Hybrid Radiative Transfer Method for Prestellar Isolated Core Collapse

A comparison of Radiative Transfer methods for Massive Star Formation

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Abstract

In the context of numerical simulations of massive star formation, the treatment of **radiative transfer** has a non-negligible impact on the launching of outflows, on the accretion and hence on the final mass of the star. In particular, as a consequence of **grey** radiative transfer (opacities averaged over the whole frequency domain), the opacity corresponds to frequencies related to the blackbody temperature of the protostar disk despite the fact that some photons are emitted at the star temperature and therefore at much higher energy. This implies an important **error on the temperature** (up to 38% in a moderately optically-thick regime, Kuiper et al 2010) and a **radiative force underestimated** by a factor of a few hundreds, in the case of an isolated star irradiating a disk. We present results of **frequency-dependent** radiative transfer 3D simulations of a protostar irradiating a disk.

Methods

- **Grey Flux-Limited Diffusion**
  - 0th-order moment of the equation of transfer
  - Solves the radiative energy conservation equation assuming that the flux follows the energy gradient
  - Made for the **optically-thick limit**
- **Irradiation with the M1 method and disk re-emission with grey FLD**
  - 0th- and 1st-order moments of the equation of transfer
  - This hybrid method handles the stellar photons with the M1 method
  - M1 **preserves the directionality of the photon flow** in both the optically-thin and –thick limits, and assumes the opacity at the stellar temperature
  - Photons are injected into the radiative energy that obeys the FLD after being absorbed.

Gas density structure maps

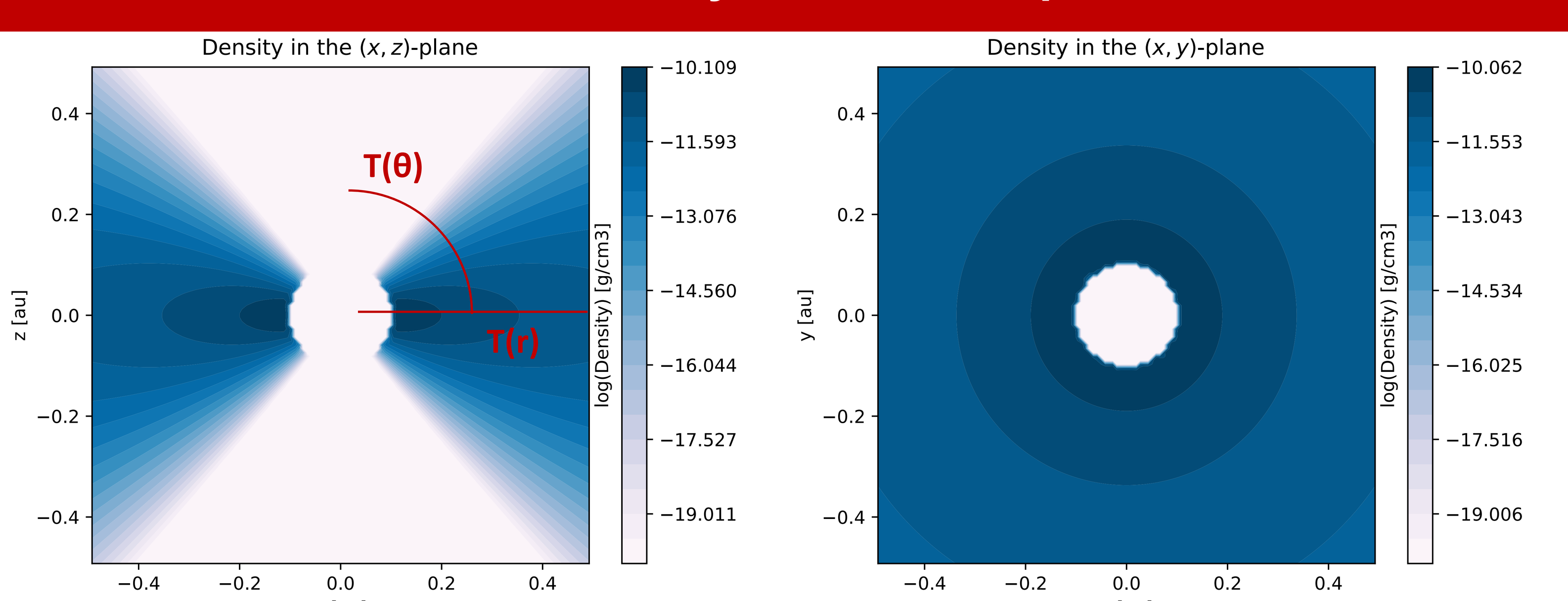


Figure 1 : Gas density maps (in log scale) in the (x,z)-plane (edge-on) and the (x,y)-plane (i.e. face-on).

Results

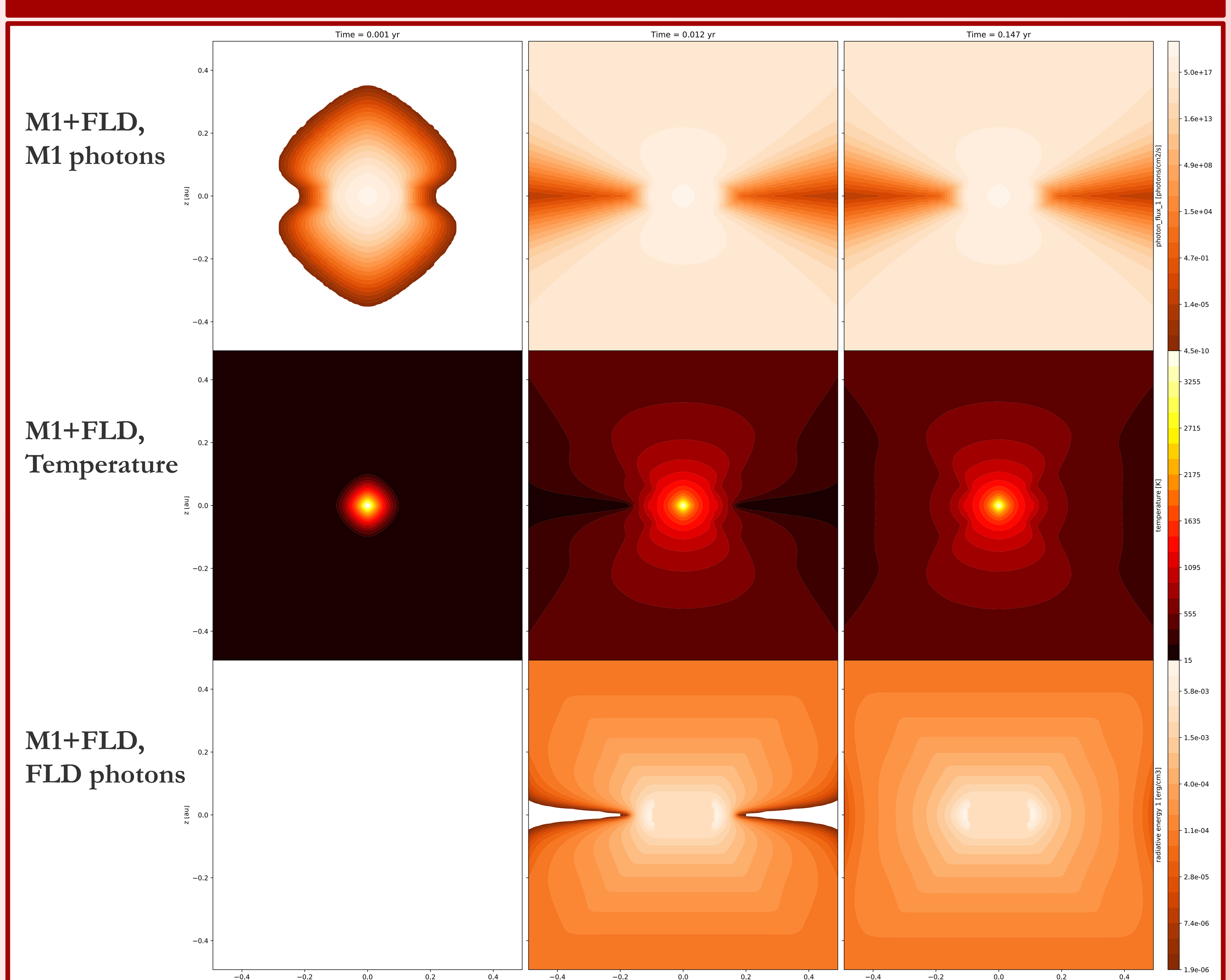


Figure 2 : Time evolution of the photon density (photons treated with M1), the temperature and the radiative energy (photons treated with FLD) for the M1+FLD simulation.

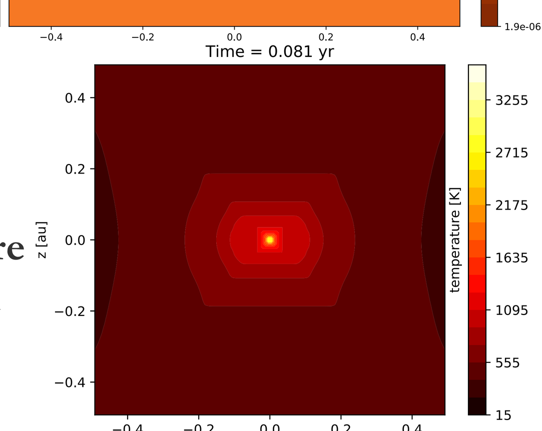


Figure 3 : Temperature structure at the end of the grey FLD simulation.

We observe two steps in the M1+FLD temporal evolution (fig. 2) :

1. Photons propagate with M1 while they also heat the gas and are absorbed at the disk edge.
2. The gas heated by the M1 radiation re-emits into the FLD radiative energy and hence partially fills the shielded region, the mid-plane of the disk.

With **Grey FLD** (fig. 3), alone, **radiation penetrates the disk** more easily because the energy is diffused along the directions of decreasing gradient, while **M1+FLD partially preserves the shielding of the mid-plane**.

Physical Setup

- A protostar of temperature 5800K, one solar radius (setup from Pascucci et al 2004)
- A disk density structure of inner radius 0.1AU (similar to fig. 1) in a diffuse background
- **Gas density profile in r^{-2}** in the mid-plane (x,y), dust-to-gas ratio : 1%
- **Protostellar feedback : stellar luminosity** injected at the center of the volume
- No hydrodynamics, **only radiative transfer** (so far)
- Look for **temperature and radiative structure** once **stationary state** is reached

Comparison of 2 models : Pure Grey Flux-Limited Diffusion and M1 + Grey Flux-Limited Diffusion

Numerical Setup

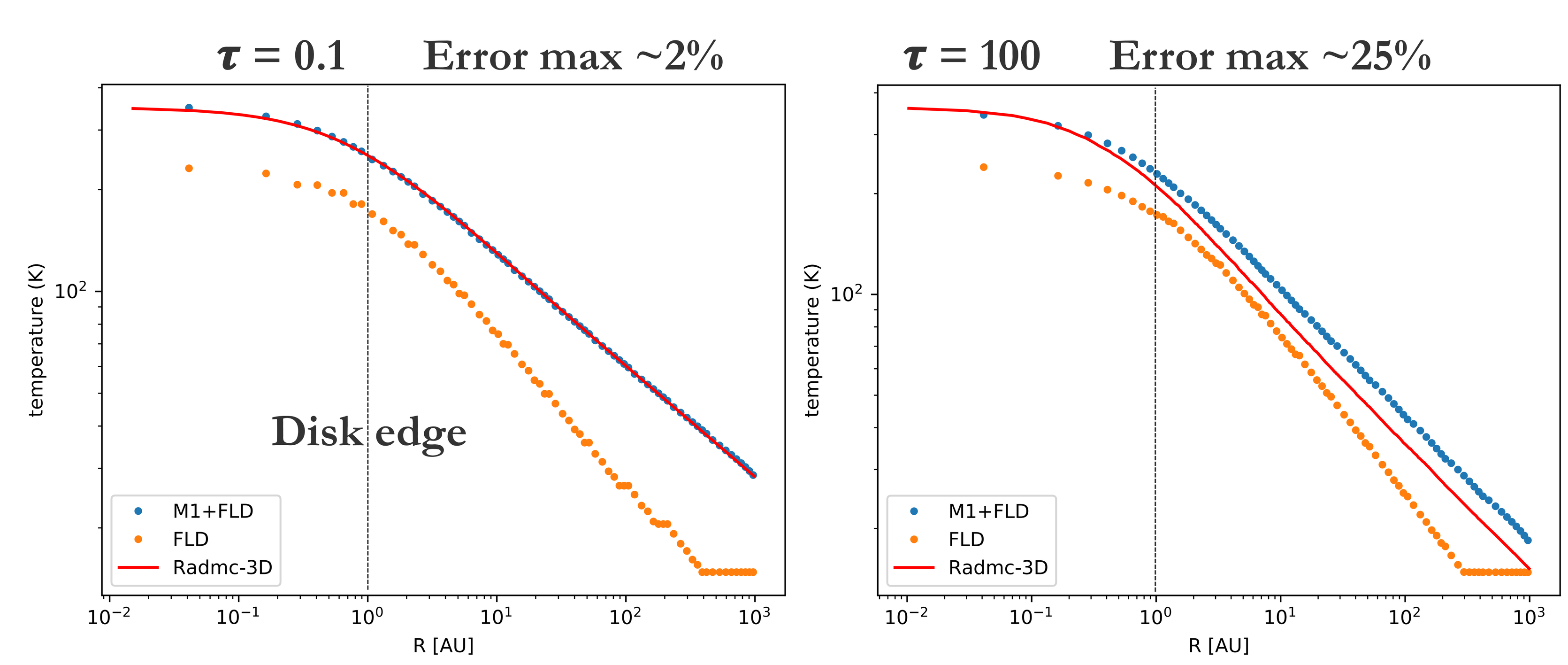
RAMSES simulations (Teyssier 2002) with :

- Cartesian grid, box of 1 AU, Δx = 0.0078 AU
- Radiative transfer with **Grey FLD** (Commerçon et al 2011) and **M1** (Rosdahl et al 2013)
- Temperature-dependent opacity from Draine & Lee 1984

Comparison with RADMC-3D radiative transfer simulations (Dullemond et al 2012) : Monte-Carlo method in spherical coordinates

Temperature profiles

Figure 4 : Radial temperature profiles in the mid-plane of the disk (which starts at 1 AU) axis : comparison between M1+FLD, pure FLD and RADMC-3D as reference. Left : $\tau = 0.1$, right : $\tau = 100$



The left panel of fig. 4 shows that the **hybrid method gives temperatures significantly closer to RADMC-3D in the optically-thin regime than FLD alone**. FLD has a grey opacity 100 times lower than the M1 opacity in the M1+FLD method, which can explain this important difference. The right panel of fig. 4 shows that in the moderately optically-thick regime the **hybrid method reaches 25% of error on the temperature** while FLD underestimates it constantly. FLD also produces a flat feature because of the reemission of the disk towards the star and the isotropy of FLD. Also, the **hybrid method's behaviour is closer to RADMC-3D**. We probe the ability of our hybrid method to capture the self-shielding in the disk with the temperature as a function of the polar angle, at a given radius, in the moderately optically-thick case (fig. 5).

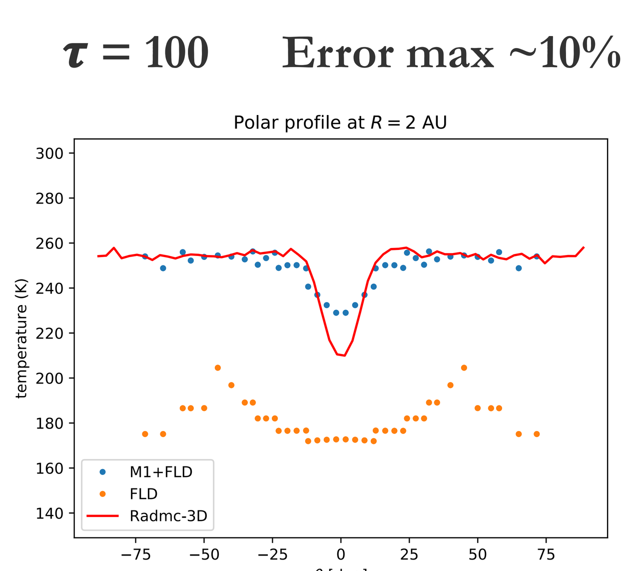


Figure 5 : Polar temperature profile at 2 AU for M1+FLD (blue dots) and FLD (orange dots) compared to RADMC-3D (red line).

Figure 5 shows that the **FLD cannot reproduce accurately the decrease of the temperature in the disk mid-plane**, due to the self-shielding made by the optically-thick disk edge, and the temperature does not depend strongly on the direction. On the opposite, the **M1+FLD method reproduces the shielding in the mid-plane of the disk and makes a maximal error of 10%.**

Conclusions and perspectives

FLD :

- **Does not reproduce accurately the shielding in the disk mid-plane**, mainly due to grey opacities and radiation following the energy gradient
- Produces flat features because of its isotropy assumption on the radiative pressure tensor.

M1+FLD :

- Gives **temperature at the disk border in agreement with RADMC-3D** and at halfway between grey and frequency-dependent analytical models in the optically-thin regime
- **Reproduces, with a maximal error of 10% at 2 AU, the shielding in the disk**
- Still not in total agreement with analytics and Radmc-3D. Possible reason : only one grey opacity for the disk radiation while disk temperature varies between 100K and 1000K.

Perspectives :

- In progress : compare the **radiative force** between FLD and M1+FLD simulations to Monte-Carlo codes in a similar setup
- Apply these methods to **massive core collapse** for more accurate temperatures and radiative force in both the optically-thin and -thick regions
- **Photo-ionization** during massive star formation with the M1 method.