprocess the stellar radiation through absorption, scattering, and thermal re-emission (see Kraus, 2019; Zickgraf et al., 1986). A physically motivated description of how dust modifies the emerging stellar flux is therefore required in order to interpret their complex spectral energy distributions (SEDs) from the UV/optical to the infrared.

In this work, we present an extension of an existing code designed to model gas and dust envelopes in B stars, and related objects.

The original model has been successfully applied to systems with complex envelopes, such as GG Car (Marchiano et al., 2012), MWC 645, FS CMa-type star (Torres et al., 2023), and HD 327083 (Cidale et al., 2026). In that framework, the total observed flux is computed by propagating the stellar continuum through three components — a gaseous envelope, a dusty envelope, and interstellar extinction — each treated separately. Up to now, the dust contribution in the code was described using an empirical wavelength-dependent extinction law of the Cardelli-Clayton-Mathis type (Cardelli et al., 1989), assigned to concentric layers of fixed temperature around the star.

We now aim to replace this empirical prescription with a more detailed dust module based on the Mie theory, explicitly including the grain size a, the dust column density N_d, and the particle type (composition).

In the present stage, a dust layer is treated as a single-species component characterized by (a, N_d, T_d), where T_d is the dust temperature, and its optical depth and thermal emission are computed from the corresponding extinction and absorption efficiencies.

This approach links the emerging continuum directly to physically meaningful dust parameters, allowing us to evaluate how different grain sizes and column densities affect the observed SED. These improvements are intended to yield a more realistic characterization of radiative interaction processes in dusty circumstellar environments and to enhance the predictive capability of the model.

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2. Theoretical framework

2.1. Previous work and base model

We start from a previously developed model that describes the observed spectral flux of a hot B-type star after propagation through three separate components: (i) a gaseous envelope, (ii) a dust envelope, and (iii) interstellar extinction. In this scheme, each component is modeled independently, and the stellar continuum is modified step by step as it crosses these regions.

To model the SED we follow the framework of Zorec (1998) and Muratore et al. (2011), in which the circumstellar material is organized in a gaseous shell located close to the star, characterized by a radius $r_{\rm g}$, while dusty shells, with radii $r_{\rm d}$, reside farther out. Each shell both attenuates the stellar radiation and contributes local emission according to its physical state. Assuming that the geometrical thickness of every shell is small compared to its distance from the star (thin-shell approximation), the emergent intensity from each shell can be computed using a plane-parallel radiative transfer solution; details of the geometric setup are given in Cidale & Ringuelet (1989). The stellar continuum is represented by a synthetic spectrum from the Castelli & Kurucz atmosphere models (Castelli & Kurucz, 2003).

In its original implementation, the circumstellar dust was not computed from first principles. Instead, it was represented through an empirical wavelength-dependent extinction curve of Cardelli et al. (1989). The corresponding optical depth $\tau_{d\lambda}$ was then applied as an attenuating screen. Geometrically, the circumstellar environment was modeled as a set of concentric layers surrounding the star. Each layer was assigned a characteristic radius (expressed in units of the stellar radius) and a dust temperature, assumed constant within that layer. In this way, the envelope could be described as a stratified structure with discrete thermal zones, without yet requiring an explicit grain size, grain composition, or dust column density.

Within this framework, the emerging, normalized flux as a function of wavelength λ can be written as

$$\frac{f_\lambda}{f_V^*} = \Big(\Big[\alpha_{g\lambda}(r_g,\tau_{g\lambda})\frac{F_\lambda^*}{F_V^*} + r_g^{-2}\,\beta_{g\lambda}(r_g,\tau_{g\lambda})\frac{S_{g\lambda}}{F_V^*}\Big]\mathrm{e}^{-\tau_{d\lambda}} + r_d^{-2}\Big[1-2\,\mathrm{E}_3\big(2\tau_{d\lambda}\big)\Big]\frac{S_{d\lambda}}{F_V^*}\Big)\mathrm{e}^{-\tau_{i\lambda}}, \quad (1)$$

where f_λ is the observed flux density, F_λ^* is the intrinsic stellar flux, $S_{g\lambda}$ and $S_{d\lambda}$ are the source functions of the gas and dust components, r_g and r_d are the characteristic radii of the gas and dust regions in units of the stellar radius, $\tau_{g\lambda}$ and $\tau_{d\lambda}$ are the optical depths due to the circumstellar gas and dust, respectively, and $\tau_{i\lambda}$ is the interstellar optical depth along the line of sight. In this expression, $\alpha_{g\lambda}(r_g,\tau_{g\lambda})$ and $\beta_{g\lambda}(r_g,\tau_{g\lambda})$ are dimensionless coefficients obtained from the analytic radiative-transfer solution for a spherical thin shell. They are nonlinear functions of r_g or $\tau_{g\lambda}$; in particular, their dependence on $\tau_{g\lambda}$ involves exponential attenuation terms and exponential-integral functions E_n. The method is described in detail in Marchiano et al. (2012).

Eq. 1 is written in normalized form, f_λ/f_V^*, where f_V^* is the stellar flux at a reference wavelength $\lambda_V = 5510$ Å. This normalization removes the dependence on stellar radius and distance, and allows a direct comparison with observed spectral energy distributions (SEDs) even when the absolute stellar luminosity is uncertain.

In Eq. 1, each term has a clear physical meaning. The first bracketed term represents the stellar continuum plus the contribution of the gaseous envelope (scattering and local emission), propagated through the gas at radius r_g. This radiation is then attenuated by the circumstellar dust through the factor $\mathrm{e}^{-\tau_{d\lambda}}$. The second term in parentheses corresponds to the thermal emission of the dust itself at radius r_d, modulated by $\big[1-2\,\mathrm{E}_3\big(2\tau_{d\lambda}\big)\big]$, which encodes self-absorption within the dusty layer. Finally, the entire spectrum is affected by interstellar extinction through the multiplicative factor $\mathrm{e}^{-\tau_{i\lambda}}$. In this sense, the model is already capable of separating the roles of gas, circumstellar dust, and the interstellar medium.

In summary, in its original form the dust component enters only through an empirical optical depth law. The code does not yet associate that extinction with specific physical dust parameters such as grain size, grain composition, or column density. This limits the possibility of testing how different dust populations would modify the emerging continuum.

2.2. Dust module reformulation

The overall geometry adopted in this model follows the scheme outlined in the previous section: we assume spherical symmetry and represent the circumstellar dust by one or more concentric layers around the star. What changes here is that each layer is now defined by explicit physical parameters:

- the grain size a,
- the dust column density N_d,
- the particle type (composition),
- the dust temperature T_d, assumed constant within that layer.

In this study, each layer is treated as a single-species component. We adopt amorphous silicates as the dust material for all layers, consistent with what is often inferred in dusty circumstellar environments around hot and interacting stars (Kastner et al., 2010; Kraus, M. et al., 2016).

We now introduce a physical reformulation of the dust module, replacing the empirical extinction prescription with a layer–by–layer description based on the Mie theory, namely the exact solution of Maxwell's equations for scattering and absorption by a homogeneous spherical grain. Given the complex refractive index $m(\lambda) = n(\lambda) + \mathrm{i}\,k(\lambda)$ and the size parameter $x = 2\pi a/\lambda$, the Mie theory yields the efficiency factors $Q_{\rm ext}(\lambda,a)$, $Q_{\rm abs}(\lambda,a)$, and $Q_{\rm sca}(\lambda,a)$ (with $Q_{\rm ext} = Q_{\rm abs} + Q_{\rm sca}$), as well as the scattering phase function (Gail & Sedlmayr, 2014).

In our implementation, $Q_{\rm ext}$ and $Q_{\rm abs}$ are computed from the adopted optical constants (Draine & Lee, 1984), tabulated as functions of (λ, a), and then interpolated onto the model spectral grid. More precisely, in the present single-species setup, the grain size a is fixed for each layer; therefore $Q_{\rm ext}$ and $Q_{\rm abs}$ are one–dimensional values, interpolated in wavelength onto the model's λ–grid (linear interpolation), with no interpolation in a.

Consequently, efficiency factors determine both the attenuation of the incoming stellar radiation and the thermal emission of the dust at temperature T_d.

In this formulation, the optical depth of a single layer at wavelength λ is

$$\tau_\lambda = N_d\,\pi a^2\,Q_{\rm ext}(\lambda, a)\,, \tag{2}$$

which links the opacity directly to two measurable (or at least physically interpretable) parameters: N_d and a.

The emergent flux after transmission through, and thermal re-emission by, that layer is then written as

$$\begin{aligned} f_\lambda^{\rm out} &= f_\lambda^{\rm in}\,{\rm e}^{-\tau_\lambda} \\ &\quad + N_d\,\pi a^2\,Q_{\rm abs}(\lambda, a)\,B_\lambda(T_d)\left(1 - {\rm e}^{-\tau_\lambda}\right), \end{aligned} \tag{3}$$

where $f_\lambda^{\rm in}$ is the incoming flux, $B_\lambda(T_d)$ is the Planck function at dust temperature T_d, and $Q_{\rm abs}$ is the absorption efficiency for grains of size a.

Eq. 3 shows explicitly the two competing effects of the circumstellar dust: (i) attenuation of the radiation originating from the star and the inner gas (first term), and (ii) addition of thermal emission from the dust layer itself (second term). This makes it possible to quantify how changes in a, N_d and T_d modify the observed SED.

The reformulated dust module therefore establishes a direct connection between the parameters of the code and physically meaningful dust properties. It also defines a clear path for further generalization: (i) including multiple grain sizes and compositions in a single layer, and (ii) replacing the discrete layers by a continuous radial temperature profile $T_d(r)$, in which T_d decreases with distance from the star.

3. Results

The current version of the code, implemented in FORTRAN, describes the circumstellar dust as a set of layers, each defined by a fixed grain radius a, dust column density N_d, dust temperature T_d, and a single dust species. For each species, the extinction and absorption efficiencies $Q_{\rm ext}(\lambda, a)$ and $Q_{\rm abs}(\lambda, a)$ are obtained from the tabulated Mie calculations based on the optical constants of Draine & Lee (1984), and interpolated onto the working spectral grid. For every dust layer, we compute the optical depth $\tau_\lambda = N_d\,\pi a^2\,Q_{\rm ext}(\lambda, a)$ and the thermal contribution $Q_{\rm abs}(\lambda, a)\,B_\lambda(T_d)$ at the corresponding T_d. The total emerging flux is computed by first propagating the stellar continuum through the gaseous envelope, obtaining the gas-processed spectrum. This spectrum is then used as the input to the circumstellar dust, which is applied layer by layer in sequence using Eq. 3 at each step. Finally, the resulting flux is attenuated by the interstellar medium.

As a test, we applied the code to a hot star characterized by $T_{\rm eff} = 23\,000$ K and $\log g = 3$. We present two hypothetical cases, each considering a single circumstellar dust layer at the same distance from the star and characterized by different temperature (see Figs. 1 and 2).

Fig. 1 shows a configuration with the dust layer of amorphous silicate, located at $r_d = 700\,R_\star$ and a fixed dust temperature of $T_d = 1500$ K. For this setup, we generated SEDs with grains of size $a = 0.1$ μm and varied the dust column density N_d over a range of representative values (see legend). As N_d increases, the infrared excess enhances, exhibiting a broad feature near ~ 10 μm.

Fig. 2 shows a clear, monotonic trend for a single dust layer at $r_d = 700\,R_\star$, with $T_d = 750$ K and grains of size $a = 1$ μm, as N_d increases (see legend). At the lowest N_d, the spectrum nearly follows the stellar continuum, with only a mild near–IR rise and a barely perceptible 10 μm silicate shoulder. As N_d increases, the UV–optical ranges of the SEDs remain clustered (since differences are small once divided by f_V^*), while the near–IR ($\sim$ 1–3 μm) lifts progressively above the photospheric level. In the mid–IR ($\sim$ 5–20 μm) a broad bump develops and increases in amplitude with N_d, and the $\sim$ 9–10 μm silicate feature is gradually diluted into the overall infrared continuum.

The behaviour of the SEDs in Figs. 1 and 2 can be understood qualitatively from simple geometric and radiative arguments. In both cases, the dust shell is located at $r_d = 700\ R_\star$, so even a geometrically thin layer encloses a very large volume and emitting surface. As the dust column density N_d increases, the amount of emitting material grows rapidly, and the reprocessed radiation produces a strong infrared excess. In Fig. 1, small silicate grains ($a = 0.1\,\mu$m) at $T_d \simeq 1500$ K already generate a noticeable excess peaking at a few microns, while in Fig. 2 the excess is further enhanced at longer wavelengths because larger grains ($a = 1\,\mu$m) at $T_d \simeq 750$ K have higher absorption and emission efficiencies at $\lambda \gtrsim 2\,\mu$m. In contrast, the UV/optical part of the SED changes only weakly with N_d. From Eq. 3, at these wavelengths the dust optical depth is small ($\tau_\lambda \ll 1$), so the transmitted term satisfies $f_\lambda^{\rm in}\,e^{-\tau_\lambda} \approx f_\lambda^{\rm in}$. In addition, the dust-emission term, proportional to $N_{\rm d}\,\pi a^2 Q_{abs}(\lambda, a)\,B_\lambda(T_d)\,(1 - e^{-\tau_\lambda})$, remains very small compared to the stellar flux.

Fig. 3 shows the effect of the grain radius on the infrared part of the emergent SED for a fixed dust shell ($R = 700\,R_*$, $T_{\rm d} = 750$ K) and column density ($N_d = 10^7\,{\rm cm}^{-2}$). At wavelengths $\lambda \gtrsim 2\,\mu$m, the SED shows a strong dependence on the grain size. Larger grains absorb a larger fraction of the stellar radiation and have higher absorption efficiencies $Q_{\rm abs}$, producing a stronger and broader IR excess, and the SED decreases more slowly toward long wavelengths. Grains with $a \lesssim 0.25\,\mu$m yield very similar SEDs, while grains with $a \gtrsim 0.5$–$1\,\mu$m produce a significantly enhanced infrared emission. This test shows that, in our Mie–based model, the mid- to far-IR SED strongly depends on the assumed grain size.

4. Conclusions and future work

We presented a reformulation of the circumstellar dust module that replaces an empirical extinction law with a

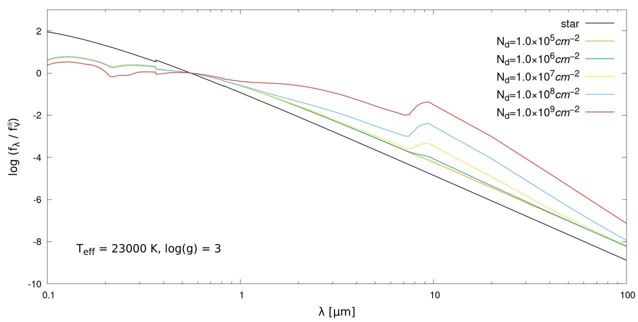

Fig. 1. Synthetic SEDs for a hot star with $T_{\rm eff} = 23\,000$ K and $\log g = 3$, normalized at f_V^* obtained from a single circumstellar dust layer with $T_d = 1500$ K placed at $r_d = 700\,R_\star$. The grain size was kept fixed at $a = 0.1$ μm while the dust column density N_d was varied as indicated in the legend. The black line shows a classical photospheric model.

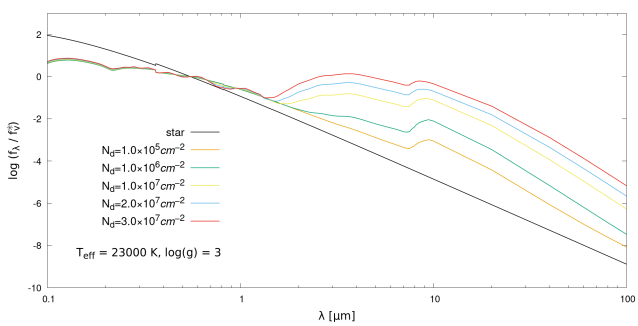

Fig. 2. Synthetic SEDs for a hot star ($T_{\rm eff} = 23\,000$ K, $\log g = 3$), surrounded by a single circumstellar dust shell with $T_d = 750$ K located at $r_d = 700\,R_\star$. All models assume grains of size $a = 1$ μm; the dust column density N_d is varied as indicated in the legend. The black curve represents the stellar photosphere; colored curves are the emergent SEDs after the interaction with dust, normalized at f_V^*.

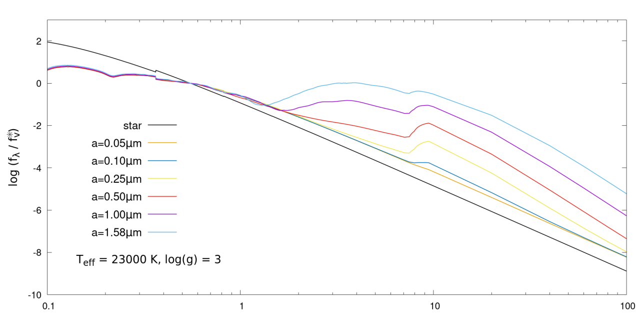

Fig. 3. Effect of grain size on the emergent SED. Synthetic SEDs for a $T_{\rm eff} = 23000$ K, $\log g = 3$ star surrounded by a single silicate dust shell with $R = 700\,R_*$, $T_{\rm d} = 750$ K and $N_{\rm d} = 10^7\,{\rm cm}^{-2}$. Curves correspond to grain radii between $a = 0.05$ and $1.58\,\mu$m; increasing a enhances and broadens the IR excess.

physically motivated, layer-based description. The new model is built on the Mie theory and is parametrized by grain size a, dust column density N_d, composition, and dust temperature T_d. Tests performed on hot-star SEDs with a single dust layer illustrate how these parameters govern the resulting observable properties, including the continuum shape and mid-IR features.

The resulting SEDs show systematic trends directly attributable to the dust parameters. Increasing N_d strengthens the overall infrared excess produced by the dust-emission term in Eq. 3, and also *increases* the attenuation of the stellar continuum at shorter wavelengths through the factor $e^{-\tau_\lambda}$. In addition, for specific combinations of grain size a and column density N_d, the model exhibits a broad emission feature around 10 μm. More precisely, the contrast of this silicate emission feature not only increases with N_d, but also depends on grain size. At fixed N_d, the 10 μm feature is relatively weak for the smallest grains, reaches its maximum prominence for intermediate radii, and becomes more diluted for the largest grains, where the dust produces almost a featureless continuum.

These calculations illustrate the main goal of the present stage of the project: by treating (a, N_d, T_d) as explicit parameters of each circumstellar dust layer, the code can predict how changes in grain size and dust column density reshape the continuum and mid-IR features of the SED. Future work will incorporate mixtures of grain sizes and compositions within a single layer, and ultimately replace the discrete layers with a continuous radial temperature profile $T_d(r)$.

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