Simulations des phases précoces de formation stellaire de faible et haute masse

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Outline

1. Introduction & Methods
2. Low-mass stars
   - fragmentation, disk formation
   - second collapse
   - synthetic observations
3. Massive dense cores
   - fragmentation inhibition by magnetic field and radiative transfer
   - observations (comparison, predictions)
4. Conclusion and perspectives
Empirical evolutionary sequence

Prestellar dense core collapse
- First collapse
  - Isothermal
    - First Larson core
      - Adiabatic
        - \( H_2 \) dissociation
          - Second collapse
            - Quasi-isothermal
              - Second Larson core

\[ T \approx 10-20 \text{K}, \ M_\odot = 0 \]
\[ t \approx 1 \times 10^7 \text{yr} \]
\[ T_bol < 70 \text{K}, \ M_\odot << M_{\text{env}} \]
\[ t < 3 \times 10^4 \text{yr} \]
\[ T_bol \approx 70-650 \text{K}, \ M_\odot > M_{\text{env}} \]
\[ t \approx 2 \times 10^5 \text{yr} \]
\[ T_bol \approx 650-2880 \text{K}, \ M_\odot \approx 0.01 M_\odot \]
\[ t \approx 1 \times 10^6 \text{yr} \]
\[ T_bol \approx 2880 \text{K}, \ M_\odot < M_{\text{Disk}} \]
\[ t \approx 10^8 \text{yr} \]

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André 2002
Empirical evolutionary sequence

Machida et al. (2010)

Prestellar dense core collapse

First collapse

 Isothermal

First Larson core

Adiabatic

H₂ dissociation

Second collapse

Quasi-isothermal

Second Larson core
Study collapse, why?

- link between CMF and IMF, i.e., between the ISM and the stellar system, SFE
- disk formation - link to planet formation
- multiplicity:
  - when/how is it set?
  - linked to the disk formation issue
- Some of the big problems:
  - fragmentation, disk formation
  - massive star formation
  - angular momentum/magnetic flux
2010 - State of the art

- ideal MHD + barotropic EOS commonly used
- first 3D calculations with radiative transfer (grey FLD) and ideal MHD
- first collapse and first Larson core formation and evolution
Influence of the magnetization

- **MU=5**
  - Strong B

- **MU=20**
  - Weak B

- **Hydro**
  - B=0

Magnetic field dominates

**NO FRAGMENTATION**

The Fragmentation Crisis (e.g., Hennebelle & Teyssier 2008)
Tool developments

- **non-ideal MHD** in the AMR code RAMSES (Teyssier 2002): ambipolar diffusion, Ohmic dissipation (Masson et al. 2012)

- **multigroup FLD** in 1D spherical code and in RAMSES (Vaytet et al. 2012, 2013, González et al. in prep)

- new method for implicit schemes on AMR grids (Commerçon et al. 2014). Factor >5 faster for FLD + can be applied for non ideal MHD

- **interface** between RAMSES outputs and the 3D radiative transfer code RADMC-3D (Dullemond, Heidelberg)
1 $M_\odot$ dense core collapse: FLD vs. barotrop

Comparison to the barotropic case

- **Hydro case**: more fragmentation
- **RMHD**: magnetic braking $\iff$ radiative feedback ($L_{\text{acc}}$)
- Significant differences in the temperature distribution $\iff$ observations

Commerçon et al. 2010, A&AL
Influence of turbulence and misalignment

**Misalignment**

Disk formation

- Keplerian disk
- Disk
- No disk

**Turbulence**

\( \mu = 5, \varepsilon_{\text{turb}} = 0.2 \)

**Convergence?**

- \( \mu = 5, r < 100 \text{ AU} \)
- \( r < 500 \text{ AU} \)
- \( r < 1000 \text{ AU} \)

Joos et al. (2012, 2013)

Ciardi & Hennebelle (2011)
Influence of non-ideal MHD

Disk formation and interchange instability

- reduce magnetic braking (suppress counter-rotation found in ideal MHD)

- similar qualitative results in the turbulent case

  *but*

- magnetic pressure is greatly reduced in the disk with AD

- changes at the first core scale

- diffusion is *controlled*
Second collapse

- grey RT does well in 1D spherical geometry

- second core accretion shock is sub-critical at the beginning (all is transferred to the protostar!)

Vaytet et al. (2012,2013)

- 3D is running in RAMSES. Stay tuned!
Synthetic observations

3D radiative transfer

interface with the 3D radiative transfer code RADMC-3D (Dullemond, ITA-Heidelberg, Germany) to postprocess the RAMSES calculations.

★ RADMC-3D features:
- dust continuum emission
- line emission

★ RADMC-3D outputs:
- dust emission maps
- spectral energy distribution
- line emission maps/profiles

ALMA PREDICTIONS

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Synthetic observations

3D radiative transfer

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Commerçon et al. (2012a)
Chemical composition

- $10^6$ tracer particles & store position, temperature & density
- Compute the chemistry using the Bordeaux NAUTILUS gas-grain chemistry code (655 species, >6000 reactions)
- 50 000 CPU hours for chemistry

=> Access to the 3D abundances within the collapsing dense cores

CO abundance in the gas phase

Hincelin et al., 2013
Line emission (under progress)

H$_2$CO @ 145 GHz

=> Rotation of the outflow!
100 $M_\odot$ turbulent dense core collapse

- Magnetic fields alone reduced fragmentation by a factor $\sim 2$
- Fragmentation zone is less extended in strongly magnetized cores

$\mu=120$
$\mu=5$
$\mu=2$

Hennebelle et al. (2011)
100 $M_\odot$ turbulent dense core collapse

✓ Early fragmentation suppressed with magnetic fields (large scale) & radiative transfer (small scales < a few 100 AU)

100 $M\odot$ turbulent dense core collapse

- Simulations reproduce remarkably well observations, but... for both the strong and weak magnetized cases.
- Find only one correlation for the number of mm-clumps versus the density at 0.05 pc, i.e., the denser the more fragmented.

Take Away for SF

✓ Magnetic field and radiative transfer cannot be neglected

✓ Strong interplay between magnetic braking and radiative feedback

✓ Disk can form but do not fragment

✓ Ideal MHD has strong limitation on the horizon of predictability
Conclusions & perspectives

- Powerful tools with a lot of physics: non ideal MHD, radiative transfer and chemistry
- Direct comparison between observations and 3D models (tracer particles)
- What next?
  - initial conditions
  - more statistics, IMF
  - second collapse in 3D
  - coupling chemistry (MHD, cooling/heating), cosmic ray
- Link to planet formation via disk formation issue and chemistry
THANK YOU