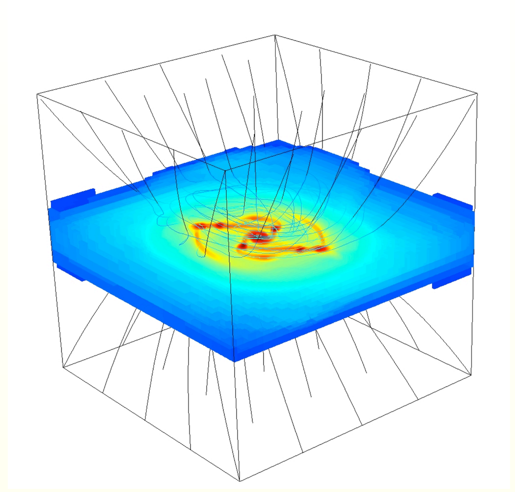

Protostellar collapse: magnetic and radiative feedbacks on small-scale fragmentation

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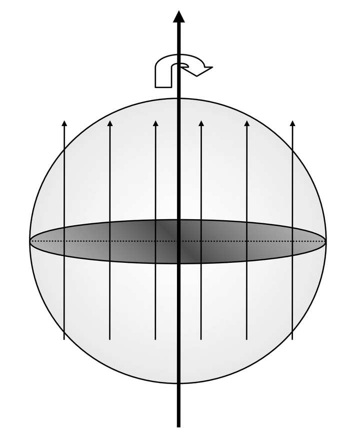
PROTOSTELLAR COLLAPSE AND NUMERICAL SIMULATION

Radiative transfer play a major role in the different phases of the protostellar collapse Until the formation of the first Larson core (Larson 1969), the accreting gas can freely radiate into space and is nearly isothermal (optically thin regime). Once the gas becomes dense enough ($\rho > 10^{-13}$ g cm^{-3}), the radiation is trapped and the gas begins to heat up (optically thick regime). The transition between these two regimes controls the collapse and fragmentation of the cloud. The cooler the gas, the more important the fragmentation. Another key issue in star formation is the role of the magnetic field, as dense cores are observed to exhibit coherent magnetic structures (e.g., Heiles & Crutcher 2005).

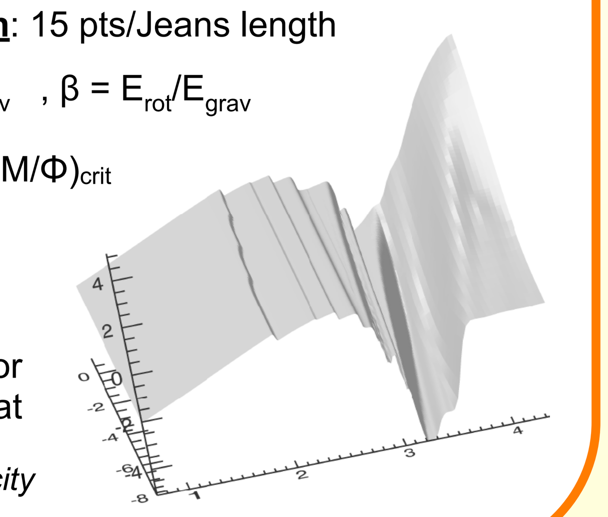
It has been shown that magnetic field suppresses the fragmentation and large disc formation (e.g. Hennebelle & Teyssier 2008). However, all the previous studies use a barotropic EOS to mimic the thermal behaviour of the gas.

We perform coherent 3D radiation-magnetohydrodynamics calculations of prestellar dense core collapse using the RAMSES code (Teyssier 2002, Fromang et al. 2006), with a high resolution (<0.5 AU). We focus our study on the first collapse and first core formation and fragmentation. We do not assume any sub-grid model to account for the radiation from a protostar. Fragmentation that occurs at this first stages is then genuine.

MODEL SETUP



- 1 $M_\odot$, Solid body rotation, uniform density
- m=2 azimuthal density perturbation
- Magnetic field aligned with rotation axis
- **Resolution**: 15 pts/Jeans length
- $\alpha = E_{th}/E_{grav}$, $\beta = E_{rot}/E_{grav}$
- $\mu = (M/\Phi)/(M/\Phi)_{crit}$



Opacity table from Semenov et al. (2003) for low temperature and Ferguson et al. (2005) at high temperature.

Rosseland mean opacity

THE FLUX LIMITED DIFFUSION APPROXIMATION

The diffusion equation is obtained assuming that the radiative flux is stationary and that the radiative pressure is isotropic. The radiative flux is then directly expressed as a function of the radiative energy. To preserve causality, the radiative flux propagation has to be limited (i.e.. $|F|<cE_r$). This is achieved thanks to a flux limiter (e.g. and Minerbo 1978).

$$\frac{\partial E_\mathrm{r}}{\partial t} - \nabla\cdot\left(\frac{c}{3\rho\kappa_\mathrm{R}}\nabla E_\mathrm{r}\right) = \kappa_\mathrm{P}\rho(4\pi B - cE_\mathrm{r})$$

$$\mathrm{F} = -\frac{c\lambda}{\kappa_\mathrm{R}\rho}\nabla E_\mathrm{r}$$

$$R = |\nabla E|/(\kappa_\mathrm{R}\rho E)$$

Minerbo flux limiter

$$\lambda = (1/R)[\coth R - 1/R]$$

THE RHD SOLVER

RHD EQUATIONS IN THE COMOVING FRAME :

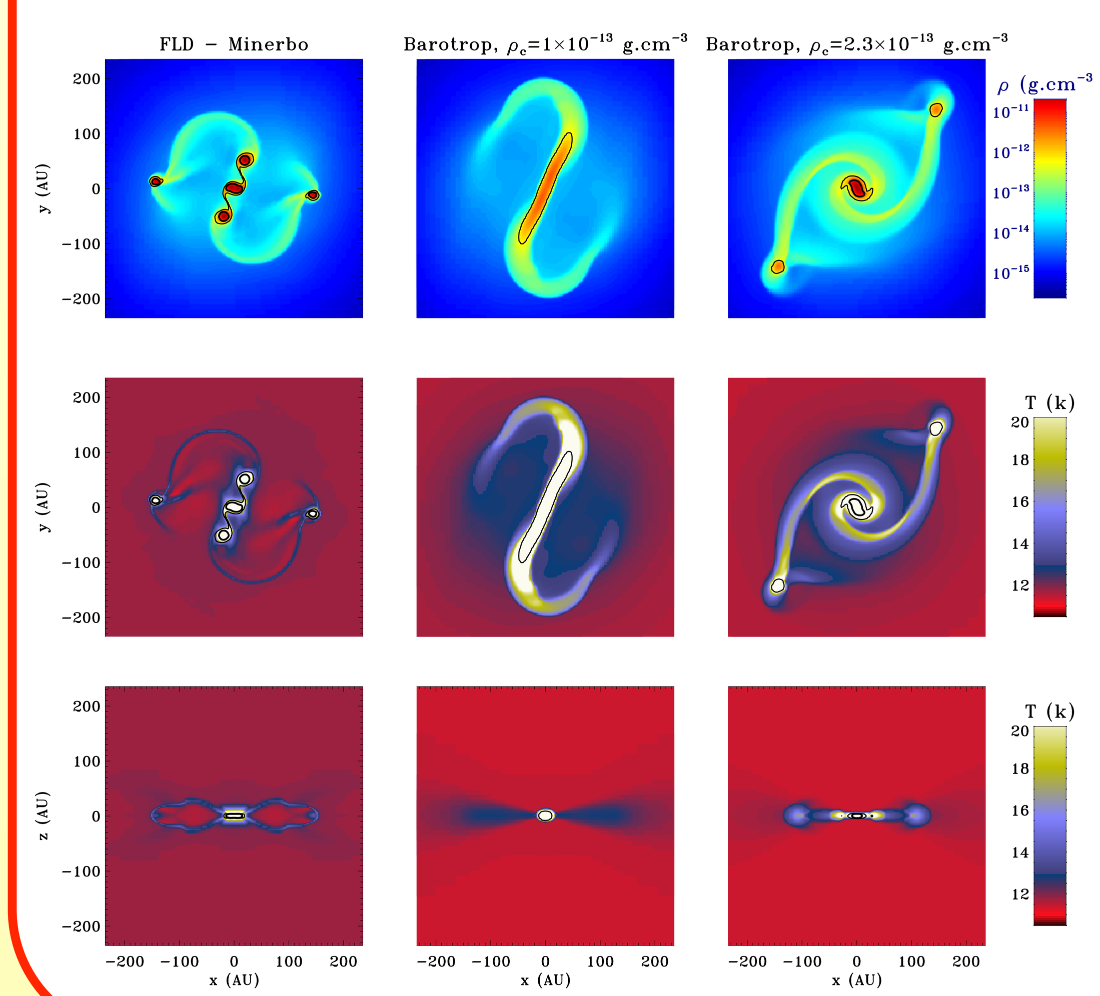
We solve the usual Euler equations with some additional terms due to the evaluation of the radiative quantities in the fluid frame. In the conservative update, we assume 1/ the diffusion limit 2/ that radiative pressure is isotropic ($P_r=E_r/3$). We then adjust these assumptions in a corrective step. The implicit step is performed using an iterative Conjugate Gradient algorithm. The four resulting RHD equations are solved using a time splitting scheme:

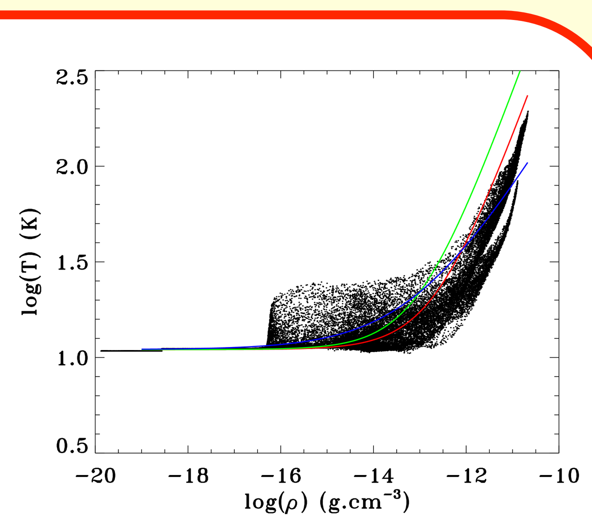
$$\left\{\begin{array}{lllll}
\partial_t\rho & + & \nabla[\rho\mathbf{u}] & = & 0\\
\partial_t\rho\mathbf{u} & + & \nabla[\rho\mathbf{u}\otimes\mathbf{u}+(P+1/3E_\mathrm{r})\mathbb{I}] & = & -(\lambda-1/3)\nabla E_\mathrm{r}\\
\partial_t E_\mathrm{T} & + & \nabla[\mathbf{u}(E_\mathrm{T}+P+1/3E_\mathrm{r})] & = & -(\lambda-1/3)\nabla(\mathbf{u}E_\mathrm{r})+\nabla\cdot\left(\frac{c\lambda}{\rho\kappa_\mathrm{R}}\nabla E_\mathrm{r}\right)\\
\partial_t E_\mathrm{r} & + & \nabla[\mathbf{u}E_\mathrm{r}] & = & -\mathbb{P}_\mathrm{r}:\nabla\mathbf{u}+\kappa_\mathrm{P}\rho c(a_\mathrm{R}T^4-E_\mathrm{r})+\nabla\cdot\left(\frac{c\lambda}{\rho\kappa_\mathrm{R}}\nabla E_\mathrm{r}\right)
\end{array}\right.$$

Riemann solver - explicit | Corrective terms - explicit | Coupling + Diffusion - implicit

HYDRO COLLAPSE

α = 0.50 , β = 0.04





Temperature-density disribution, compared with barotropic EOS

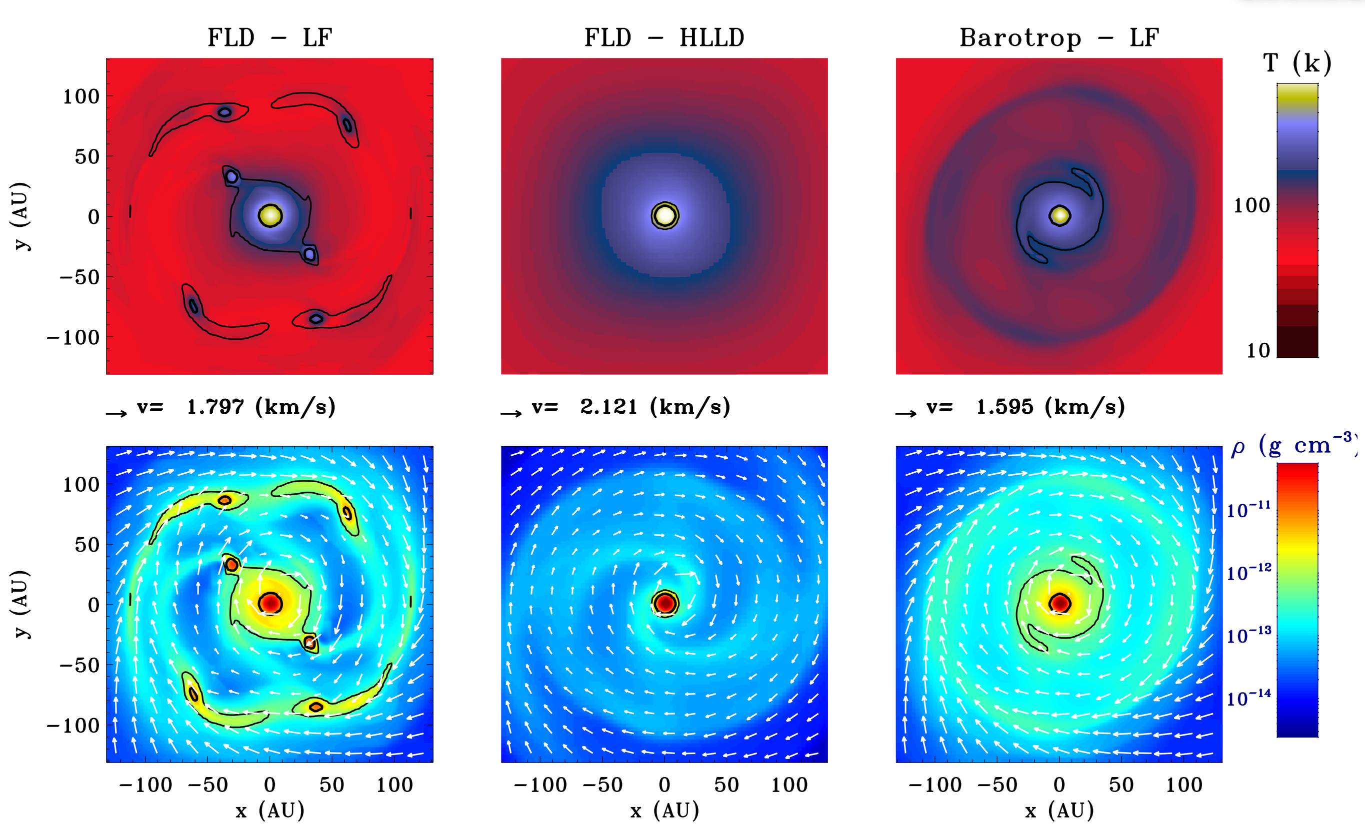
1/ More fragmentation with the FLD compared to the barotropic case. (Cooling by radiation in the vertical direction)

2/ Barotropic EOS unable to reproduce the spread in temperature for a given density

2/ Each fragments have their ***own entropy level***. Applied to the fragmentation that could occur at the 2nd collapse stage, this could be of prime importance for the initial conditions of the protostellar evolutionary models.

RMHD PROTOSTELLAR COLLAPSE

α = 0.35 , β = 0.045 , μ=20



1/ A strong magnetic field suppresses the fragmentation. The efficient magnetic braking induces a strong radiative feedback, due to the radiation escaping from the accretion shock.

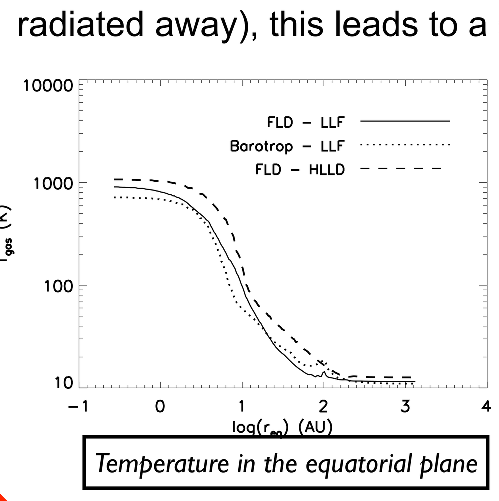
2/ Numerical diffusion and resolution become crucial. There is a strong interplay between radiative feedback and magnetic braking, which can be affected by :

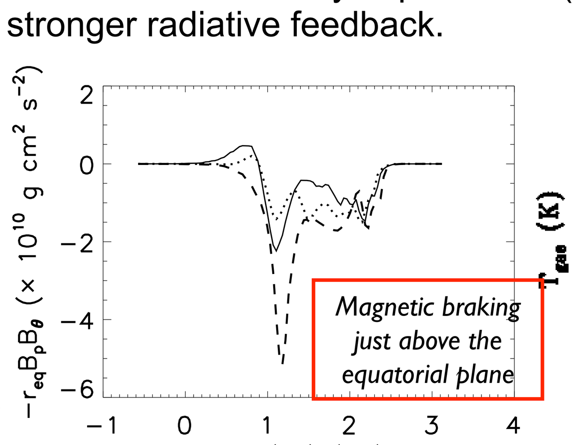
- diffusivity of the solver
- numerical resolution

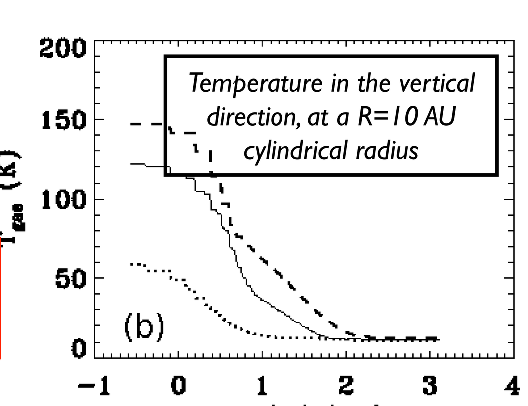
3/ Temperature structure more realistic with the FLD

==> **OBSERVATIONS**, synthetics maps

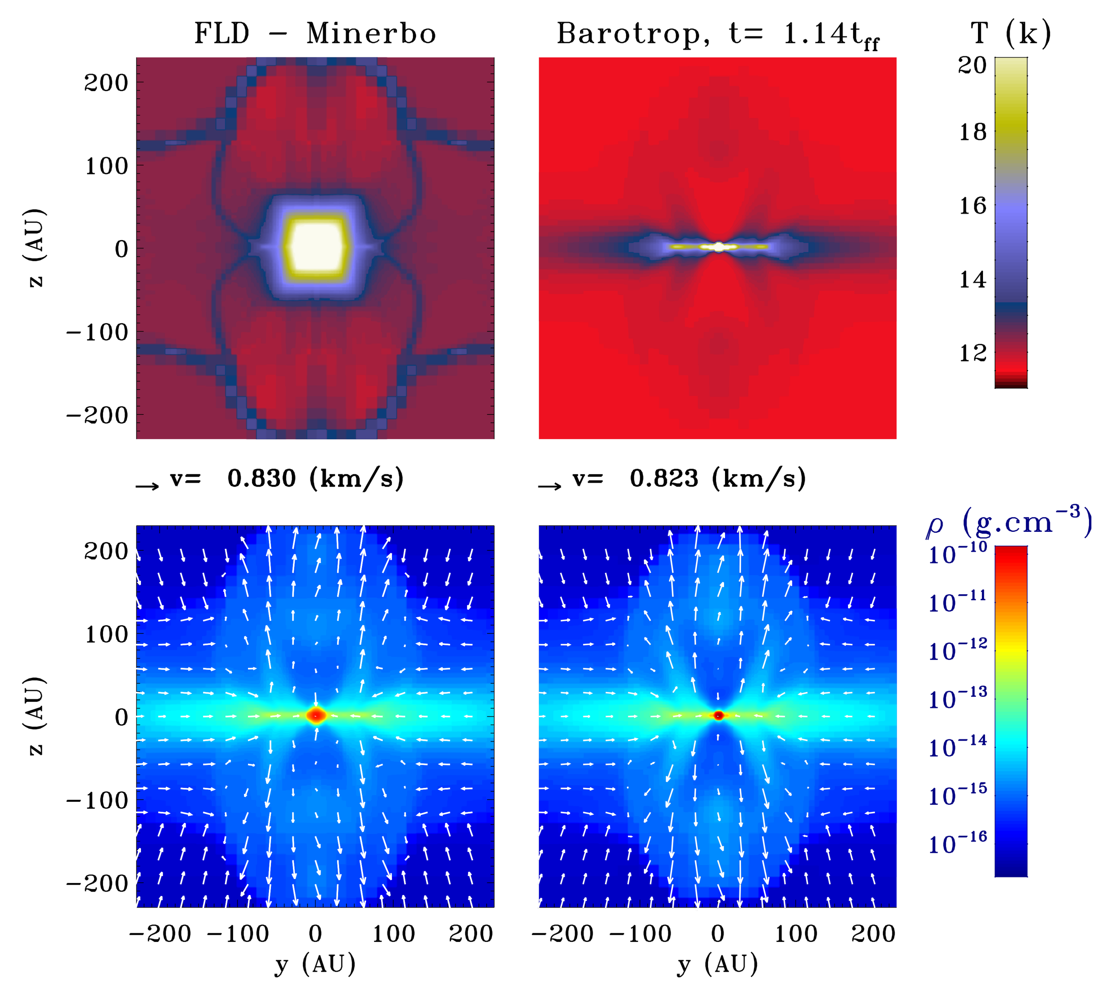
In the low magnetized case (μ=20), numerical diffusion and resolution are key issues. Using either the diffusive Lax-Friedrich (LF) Riemann solver or the less diffusive HLLD Riemann solver, the results can be totally different. On the one hand, the magnetic braking with LF is less efficient, since magnetic field lines are less twisted and compressed. The rotational velocity is then greater, which favors fragmentation (see hydro case). On the other hand, the magnetic braking is very efficient with HLLD, and the infall speed on the 1st core is higher. Since the accretion shock on the 1st Larson core is radiatively supercritical (***all*** the infall kinetic energy is radiated away), this leads to a stronger radiative feedback.

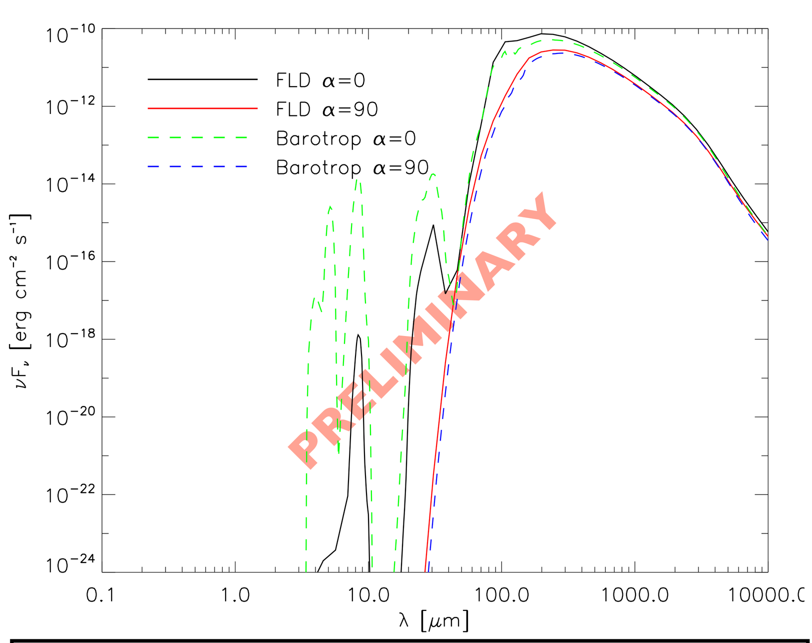






α = 0.35 , β = 0.045 , μ5





SED form the μ=5 case, computed with the 3D radiative transfer code RADMC3D developed by C. Dullemond at MPIA.

In the moderate magnetized case (μ=5), the magnetic field dominates the dynamic. With both, the FLD and the barotropic EOS, an outflow is produced, which have the same properties. However, the temperature distributions differ drastically, THe barotropic EOS cannot account for the significant heating in the vertical directions, found with the FLD. The pseudo-disk, well defined in the density distribution, is not seen in the temperature distribution with the FLD. This could have strong influences if we compare to observations via synthetic emission maps. However, the differences does not appear to be so strong for the SED (see plot on the left).

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CONCLUSION AND PROSPECTS

In agreement with previous studies, we show that a proper treatment of radiative transfer is important to correctly describe the collapse and the fragmentation of a 1 $M_\odot$ dense core. Radiative transfer enables the gas to either cool significantly or heat in different regions of equal densities, whereas a barotropic EOS approximation implies that the cooling and the heating are fixed by the density. We find a strong interplay between magnetic field and radiative transfer, via the magnetic braking and the radiative feedback due to the accretion shock.

We plan to investigate in the near future the effect of the initial angle between the magnetic field and the rotation axis on the disc formation, as well as its observational implications.