Formation of Protostellar Cores and Circumstellar Disks

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Introduction: Star Formation

Initial State: Molecular Cloud Core
Final State: Protostar, Disk, Jet, Outflow

Overall scenario is established, but details are left unknown. Complex physics: multi-dimensionality, large dynamic range, self-gravity, magnetic fields, radiation, chemistry, etc.

ALMA era → Precise modeling are strongly demanded.
⇒ Highly sophisticated computational simulations

Star ex: Sun

Protostar, Disk, Outflow
HH111 (Mckee & Ostriker 07)
Protostellar Collapse: 1D RHD

Masunaga & Inutsuka 2000

4. Second (Protostellar) core

3. Second collapse (H$_2$ dissociation)

2. First (Adiabatic) core

1. Isothermal collapse

The scenario is well established based on 1D RHD simulations. Interplay between radiation, thermodynamics and dynamics.

(see also: Larson 1969 etc.)
In reality: rotation, magnetic fields

(Historic) “Problems” in Star Formation Processes

• Angular Momentum Problem

Cloud Cores \[ j_c \approx 5 \times 10^{21} \left( \frac{R}{0.1 \text{pc}} \right)^2 \left( \frac{\Omega}{4 \text{km s}^{-1} \text{pc}^{-1}} \right) \text{cm}^2 \text{s}^{-1} \]

\[ \Rightarrow \]

\[ j_* \approx 6 \times 10^{16} \left( \frac{R_*}{2R} \right)^2 \left( \frac{P}{10 \text{day}} \right)^{-1} \text{cm}^2 \text{s}^{-1} \text{Stars} \]

→ Efficient angular momentum transport during protostellar collapse
⇒ Gravitational torque, Magnetic braking, Outflow

• Magnetic Flux Problem

Similarly, magnetic flux in cloud cores >> stellar magnetic flux
→ Magnetic fields must dissipate during the collapse
⇒ Ohmic Dissipation, Ambipolar Diffusion, (Hall effect)

• “Magnetic Braking Catastrophe” (Mellon & Li 2008,09, Li+ 2011, etc.)
Magnetic barking is too efficient; no circumstellar disk is formed
⇒ Long-term accretion, non-ideal MHD effects, etc. (Machida+ 2011)

⇒ Realistic 3D simulations with many physical processes!
ngr³mhd code

Required elements for SF studies

- Huge dynamic range: → 3D nested-grids
- MHD → HLLD (Miyoshi & Kusano 2005)
  (+ Carbuncle care → shock detection + HLLD-)
  ✓ Fast, robust and as accurate as Roe’s solver
  ✓ Independent from the details of EOS
- \( \text{div } \mathbf{B} = 0 \) constraint → Hyperbolic cleaning (Dedner+ 2002)
- Self-gravity → Multigrid (Matsumoto & Hanawa 2003)
- Radiation → Gray Flux Limited Diffusion (Levermore & Pomraning 1981)
  + Implicit (BiCGStab + ILU decomposition (0) preconditioner)
- EOS including chemical reactions ← partition functions
- Ohmic dissipation → Super Time Stepping (Alexiades+ 1996)
- Computers: NEC SX-9 at NAOJ, JAXA and Osaka-Univ.

⇒ First 3D RMHD simulations of protostellar core formation!
Simulation Setups

Two rotating models:
• Ideal MHD model
• Resistive MHD model

64^3 x 23 levels, 16 cells / \lambda_{\text{Jeans}}
\min(\Delta x) \sim 6.6 \times 10^{-5} \text{AU} \sim 0.014 \text{Rs}

End of simulations. \( T_c \sim 10^5 \text{ K}, \sim 1 \text{ yr after 2nd core formation} > 10^8 \) !

• 1 Ms unstabilized BE sphere (\( \rho_c = 1.2 \times 10^{-18} \text{ g/cc}, T=10\text{K}, R=8800\text{AU} \))
• \( B_z = 20\mu\text{G} (\mu \sim 3.8), \Omega = 0.046/t_{\text{ff}} \sim 2.4 \times 10^{-14} \text{ s}^{-1} \), aligned rotator
• 10% m=2 density perturbation
• Resistivity (Umebayashi & Nakano 2009, Okuzumi 2009)
Ohmic Dissipation

\[ R_m = \frac{UL}{\eta} = \frac{\tau_{diss}}{\tau_{flow}} \]

Resistivity (w/Dr. Okuzumi): \( \xi = 10^{-17} \) s\(^{-1}\), Neglect shielding of cosmic rays
Need no enhancement, but resolving small high-density region is crucial.
Rotating models: Outflows

Density cross section

- Ideal MHD
- Resistive MHD

Edge-on

Face-on

~140 AU
Rotating models: First cores

Ideal MHD

Resistive MHD
Rotating models: Protostellar cores

Ideal MHD

Resistive MHD
Protostellar Cores

Radii, Masses, Angular momenta

PCs acquire $\sim 0.02 \, M_\odot$ in $\sim 1$ yr

Ideal MHD model = virtually spherical

←very low angular momentum

Circumstellar disk is not formed

“Magnetic Braking Catastrophe”

Resistive MHD: large ang. momentum

→rotationally supported disk is formed

$R_{\text{disk}} \sim 0.3 \, \text{AU}$ at the end of simulation

It will continuously grow via accretion

⇒NO Magnetic Braking Catastrophe
Fast outflow from protostellar core

Toroidal fields are rapidly amplified by rotation in resistive case. → Fast outflow ($\gtrsim 15\text{km/s}$) is driven due to magnetic pressure. Consistent w/ previous MHD sims (Machida et al. 08 etc.) The magnetic tower is disturbed by the kink instability.
Summary

First direct 3D RMHD simulations of protostellar core formation
• Spherical case: consistent with preceding studies.
• In ideal MHD cases, angular momentum transport is efficient → Protostellar cores are not rotating, virtually spherical
• Angular momentum transport is suppressed in resistive cases → Rotationally-supported disk and fast outflow, the disk is small because of short simulation time, but will grow (Machida+ 2011)
• Resistivity works in high density region → High resolution is critical

HOWEVER:
We simulated only 1 year after the protostellar core formation
Timestep is too short, it takes almost as long as real star formation.
⇒ Long term simulations with accurate subgrid models
With some “imagination”...
Thank you