Maps of Magnetic Field Strength in the OMC-1 Region

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1. Introduction/Motivation.
   1. DCF method.
   2. Angle dispersion analysis.

   1. Moving kernel approach.

   1. Dispersion-LOS-angle Relation
   2. Zeeman calibration.

4. Maps of $B_{total}$ and $M/\phi$.

5. Summary

6. Future Work.
   1. Calibration of DCF method
   2. Maps of $B$ in the Gould Belt Molecular Clouds
   3. Disambiguation of $B_{POS}$ direction
Polarization dispersion and POS magnetic field: The Davis-Chandrasekhar-Fermi (DCF) method.

Mass Density ($\rho$)

Velocity Dispersion ($\sigma_v$)

Angle Dispersion ($\sigma_\phi$)

$$B_{POS} = \sqrt{4\pi \rho \frac{\sigma_v}{\sigma_\phi}}$$
Dispersion Analysis

Polarization dispersion and POS magnetic field:
Two-component dispersion function (Houde et. al., 2013)

\[
1 - \langle \cos[\Delta \phi(l)] \rangle = \frac{1}{1 + N \left[ \frac{\langle B_2^2 \rangle}{\langle B_0^2 \rangle} \right]} \left\{ 1 - \exp \left( -\frac{l^2}{2(\delta^2 + 2W^2)} \right) \right\} + a_2 l^2
\]

- Angle difference
- # turbulent cells in LOS
- Ratio of B-fields energies
- Turbulence correlation length
- Obs. Beam size

\[
\sigma^2_{\phi} \approx \frac{\langle B_2^2 \rangle}{\langle B_0^2 \rangle}
\]
Using the DCF method and dispersion function with HAWC+/SOFIA data of OMC-1.

Chuss et al., 2019

δ: 4 – 10 arcsec
\( \langle B_t^2 \rangle / \langle B_0^2 \rangle : \)
0.23 – 0.34
N: 10 - 30
\( B_0: \sim 0.3 \text{ mG} \)

δ: 9 – 34 arcsec
\( \langle B_t^2 \rangle / \langle B_0^2 \rangle : \)
0.37 – 0.43
N: 4 - 8
\( B_0: \sim 1 \text{ mG} \)

δ: 7 – 10 arcsec
\( \langle B_t^2 \rangle / \langle B_0^2 \rangle : \)
1.61 – 1.77
N: \sim 8.5
\( B_0: \sim 0.3 \text{ mG} \)
1. Applying the DCF method + dispersion analysis in a circular kernel.
Choosing the optimal kernel size.
Maps of POS B strength

MCMC solver: parameter maps.

Guerra et. al., 2021

\[
1 - \langle \cos[\Delta \phi(l)] \rangle = \frac{1}{1 + \mathcal{N} \left[ \frac{\langle B^2 \rangle}{\langle B_0^2 \rangle} \right]^2} \left\{ 1 - \exp \left( -\frac{l^2}{2(\delta^2 + 2W^2)} \right) \right\} + a_2 l^2
\]
Maps of POS B strength

Auxiliary data: Column density and Velocity dispersion.

Spectral Density Energy (SDE) fitting

NH$_3$ multi-line Gaussian fitting

Chuss et. al., 2019

Friesen et. al., 2017
Maps of POS B strength

Combining maps: common resolution.

Gaussian smoothing
• POS strength increases with resolution.
• BN/KL case:
  • Strong POS B.
  • “Cavity”
• Possibility: warm dust is deeper inside the cloud.
Local dispersion $S$:

$$S = \sqrt{\frac{1}{N} \sum_{i=0}^{N} (\phi_i - \bar{\phi})^2}$$

which is debiased

$$S = \begin{cases} \sqrt{S_m^2 - \sigma_S^2}, & S_m > \sigma_S \\ 0, & \text{otherwise} \end{cases}$$

Guerra et al., 2021
Combination of dispersion & Zeeman measurement:

Assuming the dispersion $S$ is dominated by LOS angle (Hensley et al., 2019)*

$$\sin^2(\varphi) = aS^n$$

along with

$$\tan(\varphi) = \frac{B_{POS}}{B_{LOS}}$$

the LOS component can be written as

$$B_{LOS} = B_{POS} \sqrt{\frac{1 - aS^n}{aS^n}}$$
Maps of LOS B strength

Determining power-law parameters

Exponent:

\[ \frac{P}{N(H_2)} \propto S^n \]

Constant:

\[
\ln \left[ \left( \frac{B_{\text{LOS}}}{B_{\text{POS}}} \right)^2 + 1 \right] = -\ln(a) - n \ln(S)
\]

### Wavelength (µm) | n | a | S_0 (deg)
--- | --- | --- | ---
53 | -0.68±0.01 | 2.77±0.68 | 4.47
89 | -0.34±0.01 | 1.42±0.14 | 2.80
154 | -0.52±0.01 | 1.39±0.39 | 1.88
214 | -0.41±0.01 | 1.34±0.14 | 2.04

Guerra et. al., 2021
- "Very" first approximation.
- Scarcity of Zeeman measurements.
- Covariance with $B_{\text{POS}}$ maps.

Guerra et. al., 2021
• $\phi = 90$ deg $\rightarrow$ in the POS.
• $\phi = 0$ deg $\rightarrow$ in the LOS.

Guerra et al., 2021
Maps of Total $B$ strength

- $\varphi = 90$ deg $\rightarrow$ in the POS.
- $\varphi = 0$ deg $\rightarrow$ in the LOS.

Guerra et al., 2021
Super-critical \rightarrow gravity dominated

Sub-critical \rightarrow B-field dominated

Guerra et. al., 2021
**B - Filament Alignment**

Advantage of $M/\Phi$:

- Constructing Histograms of Relative Orientation (HRO).
  - $M/\Phi > 1$ (M.D.) $\rightarrow$ Perpendicular.
  - $M/\Phi < 1$ (G.D.) $\rightarrow$ No preference.

![Graph showing $\xi$ vs $M/\Phi$]

89 $\mu$m
• DCF + dispersion analysis within kernel provides a way to construct maps of POS B field.
• Local dispersion might contain information regarding LOS B – needs further (observations + simulations) testing.
• Variation with wavelength can be more than a resolution issue.
• Maps of $M/\phi$ can complement HROs.
1. Calibration of the DCF method

DCF known biases:

- Isotropic turbulence (assumption)
- Flows (assumption)
- Angular resolution
- Turbulence scale and type (solenoidal, compressive)
- Cloud’s depth (uniform vs. non-uniform)

Numerical MHD simulations:
www.mhdturbulence.com
2. Magnetic Field in the Molecular Clouds of the Gould Belt

- **Archival data**: HAWC+, Herschel, GAS.

<table>
<thead>
<tr>
<th>Target Type</th>
<th>Cloud Complex</th>
<th>Tracer</th>
<th>Distance [pc]</th>
<th>HAWC+ Regions Observed</th>
<th>HAWC+ band</th>
<th>Spatial Scale [pc]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Orion NH$_3$(1,1)</td>
<td>450</td>
<td>OMC-1, OMC-2, D</td>
<td>A, C, D, E</td>
<td>0.01-0.04</td>
<td>0.03</td>
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<tr>
<td></td>
<td>Ophiuchus NH$_3$(1,1)</td>
<td>140</td>
<td>ρ-Oph, L1688</td>
<td>A, C, D</td>
<td>0.003-0.009</td>
<td>0.006-0.009</td>
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<tr>
<td></td>
<td>Perseus NH$_3$(1,1)</td>
<td>300</td>
<td>NGC 1333, D</td>
<td>C</td>
<td>0.02-0.03</td>
<td>0.03</td>
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<tr>
<td></td>
<td>Taurus NH$_3$(1,1)</td>
<td>140</td>
<td>L1544 Core</td>
<td>D</td>
<td>0.02</td>
<td></td>
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<tr>
<td>Secondary</td>
<td>Musca</td>
<td>160</td>
<td>Musca Filament</td>
<td>E</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aquila Rift</td>
<td>260</td>
<td>Serpens S-1</td>
<td>D, E</td>
<td>0.01-0.02</td>
<td></td>
</tr>
</tbody>
</table>

- **New observations**: SOFIA DC9 HAWC+ 214 um Survey of GB clouds.
- **Construction of M/Φ maps and HROs.**
3. Disambiguation of POS B field direction

Energy minimization:

\[ E = |J_{LOS}| + |\nabla \cdot B| \]

through simulated annealing:

- Randomly flip a vector \( \rightarrow \) calculate \( E \).
- Accept:
  - \( E < E_0 \)
  - \( P(E) = \exp\left(-\frac{(E-E_0)}{T}\right) > P_{th} \)
- Reduce \( T \).
- Repeat.