Multigroup radiation-hydrodynamics with flux-limited diffusion and adaptive mesh refinement

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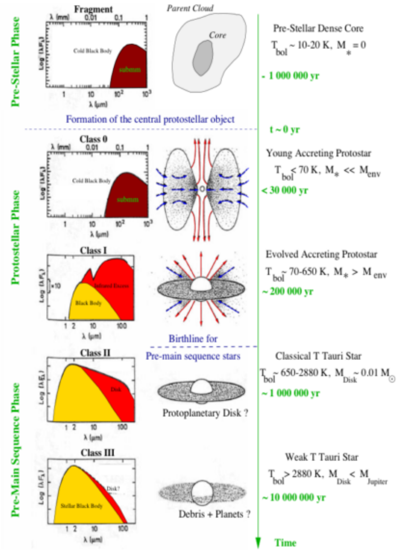
Star formation : context



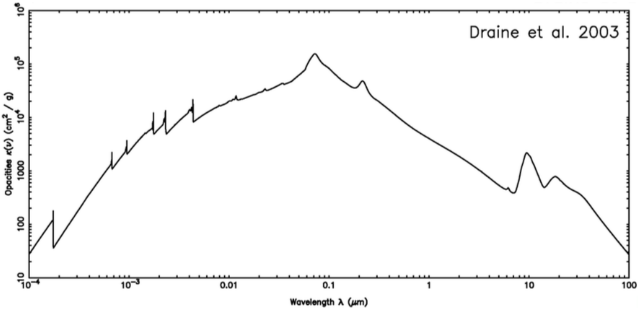
from André 2002

Pre-stellar phase :

- collapse of dense molecular cloud
- optically thin, isothermal collapse : first Larson core $R \sim 10$ AU, $M \sim 0.02\ M_\odot$, $T \sim 1200$ K, $\rho \sim 10^{-8}$ g/cm^3
- optically thick ($\rho \sim 10^{-13}$g/cm^3), adiabatic contraction
- until H_2 dissociation, new collapse : second Larson core $R \sim 0.01$ AU, $M \sim 0.001\ M_\odot$

Star formation : context (2)

- hydro or MHD calculations with barotropic EOS
- RHD with grey FLD : radiative transfer can strongly inhibit fragmentation in collapsing clouds (Price & Bate 2009, Offner et al. 2009, Commerçon et al. 2010).
- 1D multigroup RHD (Vaytet et al. 2013)



The multigroup FLD model

Moment equation of the transfer equation

If LTE and isotropic scattering are assumed :

$$\partial_t E_r^\nu + \nabla \cdot \left(\lambda \frac{-c}{\sigma_a^\nu + \sigma_s^\nu} \nabla E_r^\nu \right) = \sigma_a^\nu (4\pi B^\nu - c E_r^\nu)$$

The multigroup method splits the frequency domain into domains (called groups) where the radiative variables are considered constant.

$$\partial_t E_g + \nabla \cdot \left(\lambda \frac{-c}{\sigma_{Fg}} \nabla E_g \right) = c(\sigma_{Pg} \Theta_g(T) - \sigma_{Eg} E_g)$$

Numerical implementation

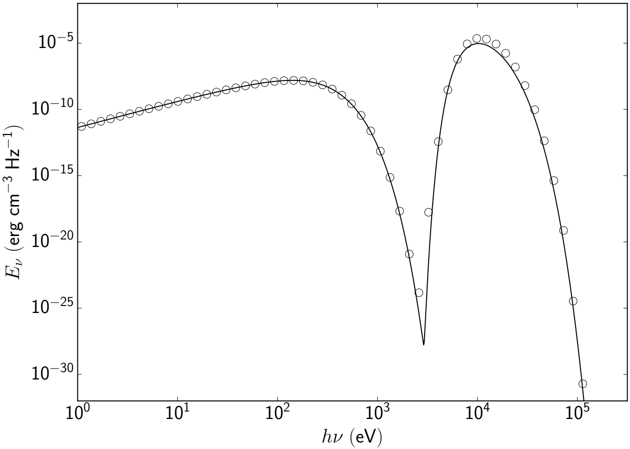
- Previous work (not exhaustive !)
  SPH code (Stamatellos et al 2007, Price & Bate 2009)
  Orion (Krumholz 2007, Hansel et al 2012)
  ATON (Aubert & Teyssier 2008)
  RAMSES-RT (Rosdhal & Teyssier 2014)
- Our implementation
  The RAMSES code (Teyssier A&A 2002, Fromang et al. 2006)

  Followed the implementation of
  - grey FLD in RAMSES in 3D (Commerçon et al. 2011, 2014)
  - multigroup method in 1D simulations (Vaytet et al. 2011, 2013)

  Implicit scheme for radiation : BiCGSTAB algorithm (van der Vorst 1992)

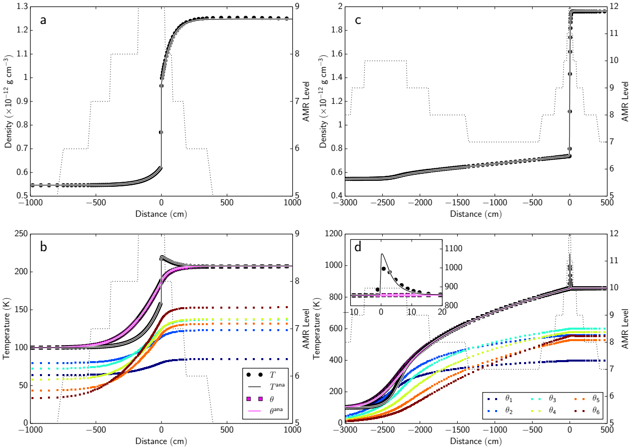
Validation tests (1) : radiating plane

- hot slab at $T_s = 1500$ eV
- cold medium at constant temperature $T_0 = 50$ eV
- opacities $\sigma_g \propto \nu_g^{-3}$
- 60 groups



Validation tests (2) : radiative shocks

- Rankine-Hugoniot jump as initial conditions
- constant Planck and Rosseland opacities
- 6 groups
- Mach number 2 and 5

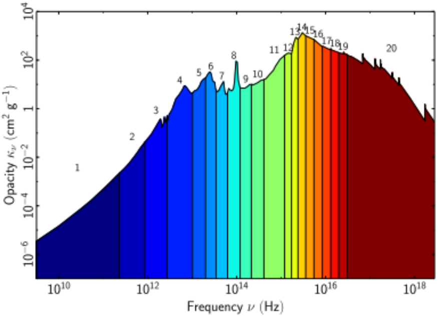


Star formation simulation setup

Isolated dense core

- 10 K, 1 $M_{\odot}$, $R_0 = 2500\ AU$
- uniform-density sphere rotating about z-axis ($\frac{E_{rot}}{E_{grav}} = 0.03$)
- surrounding medium 100 times less dense
- $\frac{E_{th}}{E_{grav}} = 0.25$
- z-aligned B with $\mu = 5$
- Jeans length sampled by a minimum of 12 cells
- finest resolution of 0.15 AU (l=5 to 11)
- $m = 2$ perturbation (with $\delta_{\rho} = 0.1$)

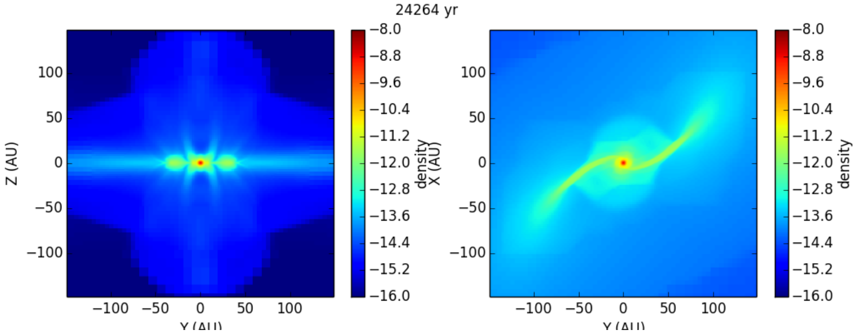
cf. setup of Commerçon et al. 2010



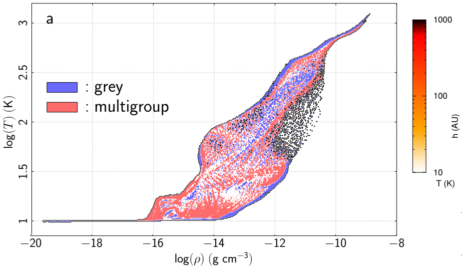
opacities from Vaytet et al. 2013 at $\rho = 10^{-18}$ g.cm^{-3} and $T = 10$ K

20 groups with 18 evenly log spaced between 5×10^{10} and 1.3×10^{14} Hz

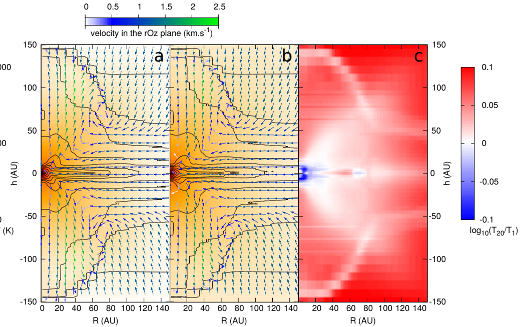
Star formation results



Star formation results



(T,ρ) of simulation cells

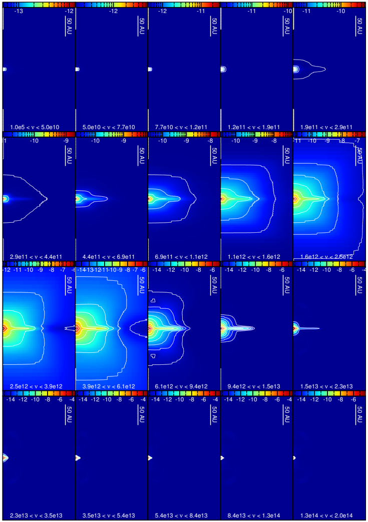


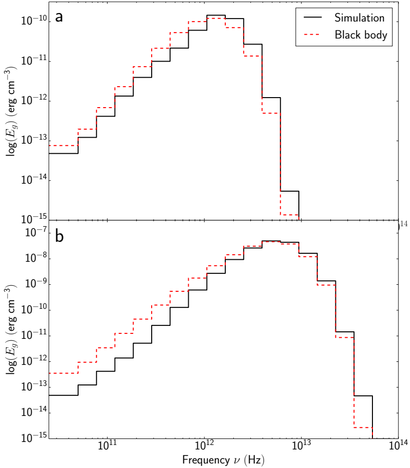
Temperature map with velocities for grey - multigroup and temperature ratio

With multigroup : colder protostar - hotter environment

Small differences ($\sim$ 20%)

Star formation results (2)





SED at 2000 AU and 20 AU

Multigroup simulations give information for channel maps and SED without post-processing software needed

Summary and perspectives

- Summary
  - development of multigroup FLD in RAMSES
  - validation with academic tests
  - simulation of 1 $M_\odot$ star formation (up to the first Larson core)

González et al. 2015, A&A, 578, A12

- Perspectives
  - massive star formation : 100 $M_\odot$
    - sink particles with radiative feedback (luminosity - prestellar evolution)
    - grey vs multigroup vs irradiation model (Kuiper et al. 2010)
  - enable non-ideal MHD terms (Masson et al. 2012)
  - global simulation of molecular cloud collapse with turbulence