Magnetic Fields in the Periphery of Giant Molecular Clouds – Zeeman Effect Observations

\[ \lambda 2.6 \text{ mm} \, ^{12}\text{CO}, J=1-0, \text{ Dame et al. (2001)} \]
Recent collaborators

- Richard Crutcher (University of Illinois)
- Edith Falgarone (ENS, Paris)
- Carl Heiles (Berkeley)
- Kristin Thompson (Ph.D., University of Kentucky)

With partial support from the US National Science Foundation
1. Background – $E_{\text{grav}}/E_{\text{mag}}$

- $\lambda$ is the normalized $M/\Phi$ ratio, where

$$\lambda \approx (E_{\text{grav}}/E_{\text{mag}})^{\frac{1}{2}}$$

*Note - $\lambda$ is the same thing as McKee’s $\mu_\phi$*
1. Background – $E_{\text{grav}}/E_{\text{mag}}$

- If $\lambda > 1$
  - Gravity dominant ($E_{\text{grav}} > E_{\text{mag}}$)
  - Cloud is magnetically “supercritical”
  - $B$ alone cannot prevent collapse of cloud

- If $\lambda < 1$
  - Magnetic field dominant ($E_{\text{mag}} > E_{\text{grav}}$)
  - Cloud is magnetically “subcritical”
  - $B$ alone will prevent collapse of cloud (as long as flux freezing is maintained)
1. Background – $E_{grav}/E_{mag}$

- The mass-to-flux ratio is an observable since

$$\frac{M}{\Phi} = \left( \frac{M}{\text{area}} \right) \propto \frac{N(H)}{B}$$

- Converted to observing units

$$\lambda \approx 5 \times 10^{-21} \frac{N(H)}{B_{\mu G}}$$
2. Measuring $B$ via Zeeman Effect

- Only known method to measure strength of $B$ in localized regions of ISM.

- Involves measurement of very weak circular polarization in radio frequency spectral lines.

- Reveals line-of-sight component $B_{\text{los}}$ only (with rare exceptions).

- Only practical for spectral lines from species with electronic angular momentum (e.g. HI, OH, CN).
2. Measuring $B$ via Zeeman Effect

- The three Zeeman species sample different densities

<table>
<thead>
<tr>
<th>Species</th>
<th>Wavelength</th>
<th>$n$(H) sampled</th>
</tr>
</thead>
<tbody>
<tr>
<td>HI</td>
<td>21 cm</td>
<td>$10^1 - 10^2$ cm$^{-3}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(diffuse gas)</td>
</tr>
<tr>
<td>OH</td>
<td>18 cm</td>
<td>$10^3 - 10^4$ cm$^{-3}$</td>
</tr>
<tr>
<td>CN</td>
<td>2.6 mm ($N=1-0$)</td>
<td>$10^5 - 10^7$ cm$^{-3}$</td>
</tr>
<tr>
<td></td>
<td>1.3 mm ($N=2-1$)</td>
<td></td>
</tr>
</tbody>
</table>
2. Measuring $B$ via Zeeman Effect

- Published Zeeman data comprise 161 measurements of $B_{\text{los}}$

<table>
<thead>
<tr>
<th>Data set</th>
<th>Reference</th>
<th>No. of $B_{\text{los}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compilation (HI, OH, CN as of 1999)</td>
<td>Crutcher 1999</td>
<td>27</td>
</tr>
<tr>
<td>OH absorption</td>
<td>Bourke, Myers, Robinson &amp; Hyland 2001</td>
<td>22</td>
</tr>
<tr>
<td>Arecibo HI absorption Millennium Survey</td>
<td>Heiles &amp; Troland 2004, 2005</td>
<td>67</td>
</tr>
<tr>
<td>Arecibo OH emission (dark clouds)</td>
<td>Troland &amp; Crutcher 2008</td>
<td>34</td>
</tr>
<tr>
<td>IRAM 30m CN, 1-0 emission</td>
<td>Falgarone, Troland, Crutcher &amp; Paubert 2008</td>
<td>11</td>
</tr>
</tbody>
</table>
3. Zeeman Effect in Molecular Cloud Peripheries

- Thompson, Troland & Heiles* used Arecibo to study Zeeman effect in galactic $OH$ absorption lines (1665 & 1667 MHz) toward extra-galactic continuum sources.

- Sources chosen to lie behind galactic molecular clouds.

*to be submitted fall, 2015
3. Zeeman Effect in Molecular Cloud Peripheries

- Lines-of-sight from background continuum sources do not sample molecular cores preferentially.
3. Zeeman Effect in Molecular Cloud Peripheries

Observed 38 velocity components against 21 sources
4. Zeeman Effect – All Data

Red dots are for molecular cloud peripheries

See Crutcher, ARAA, 2012
4. Zeeman Effect – All Data
4. Zeeman Effect – All Data

\[ B_{\text{los}} (\mu G) \]

\[ N_H (\text{cm}^{-2}) \]

\[ \lambda < 1 \text{ subcritical } \]
\[ B \text{-dominated} \]

\[ \lambda > 1 \text{ supercritical } \]
\[ \text{gravity-dominated} \]

\[ \lambda \approx 5 \]

\[ \lambda = 1 \]
4. Zeeman Effect – All Data

Molecular cloud peripheries

Cold Neutral Material (CNM)

$\lambda < 1$ \textit{subcritical}

$\lambda > 1$ \textit{supercritical}

Molecular cores
5. Zeeman Effect Results

A. For $N(\text{H}) < 10^{21} \text{ cm}^{-2}$
   $\lambda < 1$ (i.e. diffuse $\text{H}^0$ gas is magnetically subcritical)
5. Zeeman Effect Results

B. For \( N(H) \approx 10^{21} \) to \( 10^{22} \) cm\(^{-2} \)

\(- \lambda \approx 1 \) in molecular cloud peripheries (red dots)
5. Zeeman Effect Results

C. For $N(\text{H}) < 10^{22} \, \text{cm}^{-2}$

- $B$ constant with increasing $N(\text{H})$ - from diffuse H$^0$ gas through molecular cloud peripheries

- $\lambda$ increases with $N(\text{H})$
5. Zeeman Effect Results

D. For $N(H) > 10^{22}$ cm$^{-2}$

- $B$ increases with $N(H)$ - $\lambda$ becomes constant $\approx 2$-4 (i.e. molecular cores are mildly supercritical)
6. Toward a critical $N(\text{H}) \approx 10^{22}$ cm$^{-2}$

- $N(\text{H}) \approx 10^{22}$ cm$^{-2}$ appears to be a critical value, above which the role of the magnetic field changes.

- As previously noted, $B$ rises with $N(\text{H})$ for $N(\text{H}) > 10^{22}$ cm$^{-2}$
6. Toward a critical $N(\text{H}) \approx 10^{22} \text{ cm}^{-2}$

- Cloud alignment changes from parallel to perpendicular to $B$ for $N(\text{H}) > 5 \times 10^{21} \text{ cm}^{-3}$

*Taurus Molecular Cloud - Planck Collaboration XXXV (J. Soler)*
6. Toward a critical $N(H) \approx 10^{22} \text{ cm}^{-2}$

- Fractional polarization $p\%$ declines sharply for $N(H) > 2 \times 10^{22} \text{ cm}^{-2}$

Planck Collaboration
XIX (J-P Bernard)
6. Toward a critical \( N(H) \approx 10^{22} \text{ cm}^{-2} \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Trend</th>
<th>If ( N(H) &gt; ) (cm(^{-2}))</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B )</td>
<td>Increases</td>
<td>few ( \times 10^{22} )</td>
<td>Zeeman results</td>
</tr>
<tr>
<td>( p % )</td>
<td>Decreases sharply</td>
<td>( 2 \times 10^{22} )</td>
<td>Planck XIX (J-P Bernard)</td>
</tr>
<tr>
<td>Cloud alignment</td>
<td>Changes from \textit{parallel} to \textit{perpendicular} to B</td>
<td>( 0.5 \times 10^{22} )</td>
<td>Planck XXXV (J. Soler)</td>
</tr>
</tbody>
</table>
6. Toward a Critical $N(H) \approx 10^{22} \text{ cm}^{-2}$

- Crutcher et al. (2010) analyzed Zeeman data as a function of volume density $n(H)$.

- They find $B$ rises with $n(H)$ for $n(H)_{\text{crit}} > 300 \text{ cm}^{-3}$.

- If $N(H)_{\text{crit}} \approx 10^{22} \text{ cm}^{-2}$, then a critical magnetic scale length $\approx N(H)_{\text{crit}}/n(H)_{\text{crit}} \approx 10 \text{ pc}$ (sub-GMC size).

- 10 pc is close to Jeans length for a gas with $n(H) \approx 300 \text{ cm}^{-3}$ and $T = 50 \text{ K}$. 
6. Toward a Critical $N(\text{H}) \approx 10^{22} \text{ cm}^{-2}$

- Onset of gravitational instability occurs when total galactic mid-plane pressure $P_o$ equals the gravitational pressure $P_G$ (the mean weight of material in a cloud)$^1$.

- $P_o \approx 4 \times 10^{-12} \text{ dyn cm}^{-2}$ (Boulares & Cox, 1990), $P_G \approx (3\pi/20) \times G \Sigma^2$ (Williams, Blitz & McKee, 1999).

- So $N(\text{H}) \approx 5 \times 10^{21} \text{ cm}^{-2}$

$^1$C. McKee, lunchtime communication (something I learned at this conference!)
7. Conclusions

◆ The role of the magnetic field in cloud evolution changes once self gravitation becomes important.
  – Size scale $\approx 5 - 10$ pc (sub-GMC scale)
  – $n(H)$ $\approx$ few times $100$ cm$^{-3}$
  – So $N(H)$ $\approx 10^{22}$ cm$^{-2}$

◆ As this point is reached
  – $B$ rises with $N(H)$ and $n(H)$, $\lambda$ reaches 2-4 (supercritical)
  – $B$ orientation changes from parallel to perpendicular to filament axes
  – *Per cent* linear polarization $p\%$ declines dramatically