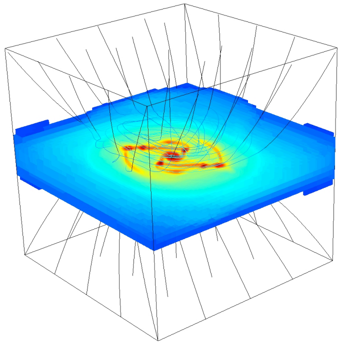
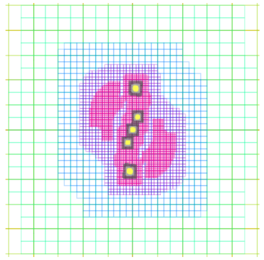
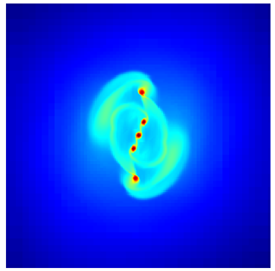
Radiative and magnetic feedbacks on small scale collapse and fragmentation







Commerçon Benoît

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Outlines

1. **Introduction**
2. **Model**
   - Numerical method
3. **Hydro collapse**
   - Fragmentation
   - Entropy content
4. **Magnetized collapse**
   - Moderate magnetic field
   - First steps to synthetic observations

Physics for star formation

- **Gravity: Poisson equation**
- **Hydrodynamics: Euler equations**
- **Radiative transfer: Radiation hydrodynamics**
  - Barotropic EOS (T=f(ρ))
  - Moment models: M1 (HERACLES code, *Gonzàlez et al. 2007*), Flux Limited Diffusion (FLD, e.g. *Minerbo 1978*)
- **Magnetic field: Magneto-Hydrodynamics**
  - Ideal
  - Ambipolar diffusion, Ohmic dissipation
- **H_2 dissociation**
- **Chemistry**
- **Etc .....**

Physics for star formation

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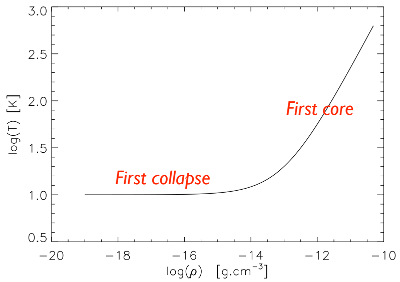
Approximate radiative transfer

⇒ **Barotropic EOS**

2 regimes: isotherm and adiabatic

$$\frac{P}{\rho} = c_s^2 = c_0^2 \left[1 + \left(\frac{\rho}{\rho_c}\right)^{2/3}\right] \propto \rho^{\gamma-1}$$

- $\gamma_{eff} = 1$ if $\rho << \rho_c$ → **ISOTHERM**
- $\gamma_{eff} = 5/3$ if $\rho >> \rho_c$ → **ADIABATIC**



⇒ **Grey Flux Limited Diffusion**

Optically thick (mean free path <<L_{sys}) ==> diffusion approximation: P_r=1/3 E_r, $\partial_t \mathbf{F}_r = 0$

==> Solve a diffusion equation on the radiative energy:

$$\frac{\partial E_r}{\partial t} - \nabla \cdot \left(\frac{c\lambda}{\rho \kappa_R} \nabla E_r\right) = \kappa_P \rho (4\pi B - c E_r)$$

Flux limiter (e.g. *Minerbo 78*)

Flux Limited Diffusion in RAMSES

- ✓ **RAMSES code** *(Teyssier 2002):* 2nd order Godunov scheme, Adaptive Mesh Refinement, ideal MHD (*Fromang et al. 2006)*

- ✓ **RHD solver in the comoving frame using the grey Flux Limited Diffusion approximation** *(Commerçon et al., submitted)*:

$$\begin{cases} \partial_t \rho & + \quad \nabla\left[\rho \mathbf{u}\right] & = \quad 0 \\ \partial_t \rho \mathbf{u} & + \quad \nabla\left[\rho \mathbf{u} \otimes \mathbf{u} + (P + 1/3 E_r)\mathbb{I}\right] & = \quad -(\lambda - 1/3)\nabla E_r \\ \partial_t E_T & + \quad \nabla\left[\mathbf{u}\,(E_T + P + 1/3 E_r)\right] & = \quad -(\lambda - 1/3)\nabla(\mathbf{u} E_r) + \nabla \cdot \left(\frac{c\lambda}{\rho \kappa_R} \nabla E_r\right) \\ \partial_t E_r & + \quad \nabla\left[\mathbf{u} E_r\right] & = \quad -\mathbb{P}_r : \nabla \mathbf{u} + \kappa_P \rho c (a_R T^4 - E_r) + \nabla \cdot \left(\frac{c\lambda}{\rho \kappa_R} \nabla E_r\right) \end{cases}$$

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

- ✓ **Largest fan of solution with speeds:**

$$\begin{cases} u - \sqrt{\frac{\gamma P}{\rho} + \frac{4 E_r}{9 \rho}} \\ u \\ u + \sqrt{\frac{\gamma P}{\rho} + \frac{4 E_r}{9 \rho}} \end{cases}$$

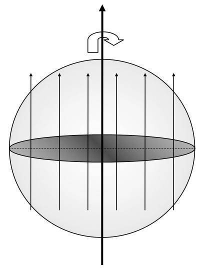
- ✓ **Implicit solved with an iterative conjugate gradient algorithm**

- ✓ Linearize emission term $(T^{n+1})^4 = 4(T^n)^3 T^{n+1} - 3(T^n)^4$

Initial conditions

1 $M_\odot$ isolated dense core: uniform density and temperature (10 K), solid body rotation ($\beta = E_{rot}/E_{grav}$), m=2 density perturbation (amplitude 10%)
==> Small-scale fragmentation

★ Ideal MHD <==> flux freezing: $\varphi \propto BR^2$
Magnetic field lines are twisted and compressed:



==> **Outflow** *(e.g. Machida et al., Banerjee & Pudritz 06, Hennebelle & Fromang 08)*

$\mu = (\varphi/M)_{crit} / (\varphi/M)$ (observations $\mu \sim 2\text{-}5$)

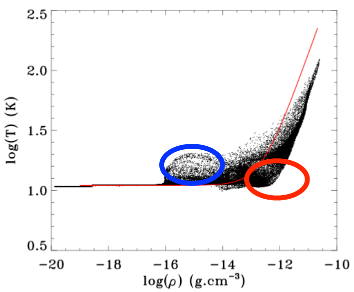
★ Radiative transfer: efficient cooling (*Attwood et al.09*) and heating (*Krumholz et al. 09, Bate 09*). Grey opacities from *Semenov et al. 03*.

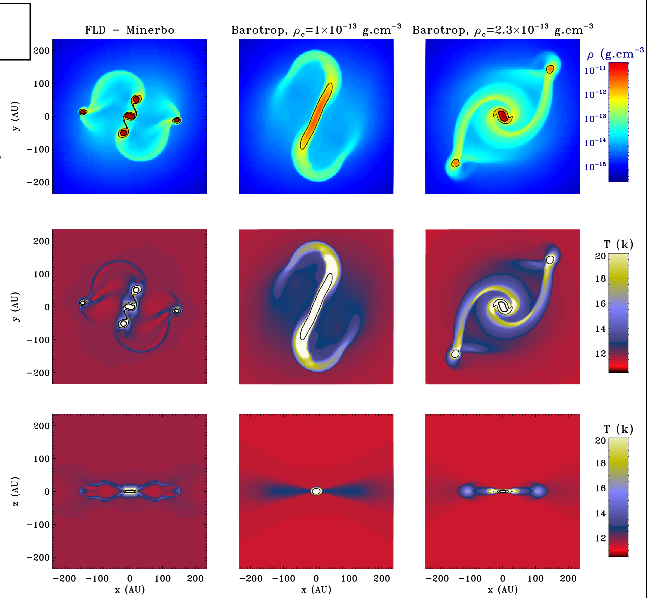
Radiation-HydroDynamics calculations

α = 0.50 , β = 0.04 , m=2 , A=0.1

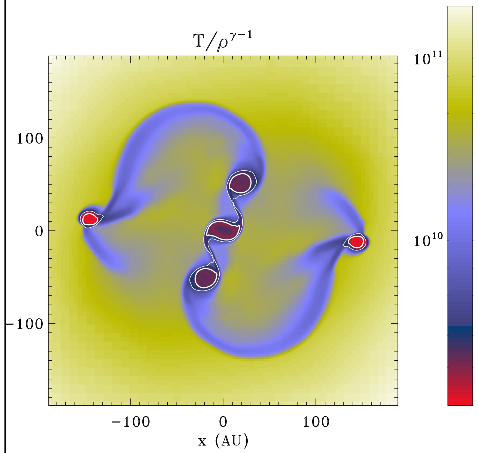
FLD: more fragments, gas cools efficiently in the vertical direction

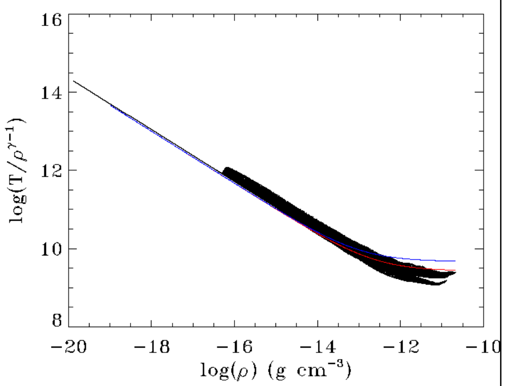
==> lower Jeans mass





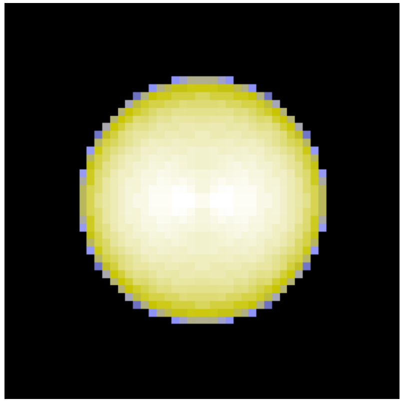
Radiation-HydroDynamics calculations





Entropy content of the fragments depends on their location and time of formation. This may have a strong influence for the PMS evolution (entropy sets the radius)

Radiation-HydroDynamics calculations



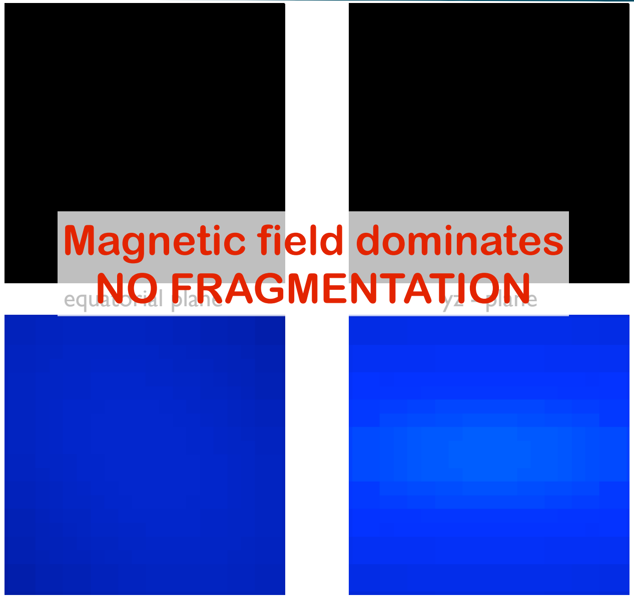
But dense core are magnetized (e.g *Heiles & Crutcher 2005*)

+ Magnetic field inhibits fragmentation (*Hennebelle & Teyssier 2008*)

=> Does the efficient cooling found with the FLD helps to fragment in presence of a magnetic field?

Moderate magnetized case, μ=5, RMHD

Temperature

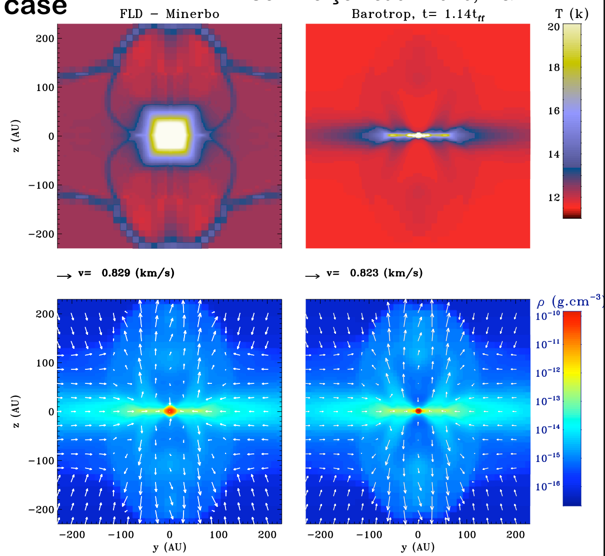


Density

Moderate magnetized case, μ=5, RMHD

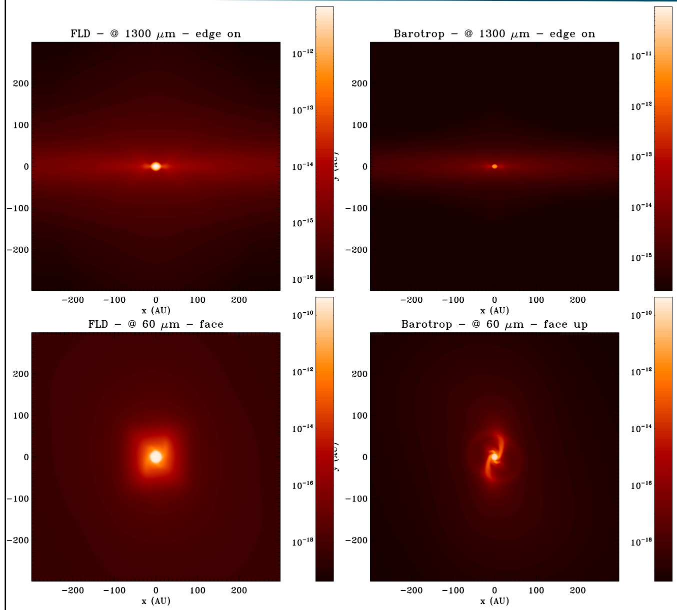
Comparison to the barotropic case

Commerçon et al. 2010, A&AL

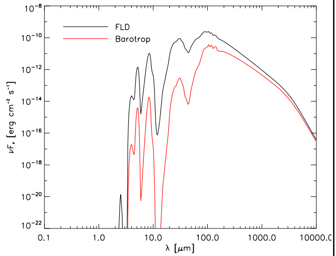


- Density set by magnetic field
- Similar outflow velocity
- Significant differences in the temperature distribution <=> **observations**

Dust continuum emission maps & SED



Edge on SED



Images & SED produced with the radiative transfer code **RADMC3D**, developed by C. Dullemond (MPIA)

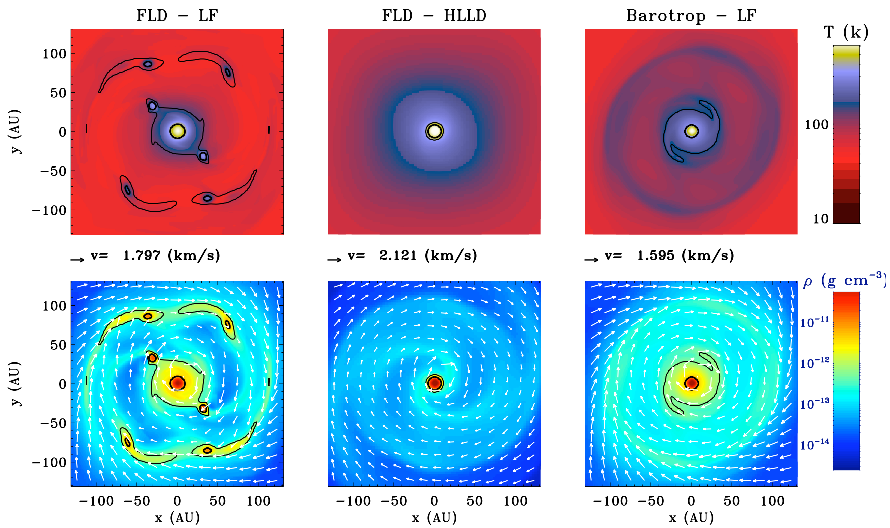
Conclusion & prospects

- ☑ **R**adiation-**M**agneto-**H**ydro**d**ynamic solver with **AMR**
- ☑ **First** full RMHDs calculations of dense core collapse at small scales (see also **Tomida** poster)
- ☑ Entropy of the first cores different => 2nd collapse?
- ☑ Magnetic field **inhibits** small-scale fragmentation, even with radiative transfer
- ☑ Magnetic braking **favors** radiative feedback (see *Commerçon et al. 2010*)

- ★ Effect of the angle rotational axis/magnetic field (*Hennebelle & Ciardi 2009*)?
- ★ Synthetics maps and SED for **HERSCHEL** and **ALMA** prediction (waiting for data of first cores!)
- ★ Combined effect of magnetic field and radiative feedback in massive star formation?

THANK YOU

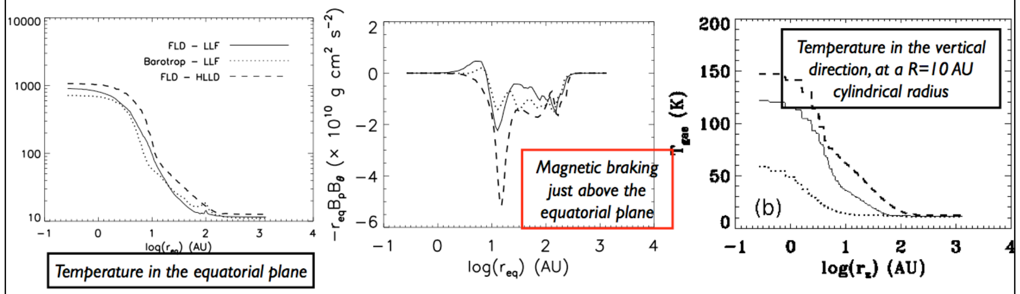
Intermediate case, μ=20 - Numerical issue



Commerçon et al. 2010, A&AL

Intermediate case, μ=20 - Numerical issue

Commerçon et al. 2010, A&AL



✓Diffusivity of the solver => 2 effects that favor fragmentation:

- ➡ inefficient magnetic braking
- ➡ more massive disk

✓ Radiative feedback depends on the magnetic braking: $L_{acc} \propto V_{inf}^3$ (supercritical radiative shock)!