Using the Faraday Effect to Probe Magnetic Fields in HII regions

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Cosmic Magnetism - From Stellar to Intergalactic Scales
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Star formation relies on the accumulation of very diffuse material from large volumes. What is the role of magnetism in star-formation?

\[ B \propto n \]

\[ B \propto n^\kappa \]

Crutcher (2008)
Star formation relies on the accumulation of very diffuse material from large volumes.

What is the role of magnetism in star-formation?
Questions:

› What is the magnetic field strength in HII regions?
› How does magnetic field strength scale with density in the diffuse ISM?
› What is the scale of magnetic field reversals in HII regions?

Previous Work:

› RRLs and HI/OH Zeeman effect can yield $B_{\parallel}$ in much denser material close to periphery of HII regions, (e.g. Bloemhof et al. 1992; Roshi et al. 2007).

› Only a handful of measurements been made of magnetic field strengths within HII regions (Heiles et al. 1980, 1981) in the 1-10 cm$^{-3}$ material.

› Recent improvements in Hα and radio polarization data allow an in-depth study of $B_{\parallel}$ in HII regions.

Methodology:

› We use measurements of the Faraday effect on linearly polarized radio waves from distant galaxies to estimate the magnetic field strength in 5 Galactic HII regions.

› Examine B vs. n relation for 5 HII regions over a factor of 20 change in density.
The Faraday Effect

- **Faraday effect**: Change in polarization angle in a magneto-ionic medium due to circular birefringence (LCP and RCP having different speeds).

\[
\Delta \chi = RM \lambda^2
\]

I’ll wager £20 that

\[
\Delta \chi = RM \lambda^2
\]

Astrophysical Measurement of the Faraday Effect

- Distant galaxies
- **HII region**: \( n_e B || dl \)
- Telescope

\[
RM = 0.81 \int_{src}^{obs} n_e B || dl
\]
A Rotation Measure Image of the Sky

Image: NVSS rotation measure catalogue, (Taylor, Stil & Sunstrum, 2009)

\[
RM = 0.81 \int_{\text{src}}^{\text{obs}} n_e B_{\parallel} dl
\]

Wednesday, 16 June 2010
Image: Hα all sky map, Finkbeiner (2003)

$I_{\text{H}\alpha} \propto \text{Emission Measure}, \quad EM = \int_{\text{obs}} n_e^2 dl$
Calculating \( n_0 \) and \( B_{||} \)

Model:

- If an HII region is clumpy, with clumps \( n_e = n_0 \) and elsewhere \( n_e = 0 \), then:

\[
\begin{align*}
n_0 &= \sqrt{\frac{EM}{fL}} \\
B_{||} &= \frac{RM}{0.81n_0fL}
\end{align*}
\]

- \( f \) = filling factor, \( L \) = path length through HII region
- Other considerations: optical extinction, RM and EM due to back/foreground.

- Given a model for the HII region and filling factor, can determine \( n_0 \) and \( B_{||} \) at each position where we have an RM.
- Use a back/foreground correction to isolate the in situ magnetic field.
- Choose regions outside Galactic plane (dust extinction).
The HII Regions

Sh 2–264

Sh 2–220
The HII Regions
1. Define boundary of HII region

2. *Inside boundary:* For each RM position, calculate the EM from $I_{H\alpha}$

3. Correct each EM for extinction by interstellar dust (assume dust in front)

4. *Outside boundary:* Calculate the RM and EM not due to the HII region and subtract from data within the boundary.

5. Calculate $B_\parallel$ and $n_0$ for each sightline.

6. Plot $B_\parallel$ vs. $n_0$ for each HII region.

$$B_\parallel = \frac{RM}{0.81n_0fL} \quad n_0 = \sqrt{\frac{EM}{fL}}$$

All-sky $E_{B-V}$ map (Schlegel, Finkbeiner & Davis 1998)
Correlation implies *in situ* magnetic field
Results: $B_\parallel$ vs. $n_0$

Filled symbols: $B > 0$
Open symbols: $B < 0$

$B = \sqrt{16\pi n_0 k T}$

$P_{\text{magnetic}} \approx P_{\text{thermal}}$

$B_\parallel = \frac{1}{\sqrt{6}} B_{\text{total}}$

Order of magnitude increase in $n_0$, very little increase in $B$.

Enhanced RM in HII regions due to increased electron density.

Uncertainties:
Filling factor, $f$ of each sight-line unknown.
Dust correction assumes all dust is in front of HII region.
### Results: Derived Parameters

<table>
<thead>
<tr>
<th>HII Region</th>
<th>$R_{\text{max}}$ (pc)</th>
<th>$n_0$ (cm$^{-3}$)</th>
<th>$B_{|}$ (μG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sh 2-27</td>
<td>15</td>
<td>10.7 (2.7)</td>
<td>- 6.1 (2.6)</td>
</tr>
<tr>
<td>Sh 2-264</td>
<td>25</td>
<td>9.8 (2.3)</td>
<td>+ 2.8 (1.8)</td>
</tr>
<tr>
<td>Sh 2-220</td>
<td>20</td>
<td>9.9 (3.1)</td>
<td>- 6.9 (2.4)</td>
</tr>
<tr>
<td>Sivan 3</td>
<td>40</td>
<td>1.5 (0.4)</td>
<td>- 2.9 (1.5)</td>
</tr>
<tr>
<td>Sh 2-171</td>
<td>30</td>
<td>17.9 (10.4)</td>
<td>- 2.3 (1.3)</td>
</tr>
</tbody>
</table>
Magnetic field structure of Milky Way derived from pulsars. Han & Zhang (2008)
HII regions have magnetic fields with \( B_{||} \approx 5 \, \mu \text{G} \) (diffuse ISM).

Characteristic electron densities range between \( 1 < n_0 < 30 \, \text{cm}^{-3} \).

Magnetic fields within an HII region range from \( 1 < B_{||} < 10 \, \mu \text{G} \).

\( B \) has a uniform line-of-sight orientation on scales of 15 - 40 pc.

There is little or no change in \( B \) in the diffuse ISM between \( 1 \) - \( 10 \, \text{cm}^{-3} \).

\[
P_{\text{mag}} \approx P_{\text{thermal}}
\]

The parallel component of the magnetic field in HII regions is consistent with the Galactic magnetic field structure derived by Han \& Zhang (2008).

**Future studies**: RM structure functions to investigate scaling of turbulence.

Talk: "The role of magnetic fields in controlling the structure of HII regions" (Gary Ferland, Thursday afternoon)