Protostellar collapse of magneto-turbulent cloud core: formation of protoplanetary disks and outflows

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Scenario of star formation: from cloud to protostar

Orion molecular cloud (optical + radio)
Sakamoto et al. (1994)

Cloud Core in Taurus (radio)
Onishi et al. (1999)

Protostar and outflow (radio)
Gueth & Guilloteau (1999)

1-10 AU
0.01 AU

First core
Protostar

$1 \text{AU}/0.1 \text{pc} = 5 \times 10^{-5}$
## Modeling of protostellar collapse

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AMR
Block-structured AMR
Double Mach reflection by SFUMATO

Density

![Density Plot](image)
Sink particles

a subgrid model for a protostar
Tests for sink particles

The sink particle is a Lagrangian particle moving on Eulerian grids. It interacts with gas only via gravity and accretion.

c.f., Krumholz+02 for ORION
Federrath+10 for FLASH
Collapse of a singular isothermal sphere: Accretion onto a sink particle

**density**

- **sink radius**: Gas within the sink radius accretes onto the sink particle.

**infall velocity**

- **black lines**: exact solution
- **colors**: grid level of AMR
- **dots**: numerical solution

radius

radius
Magnetic diffusion
AD, HE, OD
Method for magnetic diffusion

Induction equation

\[
\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) - \nabla \times (\eta \nabla \times \mathbf{B}) + \nabla \times \left[ \frac{c}{4\pi en_e} \mathbf{B} \times (\nabla \times \mathbf{B}) \right] + \nabla \times \left\{ \frac{1}{4\pi \gamma \rho_n \rho_i} \mathbf{B} \times [\mathbf{B} \times (\nabla \times \mathbf{B})] \right\}
\]

Operator splitting

- advection
- Ohmic dissipation
- Hall effect
- Ambipolar diffusion

explicit scheme

implicit scheme

with MG
Decay of Alfven wave with AD

\[ \gamma = \text{drag coefficient} \]
Decay of Alfven wave with AD

Ideal MHD

Strong AD

\[
\frac{D\Delta t}{\Delta t^2} = 0, \ 1.28, \ 2.56, \ 12.8 \\
\text{for } \gamma = \infty, \ 1000, \ 500, \ 100
\]

\( \gamma = \text{drag coefficient} \)
C-shock problem with AD.

Fig. 2.—Cartoon of oblique C-shock structure, showing field lines, the direction of shock propagation, and the coordinate system. This problem is set up by starting off with a uniform flow toward the wall and allowing the C-shock to form naturally.

Mac Low+ 95
C-shock: without AD

\[ \rho, \quad \rho \]

\[ v_x, \quad v_x \]

\[ v_y, \quad v_y \]

\[ B_y, \quad B_y \]

Simple accretion shock

\[ M = 50, \ MA = 5, \ \theta = 45^\circ \]
C-shock: with AD

\[ M = 50, \ MA = 5, \ \theta = 45^\circ, \ \rho_i = 10^{-5} \]
Comparison with exact sol.: $M=50$, $MA=5$, $\theta=45^\circ$
Protostellar collapse
Importance of turbulence and magnetic fields

- **Turbulence**
  - Interstellar medium is turbulent.
  - Supersonic turbulence on cloud scale
  - Subsonic turbulence on cloud core scale
  - Scaling law: $\Delta v \propto L^{1/2}$ (Larson 95)
  - Turbulence is origin of rotation (Burkert & Bodenheimer 00)
    - spin of protostar, rotation of protoprametary disk, driven mechanism of outflow/jet, etc.

- **Magnetic field**
  - Interstellar magnetic fields are strong.
  - Magnetic energy $\sim$ gravitational energy
  - Resistivity is effective in high density.
Initial condition of cloud cores

Density
BE sphere $\times (1.25-10)$
Center: $2 \times 10^5$/cc
Radius: $0.049 - 0.14$ pc
Mass: $1.2 - 28$ M$_\odot$
Temp.: 10K

Magnetic fields with OD:
$0.1, 0.25$ B$_{cr}$
$20 - 143$ $\mu$G

Turbulence
$\langle v^2 \rangle \propto k^{-4}$
Mean Mach number
$= 0.5, 1, 3$

Calculation
Cray-XT4@CfCA,
Hitachi-HA8000@T2K
M=1, B=0.1Bcr:
Outflow and disk formation

(200 AU)^3
(20 AU)^3
0.12pc
M = 1, B = 0.25Bcr:
Outflow and disk formation

(200 AU)^3

(20 AU)^3

0.12pc

x-y plane

y-z plane

cavity

outflow

(20 AU)^3
Cavity is filled by strong magnetic field.

Strong $B$

$\beta = 10^{-4}$

Cavity

Decoupled magnetic field creates the cavity.

(200AU)$^3$

green: $\rho = 3.E4 \rho_0$

blue: $v_r = 8 \, c_s$

Sink particle
(20AU)^3

1,000 yr after protostar formation

M=0.5, B=0.25Bcr

M=1, B=0.25Bcr

M=3, B=0.25Bcr

M=0.5, B=0.1Bcr

M=1, B=0.1Bcr

M=3, B=0.1Bcr
Growth of disks: regulated by turbulence and magnetic field

\[ r_{\text{cent}} = \frac{\bar{j}^2}{G(M_{\text{gas}} + M_{\text{sink}})} \]

\[ \bar{j} = \frac{J_{\text{gas}}}{M_{\text{gas}}} \]

Strong turbulent and weak mag field models

Weak turbulent models
Summary

• Our AMR code, SFUMATO:
  – A block-structured AMR is adopted.
  – Selfgravity, MHD, sink particles, magnetic diffusion are implemented.

• A turbulent magnetized cloud core produces a protostar with a protoplanetary disk and outflows.
  – Turbulence brings about rotation of a disk.
    • Strong turbulent models produces a large disk.
  – Rotation and magnetic field drive outflows.
  – Cavity is created by decoupled magnetic field.
    • which corresponds to “a magnetic wall” (Li & McKee 1996).