Contraction and Fragmentation of Magnetized Rotating Clouds and Formation of Binary Systems

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Introduction

- Binary Star Formation
  - Major contribution to the star formation

- Models of Binary Formation
  - Capture
    - encounter of triple single stars (Binney & Tremaine 1987)
    - encounter of stars with circumstellar disks leads to dissipative collision (Clarke & Pringle 1991)

- Fragmentation or Gravitational Instability
  - increasing density reduces the Jeans mass. \( M_f \sim \rho (c_s \tau_{ff})^3 \propto (T/G)^{3/2} \rho^{1/2} \)
  - Growth of \( m=2 \) (bar or spiral mode) leads to binary fragmentation.

\[ \rho \propto \sim \]
Effect of Magnetic Fields

- Promotion of Disk Formation
  - A pseudo-disk extending perpendicular to $B$ is formed.

- Transfer the Angular Momentum if the Cloud $\rightarrow$ discourages Disk Formation
  - $\Omega$ perp. to $B$ is promptly removed.
  - $\Omega$ parallel to $B$ is transferred by magnetic torque.--- magnetic braking
    - Gravitational torque, Magnetic torque, Hydrodyn. Torque

- Affect how Fragmentation Occurs
Initial Condition and Physical Models

- An isothermal cylindrical cloud in hydrostatic balance (Stodolkiewicz 1963)
- Perturbations with the wavelength equal to the Jeans length is added.
- Add non-axisymmetric perturbation $m=2$ as well as axisymmetric $m=0$ mode

$B \rho \propto \Omega$

$H = 10^6 [\text{AU}]$

$M = \sim 20 \, M_\odot$
Physical Models & Numerical Method

- **Ideal MHD**
  \[
  \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \\
  \rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p - \rho \nabla \phi, \\
  \frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{v} \times \mathbf{B}) = 0, \\
  \Delta \phi = 4\pi G \rho
  \]

- **Composite Polytropic Eq. of State**
  - Which mimics the result of 1D RHD (e.g., Masunaga, Inutsuka 2000).
  \[
  p = c_s^2 \rho + c_s^2 \rho_{\text{crit}} \left( \frac{\rho}{\rho_{\text{crit}}} \right)^{7/5} \\
  p \approx \begin{cases} 
  c_s^2 \rho & (\rho \leq \rho_{\text{crit}}) \text{ Isothermal} \\
  K \rho^{7/5} & (\rho > \rho_{\text{crit}}) \text{ Adiabatic}
  \end{cases}
  \]

- **Parameter**
  - Magnetic-to-Thermal Pressure Ratio
    \[
    \alpha = \frac{B_0^2}{4\pi c_s^2 \rho_{0c}}
    \]
  - Angular Rotation Speed / Free-Fall Rate
    \[
    \omega = \Omega \left( 4\pi G \rho_{0c} \right)^{1/2}
    \]
Why this is so Hard?

- Non-homologous Collapse
  - Dynamic ranges of size and density scales are huge.
    \[
    \rho_{1\text{SM}} \sim 10^2 \text{cm}^{-3} \quad \rho_{2\text{ND CORE}} \sim 10^{17} \text{cm}^{-3} \\
    L_{1\text{SM}} \sim 0.1 \text{pc} \quad L_{2\text{ND CORE}} \sim 10^{11} \text{cm}
    \]

- "Nested Grid" Technique
  - Coarser grid: covers global structure
  - Finer grid: small-scale structure near the center.
    - # of cells: \(128(x) \times 128(y) \times 32(z) \times 17\) (level)
    - Equivalent to simulations with \(\approx 1.5 \times 10^{20}\) grids at the center.

- Jeans Condition (Truelove et al. 1997)
  - To achieve physically correct answer:
    \[
    \Delta x < \lambda_j / 4 = \left[ (4\pi G \rho)^{1/2} / c_s \right] / 4
    \]
  - Simulations continues till the "Jeans Condition" is violated at the deepest level of grid (17th Level).
\( \alpha = 1, \; \Omega_0 = 5 \) (L2)
(A_{m2}, \alpha, \omega) = (0.2, 1, 0.5)

Model with strong magnetic field and high rotation speed

Only after the sufficiently thin disk is formed, the non-axisymmetric perturbation can grow.

Initial state
\[ \rho = 10^3 \text{ cm}^3 \]
\[ L = 1 \]

\[ \rho = 10^4 \text{ cm}^3 \]
\[ L = 2 \]

\[ \rho = 10^5 \text{ cm}^3 \]
\[ L = 3 \]

\[ \rho = 10^7 \text{ cm}^3 \]
\[ L = 6 \]

\[ \rho = 10^9 \text{ cm}^3 \]
\[ L = 9 \]

\[ \rho = 10^{10} \text{ cm}^3 \]
\[ L = 11 \]

\[ \rho = 10^{11} \text{ cm}^3 \]
\[ L = 12 \]

3. Results

Side view
\( x=0 \) plane

Pole-on view
\( z=0 \) plane

Isothermal phase \hspace{5mm} Adiabatic phase
Typical Model
\((A_{m2}, \alpha, \omega) = (0.01, 0.01, 0.5)\)

In this model, the non-axisymmetry hardly grows because disk formation is delayed for weak magnetic fields.
Initial state $\rho=10^2 \text{ cm}^{-3}$ $L=1$

$\rho=10^3 \text{ cm}^{-3}$ $L=1$

$\rho=10^4 \text{ cm}^{-3}$ $L=2$

$\rho=10^5 \text{ cm}^{-3}$ $L=3$

$\rho=10^7 \text{ cm}^{-3}$ $L=6$

$\rho=10^9 \text{ cm}^{-3}$ $L=9$

$\rho=10^{10} \text{ cm}^{-3}$ $L=11$

$\rho=10^{11} \text{ cm}^{-3}$ $L=12$

This corresponds to strong B-field & slow rotation.

Core Model $(A_{m2}, \alpha, \omega)=(0.01, 1, 0.1)$

Disk $\rightarrow$ Spherical core

Isothermal phase $\rightarrow$ Adiabatic phase
Definition of oblateness and axis-ratio of cores

Oblateness $\equiv \varepsilon_{ob} = \sqrt{\frac{h_{\text{long}}}{h_{\text{short}}}}$ \\
Axis-ratio $\equiv \varepsilon_{ar} = \frac{h_{\text{long}}}{h_{\text{short}}}$ \\
$h_z$ : length of the z-axis \\
$h_{\text{long}}$ : length of the long axis \\
$h_{\text{short}}$ : length of the short axis

- oblateness: thickness of the disk \\
- axis ratio: degree of the non-axisymmetry
(1) Non-axisymmetric deformation begins to grow after a disk is formed.
(2) The critical oblateness above which a bar grows is approximately equal to 4.
(3) A disk is formed earlier. Then, the bar-mode grows greatly.
Modes of Fragmentation

**bar fragmentation**
\[ A_{m2} = 0.2 \quad \delta = 1.0 \quad \Omega = 0.5 \]

**ring fragmentation**
\[ A_{m2} = 0.01 \quad \delta = 0.01 \quad \Omega = 0.5 \]

Density (false color, contour)
Velocity (arrows)

Shape of the magnetic field line (red stream lines)
Outflow region (blue isovolume)
Effect of Magnetic Fields

• Non-Magnetic Cloud Collapse
  • For the first core to fragment: A Bonnor-Ebert-like cloud should have $\omega > 0.05$ (Matsumoto & H '03; Poster #)

• Magnetic Cloud
  • Boss (1999) showed $\alpha = 4.4$ and $\omega > 0.077$ clouds fragment.
  • Our lower bound for fragmentation is much high.
    • Magnetic torque plays a role to remove the angular momentum in our model.

Boss 02

MH 03

Shape at the core-formation epoch.

0 0.1 0.5 1 5
$\alpha$ magnetic parameter

0 0.1 0.5 1 5
$\omega$ rotation parameter

Fragmentation
Outflow
$A_m=0.01$
$A_m=0.1$
$\times$ merge
$\times$ survive

Fragmentation occurs if the oblateness is over 4 at the beginning of the adiabatic phase. After fragmentation, some binary fragments result in merger. To survive at the end of the simulation, the axis ratio must be a smaller than 2 (ring fragmentation) or greater than 10 (bar fragmentation).

The necessary condition for the binary formation is following:
- oblateness > 4
- axis-ratio < 2
- or axis-ratio > 10

Survive to form binaries:
- : core
- : disk
- : ring
- : bar

After fragmentation:
- not merge
- merge
Classification of Evolution

- $\varepsilon_{ob} < 4$
- $\varepsilon_{ar} < 2$
- $\varepsilon_{ob} > 4$
- $\varepsilon_{ar} > 2$
- $\varepsilon_{ar} > 10$
- $2 < \varepsilon_{ar} < 10$

- Initial
- Disk
- Bar
- Fragmentation
- Core
- Ring
- Merge

- Isothermal phase
- End of the isothermal phase
- Adiabatic phase

$\varepsilon_{ob}$: Oblateness
$\varepsilon_{ar}$: Axis ratio
$t$: Time
Summary

- Fragmentation in magnetized cloud is studied by 3D MHD nested grid simulations.
- Two types of fragmentation appear: ring fragmentation, bar fragmentation.
- Two effects of magnetic field:
  - transfers the angular momentum from the core and forms a non-fragmented core.
  - Promotes the disk formation and encourage the bar fragmentation.