Coimbra, Portugal

7-11 July, 2025

RHADaMAnTe: A code to estimate the SED of the wall of a gap opened by a planet in a protoplanetary disk.

Rendón, F.[1]

[1]Instituto de Agroingeniería, Universidad del Papaloapan; Loma Bonita, Oaxaca, México

Abstract

When a star is born, a protoplanetary disk made of gas and dust surrounds the star. The disk can show gaps opened by different astrophysical mechanisms. The gap has a wall emitting radiation which contributes to the spectral energy distribution (SED) of the whole system (star, disk and planet) in the IR band. As these new-born stars are far away from us, it is difficult to know whether the gap is opened by a forming planet. I have developed RHADaMAnTe, a computational astro code based on the geometry of the wall gap coming from hydrodynamical 3D simulations of protoplanetary disks. With this code it is possible to make models of disks to estimate synthetic SEDs of the wall gap and prove whether the gap was opened by a forming planet. I have implemented this code to the stellar system LkCa 15. I found that a planet of 10 Jupiter masses is capable of opening a gap with a curved wall with height of 12.9AU. However, the synthetic SED does not fit to Spitzer IRS SED ($\chi^2 \sim 4.5$) from 5μm to 35μm. This implies that there is an optically thick region inside the gap.

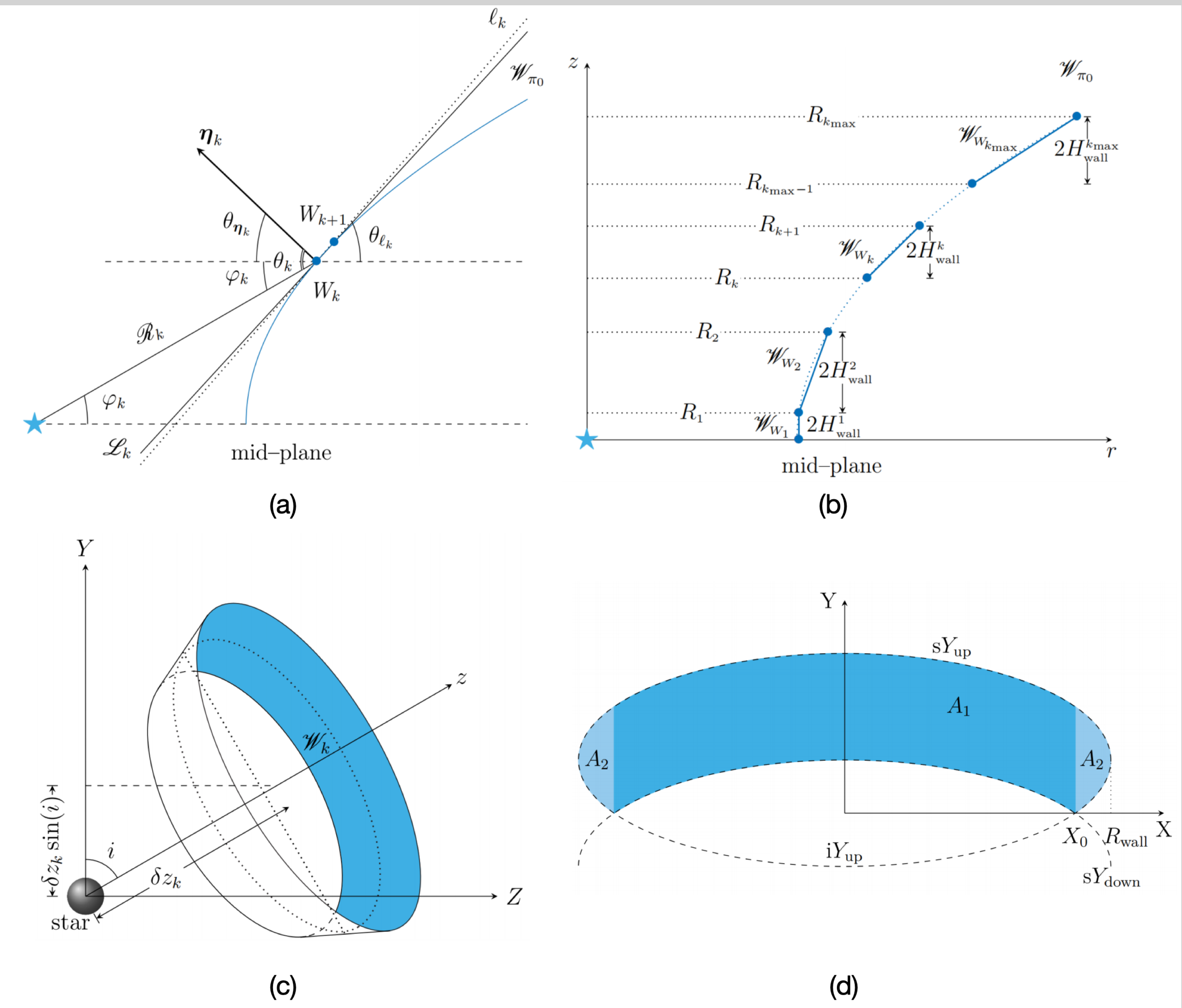
Introducción

A key element that produces characteristic features in the SEDs of protoplanetary disks is the outer wall of the gap or hole facing the star. To simplify SED wall models, it is often assumed that the wall is uniform in the vertical direction and frontally irradiated by the central star (Espaillat et al. 2007a,b). But this assumption is physically wrong, in Rendón (2023) it was found that the wall of the gap in LkCa 15 is curved. To model the structure and SED of gaps or holes in protoplanetary disks many free available radiative codes, such as ProDiMo (Woitke et al. 2009), DALI (Bruderer 2013) or RADMC-3D (Dullemond et al. 2012), are implemented. However, these codes do not consider the contribution of the wall to the the total SED, and they are focused on the thermo-chemical gas/dust modeling of the disk. In order to create the synthetic SED of a protoplanetary disk considering the contribution of the outer *curved wall* of the gap or hole, to explain the strong infrared excess emission detected at wavelengths around $\sim 10\,\mu$m, I have developed the computational code called RHADaMAnTe.

The RHADaMAnTe code

RHADaMAnTe is a code written in the FORTRAN 90 language, and uses the geometry of the wall to estimate the SED. The wall arises from the analysis of a 3D simulation of the star-disk-planet interactions via the ARTeMiSE code. As I am interested in estimating the radiation re–emitted by the projection of a tri–dimensional wall $\mathscr{W}$ on the plane of the sky, the code firstly calculates the angle between the radial ray and the normal to the two–dimensional wall $\mathscr{W}_{\pi_0}$ for each incident radial radiation ray coming from the central star, as seen in Figure 1(a). Then, it is constructed the tri–dimensional wall as the finite union of tri–dimensional conic rings obtained by rotating inclined line segments about the z–axis at different heights. (see Figures 1(b) and 1(c)). Next, it is calculated the surface projection on the plane of the sky of these rings (Figure 1(d)) which is needed to estimate the radiation emitted by each of them, by multiplying the emergent intensity I_ν by the solid angle Ω_{wall}. Finally, the contribution of the emission of all the projected rings are added to create the synthetic SED.

Figure 1: (a) Geometry of the incidence of the stellar radiation along a ray $\mathscr{R}_k$ on the wall $\mathscr{W}_{\pi_0}$. (b) Construction of segment lines $\mathscr{W}_{W_k}$ connecting points W_{k-1} and W_k in the two-dimensional wall $\mathscr{W}_{\pi_0}$. (c) Projection of a ring $\mathscr{W}_k$ on the Y-axis. (d) Area of the projection of the whole vertical wall on the plane of the sky XY.



(a) (b) (c) (d)

The thermal emergent intensity, approximated as isotropic, is given by

$$I_\nu \approx \int_0^\infty B_\nu[T_d(\tau_d)] \exp\left(-\tau_\nu\right) d\tau_\nu, \tag{1}$$

where B_ν is the Planck function, τ_d is the total mean optical depth at the disk frequency band, and $\tau_\nu = \tau_d(\kappa_\nu/\chi_d)$, with opacity κ_ν.

Dust grain opacity

Equation (1) requires the calculation of the opacity κ_ν which depends on the chemical composition, pressure and temperature of the dust, as well as the frequency ν of the incident light. In the code the Rosseland mean opacity is implemented:

$$\frac{1}{\langle \kappa^R \rangle} := \left(\int_0^\infty \frac{1}{\kappa_\nu} \frac{\partial B_\nu}{\partial T} d\nu \right) \cdot \left(\int_0^\infty \frac{\partial B_\nu}{\partial T} d\nu \right)^{-1}, \tag{2}$$

To calculate the total Rosseland mean opacity κ^{R}, I consider a mixture of dust grains made of small and big grains:

$$\kappa_{\mathrm{R}}(x,z) = \zeta_{\mathrm{small}}(x,z)\kappa_{\mathrm{R}_{\mathrm{small}}} + \zeta_{\mathrm{big}}(x,z)\kappa_{\mathrm{R}_{\mathrm{big}}}, \tag{3}$$

where $\kappa_{\mathrm{R}_{\mathrm{small}}}$ and $\kappa_{\mathrm{R}_{\mathrm{big}}}$ are the Rosseland mean opacities associated to the small dust grain size distribution and big dust grain size distribution, respectively. And ζ_{small} and ζ_{big} represent the abundances (dust-to-gas mass ratio) of the small and big grains, respectively:

$$\zeta_{\mathrm{small,\,big}}(x,z) = \tfrac{1}{2}\zeta_{\mathrm{small},0}\left\{ 1 \mp \tanh\left[k\left(1 - \frac{z}{\delta H}\right)\right]\right\}, \tag{4}$$

here δH represents a small fraction of the scale height of the disk, and k is a factor which defines a smooth transition between small and big grains. The monochromatic opacity κ_ν in Equation (2) is calculated via:

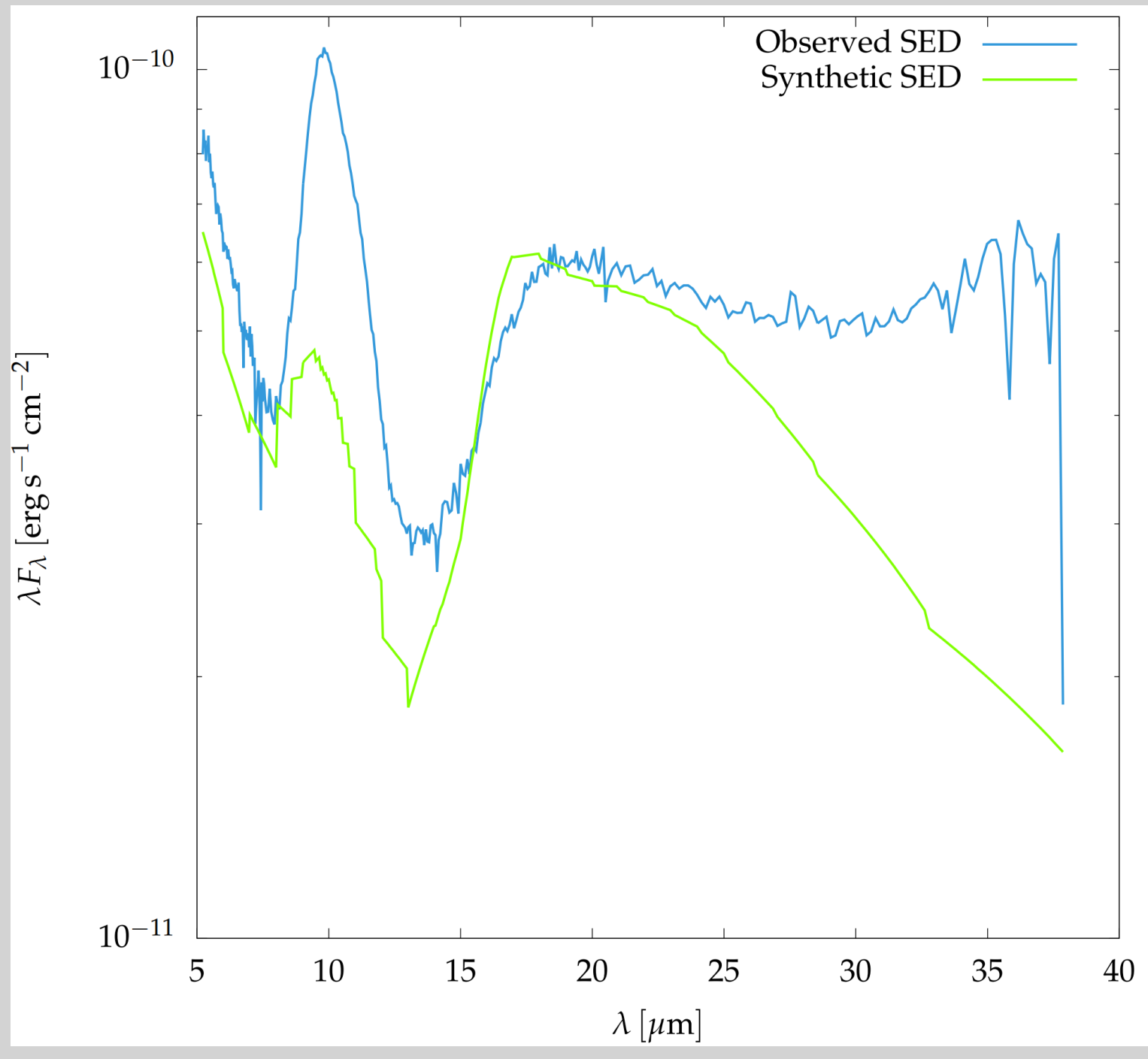
$$\kappa_\nu = \sum_q^{q_{\max}} \kappa_\nu^q(a^q_{\min}, a^q_{\max}, \sigma^q, \eta^q), \tag{5}$$

where $a^q_{\min}$ and $a^q_{\max}$ are the sizes of the small and big grains, and σ^q and η^q are the abundance and refraction index of the species. Here q is running over the name of the species in the dust composition of the disk.

Results: An implementation to the stellar system LkCa 15

I found that for a $10M_{♃}$ planet located at 23 AU from the central star with a curved wall starting at $\sim$ 52 AU as suggested by observations (Thalmann et al. 2014). The synthetic SED of LkCa15 is well compared ($\chi^2 = 0.65$) to the observed SED, measured by The Spitzer Telescope, for $15\,\mu m < \lambda < 20\,\mu m$ (see in Fig. 2). However for other wavelengths the fit is not good. I think that it must be considered the contribution of a small optically thick disk surrounding the central star as it suggests a model of LkCa15 disk by Mulders et al. (2010). This model also cannot reproduce the peak of silicates at $\sim 10\,\mu m$.

Figure 2: Synthetic SED (green line) that best fit the observed SED (blue line) of LkCa15. With model parameters: $\cos(i) = 0.6427$, $R_{wall} = 58.11AU$, $H_{wall} = 5.27AU$, $z_{umb} = 6.73AU$. The dust in the inner disk consists of small grains ($a_{\min} = 0.005\mu m$) and big grains ($a_{\max} = 0.25\mu m$) of silicates and graphite, while in the outer disk, the dust consists of small ($a_{\min} = 0.005\mu m$ and $a_{\max} = 0.25\mu m$) and big grains ($a_{\min} = 0.005\mu m$, $a_{\max} = 1000\mu m$) of glassy olivine with 50% Fe and 50% Mg and with a small amount of organics and troilite grains.



References

Bruderer, S. 2013, A&A, 559, A46
Dullemond, C. P., Juhasz, A., Pohl, A., et al. 2012, RADMC-3D: A multi-purpose radiative transfer tool, Astrophysics Source Code Library, record ascl:1202.015
Espaillat, C., Calvet, N., D'Alessio, P., et al. 2007a, ApJ, 664, L111
Espaillat, C., Calvet, N., D'Alessio, P., et al. 2007b, ApJ, 670, L135
Mulders, G. D., Dominik, C., & Min, M. 2010, , 512, A11
Rendón, F. 2023, Universidad Tecnológica de la Mixteca, 5
Thalmann, C., Mulders, G. D., Hodapp, K., et al. 2014, AA, 566, A51
Woitke, P., Kamp, I., & Thi, W. F. 2009, A&A, 501, 383

contact: `frendon@unpa.edu.mx`