Expected Observations of the Star Formation Process: Magnetic Field\textsuperscript{[1]} and First Hydrostatic Core\textsuperscript{[2]}

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Based on:
\textsuperscript{[1]} Kataoka, Tomisaka, & Machida (2012; ApJ in press)
\textsuperscript{[2]} Tomisaka & Tomida (2011; PASJ, 63, 1151)
Observational Visualization

- How is the simulation result observed?
  This enables us to compare simulation with observation directly.

- Identification of a first hydrostatic core
  - Apply non LTE radiation transfer (MC method)
  - Identification of FC by radio molecular line obs.
    KT & Tomida (2011)

- Configuration of B-field realized in star forming stage
  - Barotropic MHD simulation of grav. Contraction of molecular cores.
  - Sink cell method is applied for protostar phase.
    Kataoka, Machida & KT (2012; astro-ph this week)
Magnetic Field Observation

- **Direction / Configuration** ↔ **Linear Polarization**
  - Interstellar dust is aligned as its major axis is perpendicular to the interstellar magnetic field.
  - Polarization of thermal emission from interstellar dust $\Rightarrow E_{pol} \perp B_{ISM}$
  - Dichroic extinction leads $\Rightarrow E_{pol} \parallel B_{ISM}$

- **Zeeman splitting**
  - Strength of $B$

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Interstellar B-Field

Thermal dust emission

Background star

Dichroic extinction

mm, submm

IR, opt

E
Hourglass B-Field

Polarization of dust thermal emission NGC1333 IRAS 4A

Girart + 2006

(1) Hourglass shape B-field

(2) Polarization degree is low in the direction of major axis of the disk.

Goncalves + 09

Fig. 1. Map of NGC 1333 IRAS 4A, from GRM06. Contours show the continuum emission at 877 μm, bars indicate the direction and degree of polarization (magnetic field vectors), and the color map shows the polarized intensity. At the distance of 300 pc, 1" corresponds to 300 AU.
S-shaped Magnetic Field

Shinnaga + 2012

Polarization E-vector

350μm Total intensity

CO outflow

disk

jet

massive protostar

0.5 pc
- 2D polarization is a consequence of the 3D configuration of B-field.

- To study B-field from polarization, we have to solve ‘inverse problem’ 2D $\rightarrow$ 3D. However, this is hard to solve.

- We perform MHD gravitational collapse simulation. Then, evolution of polarization pattern is calculated for each snapshot.

**Initial models**

- **No rotation**
  - Bonnor-Ebert sphere

- **Aligned rotation**
  - Rotating disk
  - Poloidal field

- **Misaligned rotation**
  - Fast rot.
  - Slow rot.

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- **In protostar phase**
  - Pseudo-disk
  - Pure Poloidal B-field
  - Poloidal+Toroidal B-field
  - Rotation dominated
  - B-Field dominated
No Rotation Model

Early Phase of Prestellar Stage

\[ M_{\text{cl}} \approx 1.1 M_\odot \]

Late Phase of Prestellar Stage

\[ \varepsilon_{\text{cl}} = 0.05 \]

Early Phase of Protostar Stage

\[ M_* \approx 0.05 M_\odot \]

Late Phase of Protostar Stage

\[ M_* = 0.55 M_\odot \]
Early Phase of Prestellar Stage

$M_{cl} \approx 1.1M_\odot$

Early Phase of Protostar Stage

$M_* \approx 0.05M_\odot$

Late Phase of Prestellar Stage

Late Phase of Protostar Stage

$M_* \approx 0.55M_\odot$

Edge-on Polarization

Hourglass type pol. pattern

Total intensity

Polarization degree
Effect of Inclination

Low polarization degree region extends in the direction of major axis of the total column.

Late Phase of Protostar Stage
Depolarization

(1) Foreground and background B-field lines intersect each other with $\sim 90$ deg.
(2) Dust alignment is perpendicular.
(3) This leads low polarization.

3D View of B-Field
$\theta = 60$ deg

This does not occur for edge-on.
Comparison with Observation

Polarized Intensity

GOOD AGREEMENT
Rotating Case = Poloidal + Toroidal B-Field

(1) Disk rotation amplifies toroidal B-field from poloidal B-field.

(2) B-field is composed of poloidal + toroidal components above the disk.

(3) When poloidal and toroidal components are approx. equal, cancelation occurs between fore and rear side of B-field.

(4) Low polarization regions and horizontal direction pol. are made above and below the disk.
Effect of Inclination Angle

Indication of Existence of toroidal comp as well as poloidal comp.

Low polarization degree regions extend in a point-symmetric way rather than the line-symmetric way.
Why do I emphasize the toroidal B-Field?

- To extract angular momentum, $F\phi$ is needed.
- Lorentz $j \times B$ force in $\phi$-direction comes from poloidal current $J_p$ and poloidal B-field $B_p$.
- $J_p$ comes from toroidal B-field $B\phi$.
- To extract angular momentum, both components of $B_p$ and $B\phi$ are important.
Misaligned Rot.-Dominated Model

early phase of prestellar stage → final phase of prestellar stage → Late phase of protostar stage

From X-axis

(a) t=6.3 × 10^6[yr], n=2.3 × 10^4[cm^3], Φ=0°

S-Shape

(b) t=7.3 × 10^6[yr], n=2.4 × 10^4[cm^3], Φ=0°

S-Shape

(c) t=1.1 × 10^7[yr], M_p=0.5[M_{Sun}], Φ=0°

Hourglass shape

From Y-axis

(d) t=6.3 × 10^6[yr], n=2.3 × 10^4[cm^3], Φ=90°

S-Shape

(e) t=7.3 × 10^6[yr], n=2.4 × 10^4[cm^3], Φ=90°

Hourglass shape

(f) t=1.1 × 10^7[yr], M_p=0.5[M_{Sun}], Φ=90°

Hourglass shape

Another configuration S-shape appears as well as hourglass. Hourglass axis and disk minor axis do not coincide.
3D Configuration and Polarization

(1) A disk is made perp to the rotation axis.
(2) Viewing from the x-axis, S-shape pol. pattern is observed.
(3) Viewing from the y-axis, hourglass-shape pol. pattern is seen. But disk is inclined.
The early phase of protostar phase

In both directions, an hourglass type polarization pattern is observed, even in the early phase of protostar phase. Magnetic axis perp to the disk.
Summary

- Linear polarization of thermal dust emission is calculated for gravitational collapse.
- Poloidal field gives hourglass shape.
  - Depolarization occurs in the direction of major-axis of the disk.
- Rotation amplifies toroidal B-field
  - Identification of toroidal is explored;
  - Depolarization occurs just below/above the disk.
  - Point-symmetric polarization degree distribution.
- In misaligned case, not only hourglass shape but also S-shape pol. pattern is expected, especially in rotation-dominated case
  - In B-dominated case, we expect hourglass shape.