Zeeman Measurements of Magnetic Fields in Star Forming Regions

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Magnetic Fields in Astrophysics – A Brief History

H. C. van de Hulst (1988): \[
\frac{B}{\rho p} = \frac{S}{P_s}
\]

Magnetic fields are to astrophysics what sex is to psychology.

Parallels in development over the years:

1. Everyone knew it existed but good form to ignore it
2. Puzzling phenomena ascribed to it – although beyond explanation
3. It is just a form of energy, although exact understanding may still take a long time

Perhaps, as we are seeing at this conference, our understanding of magnetic fields in astrophysics, while still not exact, has advanced significantly in the past 27 years!
Zeeman Effect – Detected in the ISM

**ONLY** direct measurement of magnetic field strengths available in regions of star formation

Sensitivity limits results to component of $\mathbf{B}$ along the line of sight

Inability to observe directly the magnitudes of all 3 components of $\mathbf{B}$ is the source of much of the controversy on the role of magnetic fields in star formation

<table>
<thead>
<tr>
<th>Species</th>
<th>Wavelength</th>
<th>$n(\text{H})$ traced</th>
</tr>
</thead>
<tbody>
<tr>
<td>H I</td>
<td>21 cm</td>
<td>$10^1 - 10^2 \text{ cm}^{-3}$</td>
</tr>
<tr>
<td>OH</td>
<td>18 cm</td>
<td>$10^3 - 10^4 \text{ cm}^{-3}$</td>
</tr>
<tr>
<td>CN</td>
<td>2.6, 1.3 mm</td>
<td>$10^5 - 10^7 \text{ cm}^{-3}$</td>
</tr>
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</table>
Mass to Magnetic Flux Ratio

\[ M/\Phi \Rightarrow \text{relative importance of gravity to magnetic support} \]

\[ M_{\text{critical}} = \frac{\Phi}{2\pi\sqrt{G}} \]

\[ M = \left(1 + \frac{He}{H}\right)m_H N_H \times \text{area} \]

\[ \Phi = B \times \text{area} \]

\[ \frac{[M]}{\Phi} = \left[\frac{(1 + He/H)m_H}{2\pi\sqrt{G}}\right] \times \frac{N_H}{B} \] (with respect to critical)

\[ [M/\Phi] < 1 \Rightarrow \text{subcritical}, \quad [M/\Phi] > 1 \Rightarrow \text{supercritical} \]
Formation of Molecular Cores

Ambipolar Diffusion  

- clouds initially supported against gravity by magnetic pressure

- \( n_e/n_H \) is lowest in more shielded centers, so mass & magnetic field coupling is weakest

- neutrals collapse through field toward center, slowed by collisions with ions

- mass in center increases until gravity dominates magnetic support in core

- collapse accelerates near center, forming a dense core

Turbulence & Reconnection  

- turbulent flows lead to formation of over dense regions

- magnetic reconnection is inevitable in the turbulent interstellar medium

- reconnection rate \( \propto L^{0.5} \), so important on larger scales, where turbulence is strongest

- initially leads to \( B \sim \) constant, so \( M/\Phi \) can become supercritical on fast time scale, leading to near free-fall collapse

- population of dense cores depends on properties of the turbulence that forms self-gravitating regions
Three Observational Predictions

Ambipolar Diffusion

1. population of self-gravitating, subcritical clouds

2. $M/\Phi$ increases with decreasing radius

3. $B$ scales slowly with density, $B \propto n^\kappa$, with $\kappa < 0.5$

Turbulence & Reconnection

1. no (or few) self-gravitating, subcritical clouds

2. $M/\Phi$ decreases with decreasing radius

3. $B \sim$ constant until free-fall time scale is shorter than reconnection rate ($n \sim 10^4$), then $B \propto n^{2/3}$
CARMA & IRAM CN 2-1 Zeeman Observing

W3OH Position 1 CN  N=2-1 Stokes I Lines
W3OH CARMA CN  N=2-1 Zeeman Results

Position  \( B_{\text{los}} \)
1  +5 ± 1 mG
2  +4 ± 1 mG
3  -2 ± 2 mG
4  -2 ± 1 mG
W3OH IRAM 30m CN 2-1 Zeeman Mapping
W3OH IRAM & CARMA CN 2-1 Line Profiles

![Graph showing line profiles with LSR Radial Velocity (km/s) on the x-axis and Line Strength on the y-axis, comparing CARMA and IRAM data.](image-url)
DR21OH CARMA CN  N=2-1 Zeeman Results

Position | $B_{\text{los}}$ |
--- | --- |
1 | $-8 \pm 2$ mG |
2 | $-5 \pm 2$ mG |
3 | $-6 \pm 2$ mG |
Test 1: Subcritical self-gravitating clouds?

Heiles & Troland 2004
Crutcher 1999
Bourke et al 2001
Troland & Crutcher 2008
Falgarone et al. 2008
Thomas & Troland 2015

\begin{align*}
M/\Phi & \approx 2-3
\end{align*}
Test 2: M/Φ Change from Envelope to Core

\[ M \propto N_H \propto T_{line} \Delta V \]

\[ \Phi \propto B = B_{los} / \cos \theta \]

\[ \frac{[M / \Phi]_{core}}{[M / \Phi]_{envelope}} = \frac{[T_{line} \Delta V / B_{los}]_{core}}{[T_{line} \Delta V / B_{los}]_{envelope}} \]
Test 2: M/Φ Change from Envelope to Core

Crutcher, Hakobian, Troland 2008
# Test 2: M/Φ Change from Envelope to Core

<table>
<thead>
<tr>
<th>Cloud:</th>
<th>L1448</th>
<th>B217-2</th>
<th>L1544</th>
<th>B1</th>
</tr>
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<tbody>
<tr>
<td>(B_{\text{LOS}}(\text{core})):</td>
<td>-26 ± 4</td>
<td>+14 ± 4</td>
<td>+11 ± 2</td>
<td>-27 ± 4</td>
</tr>
<tr>
<td>(B_{\text{LOS}}(\text{envelope})):</td>
<td>-0 ± 5</td>
<td>+2 ± 4</td>
<td>+2 ± 3</td>
<td>-8 ± 3</td>
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\[
\frac{M/\Phi (\text{core})}{M/\Phi (\text{envelope})} : \quad 0.07 ± 0.34 \quad 0.19 ± 0.41 \quad 0.46 ± 0.43 \quad 0.44 ± 0.19
\]

Ambipolar diffusion models require ratio >1

Difference from 1: \(2.7 \sigma\) \(2.0 \sigma\) \(1.3 \sigma\) \(2.9 \sigma\)

Probability \(\geq 1\): \(0.005\) \(0.05\) \(0.11\) \(0.01\)

Probability that \textit{all 4} cores were formed by ambipolar diffusion: \(3 \times 10^{-7}\)

Crutcher+ 2009
Test 3: Scaling of B with Density

Bayesian Analysis of Zeeman Results

| \( |B_z| (\mu G) \) | \( n_H (\text{cm}^{-3}) \) |
|----------------|----------------|
| 1000           | 10^1           |
| 10000          | 10^2           |
| 1000000        | 10^3           |
| 100000000      | 10^4           |
| 10000000000    | 10^5           |
| 1000000000000  | 10^6           |
| 100000000000000| 10^7           |

CRUTCHER+ 2010
Results from Bayesian Analysis

1) PDF of $B_{\text{total}}$ is flat, not delta function (although other PDFs, such as log normal, were not tested)

2) scaling of $B$ with density, $B \propto n^K$

PDF of $K$ from Bayesian analysis
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<td>3) $B \propto \rho^{2/3}$</td>
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Is this definitive and is the issue closed?