Simulations of massive magnetized dense core collapse

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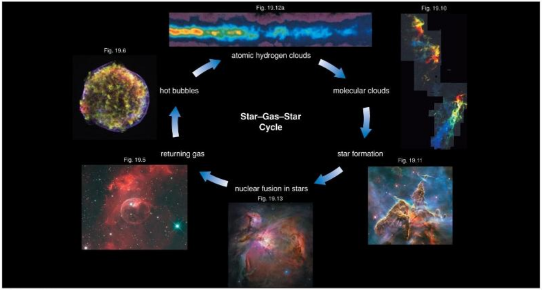
Outline

Star formation : context



Interstellar medium life cycle

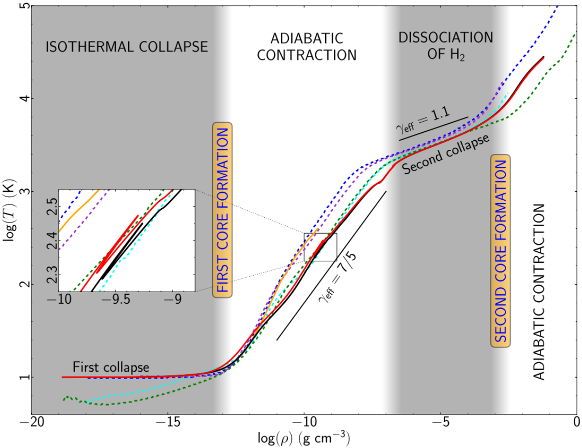
Open questions

- angular momentum transport
- disc formation
- fragmentation IMF/CMF

Pre-stellar phase of star formation

- pre-stellar dense core : R $\sim$ 0.1 pc
- first Larson core : R $\sim$ 10 AU
- second Larson core : R $\sim$ 0.01 AU

Vaytet et al. 2013



Why studying the high-mass stars ?

high-mass stars ($M>8M_\odot$, $L>10^3\ L_\odot$) :

- a few ($\simeq 1\%$)
- but dominant in energetic budget
  - kinetic : outflows, jets, winds, SN explosion
  - radiative : luminosity, ionisation, radiative pressure

Few observational constraints

- short lifetime
- fewer in number

Main difference compared to low-mass star formation :

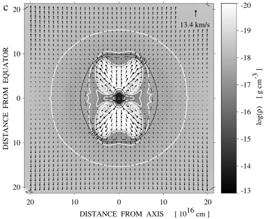
- still accreting when star forms

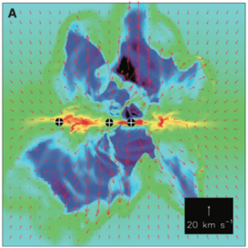
$\Rightarrow$ important feedback : radiative pressure, ionization

The radiation barrier

- stars up to 150 $M_\odot$ are observed (Figer 05, Crowther+10 ;16)
- 1D analytical (Larson & Starrfield 71) and numerical (Kuiper+10) estimate of 20 $M_\odot$
- 2D effect : disc-accretion, flashlight effect (Yorke & Sonnhalter 02, Kuiper+10)
- 3D simulations : Rayleigh-Taylor instabilities (Krumholz+07, Rosen+16)

Yorke & Sonnhalter 02





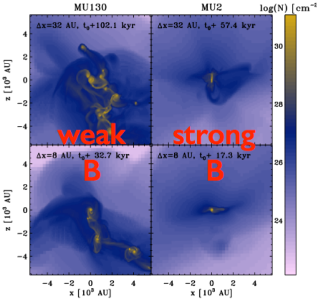
Krumholz+09

But the magnetic field is neglected

The fragmentation issue

2 scenarii

- competitive accretion (Bonnell et al. 2004)
- core accretion (McKee & Tan 2003)



Interplay between radiative feedback and magnetic field reduces the fragmentation (Commerçon+11, Myers+13)

We build up on these results of isolated massive core by including non-ideal MHD and radiative transfer

Star formation simulation setup

We use RAMSES (Teyssier 2002) with

- grey FLD (Commerçon+11, González+15)
- sink particles (Bleuler & Teyssier 2014) with protostellar feedback (Hosokawa+10)
- hydro or ideal MHD or ambipolar diffusion (Masson+12,16)

$$
\begin{aligned}
\partial_t \rho &+ \nabla \cdot [\rho \mathbf{u}] &&= 0 \\
\partial_t \rho \mathbf{u} &+ \nabla \cdot [\rho \mathbf{u} \otimes \mathbf{u} + P\mathbb{I}] &&= -\rho \nabla \Phi - \lambda \nabla E_\mathrm{r} + (\nabla \times \mathbf{B}) \times \mathbf{B} \\
\partial_t E_\mathrm{T} &+ \nabla \cdot [\mathbf{u}\,(E_\mathrm{T} + P_\mathrm{T}) - \mathbf{B}(\mathbf{B} \cdot \mathbf{u}) - E_\mathrm{AD} \times \mathbf{B}] &&= -\rho \mathbf{u} \cdot \nabla \Phi - \mathbb{P}_\mathrm{r} \nabla : \mathbf{u} - \lambda \mathbf{u} \nabla E_\mathrm{r} + \nabla \cdot \left(\frac{c\lambda}{\rho \kappa_\mathrm{R}} \nabla E_\mathrm{r} \right) \\
\partial_t E_\mathrm{r} &+ \nabla \cdot [\mathbf{u} E_\mathrm{r}] &&= -\mathbb{P}_\mathrm{r} \nabla : \mathbf{u} + \nabla \cdot \left(\frac{c\lambda}{\rho \kappa_\mathrm{R}} \nabla E_\mathrm{r} \right) + \kappa_\mathrm{P} \rho c (a_\mathrm{R} T^4 - E_\mathrm{r}) \\
\partial_t B &- \nabla \times (\mathbf{u} \times \mathbf{B}) - \nabla \times E_\mathrm{AD} &&= 0
\end{aligned}
$$

Ambipolar diffusion EMF : $E_\mathrm{AD} = \dfrac{1}{\gamma_\mathrm{AD} \rho_\mathrm{i} \rho} [(\nabla \times \mathbf{B}) \times \mathbf{B}] \times \mathbf{B}$

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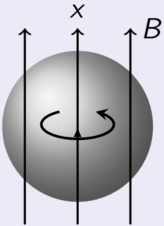
Initial conditions

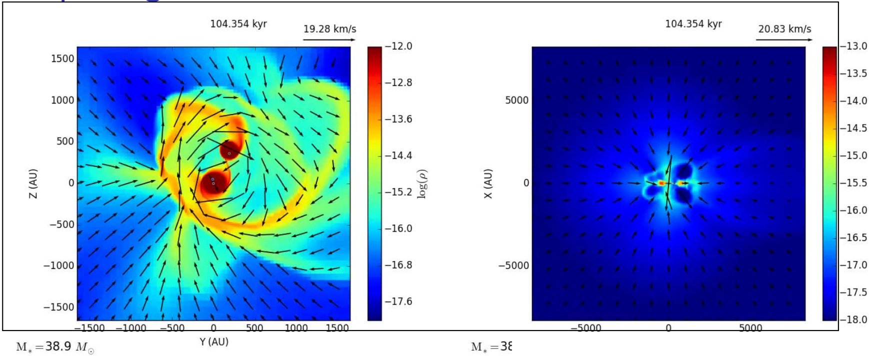
cf. Krumholz et al. 2009, Kuiper et al. 2010

- isolated massive dense core
- 20 K, 100 $M_\odot$, $R_0 = 0.2$ pc
- finest resolution of 5 AU
- $B \simeq 170\ \mu$G ($\mu = 2$)



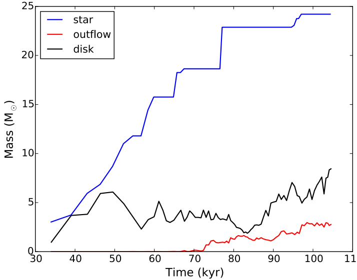
solid body rotation

Morphologies with HYDRO



$M_* = 38.9\ M_\odot$

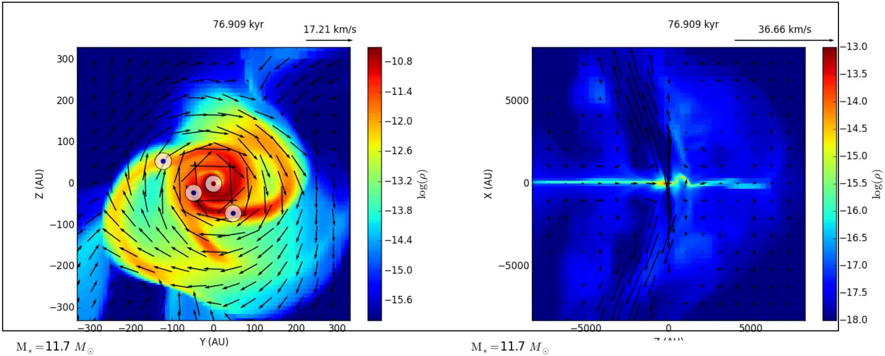
$M_* = 38$



Results

- binary system (25 $M_\odot$ and 14 $M_\odot$)
- outflow of $\simeq$ 1500 AU

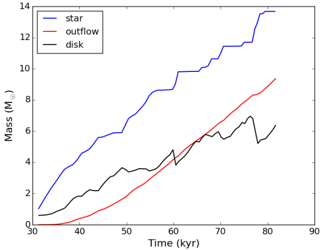
Morphologies with Ambipolar Diffusion



$M_* = 11.7\ M_\odot$ $M_* = 11.7\ M_\odot$

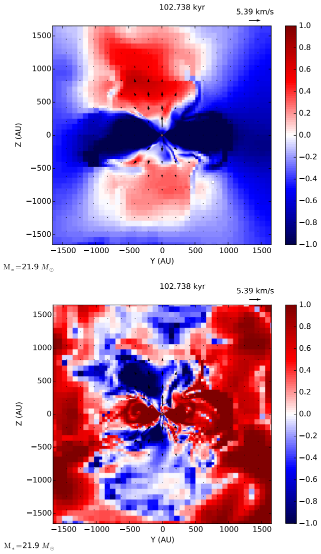
Results

- single star
- massive and large (80 000 AU) outflow



Outflow origin

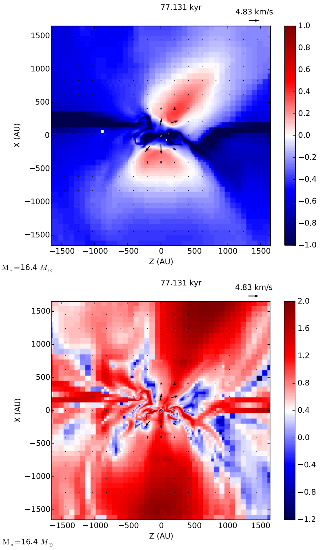
ideal MHD



$$\log(f_{\mathrm{rad}}/f_{\mathrm{grav}})$$

$$\log(f_{\mathrm{Lor}}/f_{\mathrm{rad}})$$

Ambipolar Diffusion



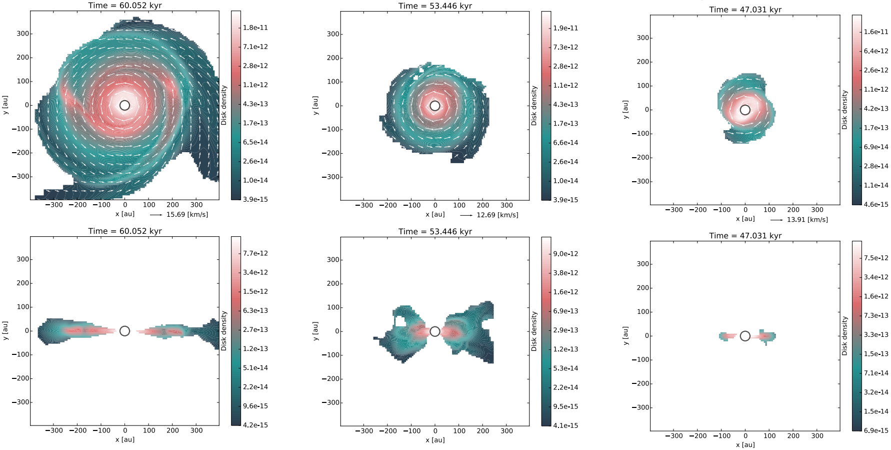
Radiative origin

Magnetic origin

Disc properties

Disc selection criteria (Joos et al. 2012) : $\rho > 10^{-15}$ g/cm^3, $v_\phi > 2v_{r,z}$, $\rho v_\phi^2 > P$

Hydro   ideal MHD   Ambipolar Diffusion

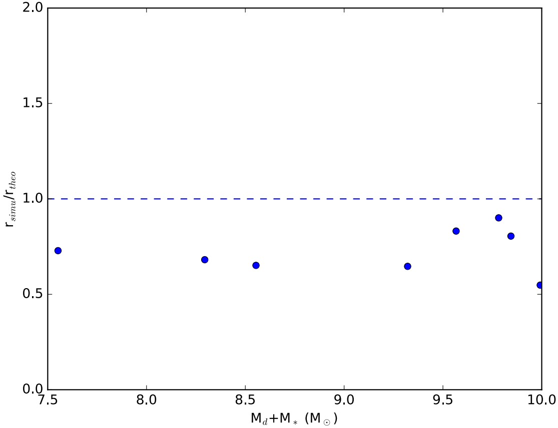


large disc
dominated by $\mathrm{P_{mag}}$

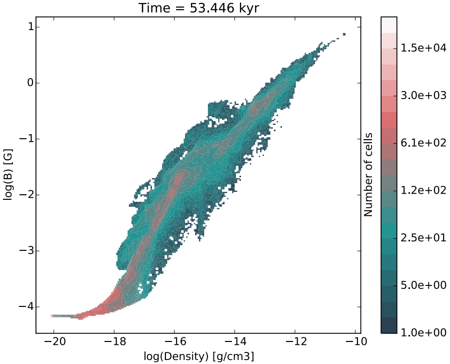
small disc
dominated by $\mathrm{P_{th}}$

Disc size

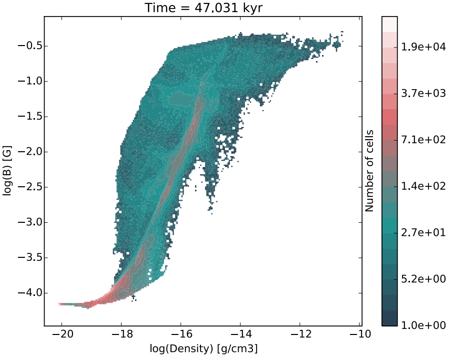
Comparison to an analytical model (Hennebelle+16)



Magnetisation



iMHD



AD

AD reduces B_{max} by one order of magnitude with a plateau at about 0.3 G

Summary and perspectives

100 $M_\odot$ dense core collapse with AD

article in prep.

- magnetic outflow collimated by toroidal magnetic field
- no radiative Rayleigh-Taylor instabilities
- thin and small discs dominated by thermal pressure

Perspectives

- grey vs multigroup/irradiation model (Kuiper et al. 2010) cf. R. Mignon-Risse
- global simulation of molecular cloud collapse with turbulence
- synthetic observations

Numerical perspectives : towards exascale computing

- heterogeneous hardware : CPU, GPU, MIC...
- more complex parallelism
- load balancing, scaling (up to 100,000 cores)
- fault-tolerant
- I/O

$\Longrightarrow$ need to adapt/re-write our codes : RAMSES + canoP (MDLS)
$\Longrightarrow$ development/test/maintain (e.g. RAMSES_ISM)

Specificity of radiation (M)HD

- implicit solver
- iterative method with large matrix inversion

$\Longrightarrow$ coupling with linear algebra libraries ? (Kokkos/Trilinos, PETSc)