Observing Magnetic Field In Molecular Clouds

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\( \frac{\partial B}{\partial t} = \nabla \times (v \times B) + \eta \nabla^2 B \) (Induction Equation)

*Coupling between gas and B-field*

Image courtesy: of NASA
**turbulence > the B-field**

**Coupling between gas and B-field**

$$M_A = \frac{\sigma}{V_A}$$
### Observation tools

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<td><strong>Dust grain alignment:</strong></td>
<td><em>polarization</em> of dust thermal emission</td>
<td>⊥B</td>
<td>A&lt;sub&gt;v&lt;/sub&gt; &gt; 100 mag</td>
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<td><em>polarization</em> of background star light</td>
<td>//B</td>
<td>A&lt;sub&gt;v&lt;/sub&gt; &lt; 5 mag</td>
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<td><strong>Zeeman effect</strong></td>
<td>freq. splitting of <em>circular</em> line polarization</td>
<td>B&lt;sub&gt;los&lt;/sub&gt;</td>
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<tr>
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<td><em>linear</em> line polarization</td>
<td>⊥ or //B</td>
<td>Goldreich-Kylafis effect</td>
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- **B-field:** Arrow indicating the direction of the magnetic field. 
- **Transitions:** Diagram showing energy level transitions. 
- **Spectra:** Comparison of spectra with and without a magnetic field.
FIRST MULTISCALE STUDY of CLOUD MAGNETIC FIELDS from $10^2$ to $10^{-2}$ pc

• One of the nearest massive star forming region (~1.7 kpc away)
• Other sites forming massive stars are usually too far away to use starlight polarization
• Combine optical/sub-mm polarization data and try to understand the role of B-field

NGC 6334

mage credit: S. Willis (CfA+ISU); ESA/Herschel; NASA/JPL-Caltech/Spitzer; CTIO/NOAO/AURA/NSF

Multiscale Study of B-field in NGC6334: From 100pc to 10pc scale

- Intercloud medium (ICM)
  - Optical Polarimetry (Heiles 2000)
  - IRAS 100-μm map

- Zooming in to the cloud
  - SPARO 450-μm polarimetry
  - CSO 350-μm map

- The cloud preserve the initial B-field direction

- Pinching of field lines at density peaks
Multiscale Study of B-field in NGC6334: From 10pc to 1pc scale

- Cloud scale
  - SPARO 450-μm polarimetry
  - CSO 350-μm map
- Zooming into the clump scale
  - CSO 350-μm polarimetry & map (Dotson et al. 20)
- The cloud preserve the initial B-field direction
- Pinching of field lines at density peaks
Multiscale Study of B-field in NGC6334: From 1pc to 0.1pc scale

- Clump scale
  - CSO 350-μm polarization & intensity map
- Zooming into the core scale
  - SMA 870-μm polarization & intensity map
- The cloud preserve the initial B-field direction
- Pinching of field lines at density peaks
Sub-Alfvenic Turbulence?

Mean magnetic field direction in respective cores

Orientation of the cloud
  • Its relation with B-field

Opening Angle of 30°
  • Competition between B-field & turbulence
Sub-Alfvenic Turbulence!

Observation I:
The cloud orientation are preferentially aligned perpendicular to the mean B-field in all probed scales.

Lorentz Force keeps the gas from collapsing \( \perp \) to B-field.

Channel of matter along the field Lines.

competition between gravity and turbulence in a medium dominated by B fields.

Li et al. 2013
Sub-Alfvenic Turbulence!

Observation II
All the field orientations in Fig. 3 are within this $30^\circ$

Assume turbulence is:
- The Only force that drives the B-field
- Carrying the same energy as the B-fields

$\Delta \phi \sim 30^\circ$

Chandrasekhar Fermi method (1953)

$$B_\perp = (4\pi \rho)^{1/2} \frac{\Delta V}{\Delta \phi}$$

$\Delta \phi < 30^\circ$ Turbulence is sub-alfvenic!!
Coupling between gas and B-field

\[ \mathbf{M} \mathbf{A} = \frac{\sigma}{V_A} \]
Estimating the B-n relation

Applying force balance

\[ F_G = F_P + F_T \]

If B-field is dynamically unimportant:

\[ B \propto n^{0.41} \]

\[ B \propto n^{\frac{2}{3}} \]
Some might say:
Are you really tracing the B-field?
Polarization Hole?

Polarization Fraction decreases with increasing density
It is often seen from dark clouds to active star forming region

Alves et al. 2014
Starless core in pipe nebula

Matthews et al. 2009
W3 main
massive star-forming complex
Explanation given to understand P.Hole:
1. Low grain alignment efficiency in high density

- Dust grains are no longer aligned with magnetic field at some particular density: $A_v > 3$ mag

MHD Simulation:
Super-Alfvenic and Supersonic

- Higher collision rate
- Misalignment of dust grains
- Growth of rounder grains ?!
- Lack of radiation to align dust grains?

*Padoan et al. 2001:*
Dust grains are no longer aligned with magnetic field at some particular density: $A_v > 3$ mag
Explanation given to understand P.Hole

2. Geometrical Effect of magnetic field

*Fiege & Pudritz 2000*

Model the polarization pattern
For filamentary cloud threaded by
*Helical magnetic field*

*Cloud Scale*

*Goncalves et al. 2008*

Simulate polarization map from supersonic/sub-alfvenic simulation
Explaination given to understand P.Hole

2. Geometrical Effect of magnetic field

- Bending of magnetic field lines that counteract the inward pull of gravity
- When B-field lies closer to the line of sight, lower degree of polarization should be observed

Core Scale

0.2 pc
Gonçalves et al. 2005
6000 AU
Kataoka et al. 2012
Insights from archival data?

1. Zoom into the polarization holes
2. Synthesize the beam of single dish telescope
3. Implication of this study
Sub-mm Polarization Data

**Interferometer**
- CARMA
- ~ 2.5 “ resolution
- Capable of resolving cores/discs
- TADPOL 1330um survey (Hull et al. 2014)

**Single Dish Telescope**
- JCMT
- ~ 20” resolution
- Field morphology of clumps
- SCUPOD 850um legacy survey (Matthews et al. 2009)

*Calibration on wavelengths for Polarization Fraction:*
- Polarization Ratio ($\lambda$) compiled from 17 clouds
- Vailliancourt et al. 2008
- $P(850\text{um}) / P(1330\text{um}) \sim 1.7/2.1$
Observation I:
Degree of Polarization is HIGHER in the core?! 

1. $P\%_{\text{CARMA}} > P\%_{\text{SCUBA}}$ in the same telescope pointing!
2. Detection at High density
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Polarization Hole from single dish telescope cannot be explained with:

1. P% CARMA > P% SCUBA in the same telescope pointing!
2. Detection at High density
Observation I: Degree of Polarization is HIGHER in the core?!  

Interferometer (CARMA)  

Polarization Hole from single dish telescope cannot be explained with: The lost of alignment in the dense core!  

Interferometer filters out the diffuse region, sampling a shorter line of sight. Focusing in high density region.

1. $P\% \text{ CARMA} > P\% \text{ SCUBA}$ in the same telescope pointing!  
2. Detection at High density  

If grain alignment is turned off in high density region: low degree of polarization should be observed instead from high density region, opposite to what is observed.
Then why would we see a lower polarization degree in dense region?

- To what extent the unresolved structures on the plane of sky would lower the P%?
- Recover the P% (Single dish trend) ?!
- Smoothing of CARMA detection to SCUBA resolution → Synthesized SCUBA

\[
Q_i = I_i P_i \cos 2\theta_i, \quad U_i = I_i P_i \sin 2\theta_i \\
U_{tot} = \sum_{\text{Beam}} U_i, \quad Q_{tot} = \sum_{\text{Beam}} Q_i, \quad I_{tot} = \sum_{\text{Beam}} I_i \\
\langle P \rangle = \sqrt{\frac{Q_{tot}^2 + U_{tot}^2}{I_{tot}}}
\]
Observation II:  
Smearing effect within the beam

\[
\begin{align*}
Q_i &= I_i P_i \cos 2\theta_i, \\
U_i &= I_i P_i \sin 2\theta_i, \\
U_{\text{tot}} &= \text{Beam} U_i, \\
Q_{\text{tot}} &= \text{Beam} Q_i, \\
I_{\text{tot}} &= \text{Beam} I_i \\
(P) &= \frac{Q_{\text{tot}}^2 + U_{\text{tot}}^2}{I_{\text{tot}}}
\end{align*}
\]

Recipe:  
Mimic the beam of single dish with interferometer data!

Smoothing the interferometer polarization:  
Recover the trend traced by SINGLE DISH
Observation II: Smearing effect within the beam

Counts Ratio = \( \frac{P_{\text{CARMA}} \%}{P_{\text{synthesized}} \%} \)

Majority of the CARMA data has higher P% than the synthesized beam !!!!

The fluctuation within the beam has significant effect in bringing down the P%
Observation II:
Smearing effect within the beam

Stokes I intensity from SCUBA

Ratio = $\frac{P_{\text{CARMA}}\%}{P_{\text{synthesized}}\%}$

Histogram of polarization ratio for all samples
Discussion:
Efficiency of grain alignment ?!

- High Column density
  - longer line of sight dimension $l$
  - Host more turbulent energy
  - $B$-field as Alfven waves
  - Fluctuations of $B$-field $\sigma_v \propto l^{\frac{1}{3}}$ (Larson’s Law)

- Many unresolved $B$-field structures within the beam
  - Fluctuating $B$-field on the line of sight volume
  - Pinching of magnetic field by gravity

- Depolarization/Polarization Hole originates from the unresolved structures within the beam

(Chandrasekhar and Fermi 1953)
Conclusion and Further Work

• Even Higher P% is observed when zooming into Polarization Hole
• Unresolved B-field structure significantly bring down the P%
• Cannot be Explained by the lost of alignment at some particular density/ Av
• We believe line of sight structures would bring P% down greatly
• P% (850um) =/= P%(1100um): contribution from different grains?
  • Can be tested with polarization data with same wavelengths
• Filtering effect of interferometer on polarization?
• Need some better understanding in grain alignment theory!