Magnetic fields and massive stellar feedback

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★ Evolution of massive star-forming regions and its impact on the magnetic field:

- some examples: strength & orientation of the field
- what happens to the magnetic field in photodissociation regions (PDRs)?

★ An analytical solution of the magnetic field in an interstellar bubble (HII region + PDR + molecular cloud)

★ Under which conditions do we expect magnetic fields to dominate the dynamical evolution of PDRs?

★ The future: study the magnetic field in PDRs with SOFIA, IRAM 30m & ALMA
Massive stars are the main sources of turbulent energy injection in the interstellar medium (ISM):

- Powerful stellar winds
- Starlight momentum
- HII regions
- Supernovae

The surrounding ISM is swept up into a dense shell → interstellar bubble

Photodissociation regions (PDRs) are found at the edge of these interstellar bubbles: the interface between the HII region and the molecular clouds, illuminated by the FUV photons from the massive stars.

PDRs are usually modelled ignoring gas dynamics (Hollenbach & Tielens 1999):
→ *Is the magnetic field important for the dynamical evolution of PDRs?*
Magnetic fields in PDRs: Sh2-29 HII region

Santos et al. (2014); ~15’ × 15’

$B$ lines are pilled up at the border of the HII region.

Davis-Chadrasekhar-Fermi method (Davis 1951, C&F 1953):

$$B \propto \frac{\Delta V \sqrt{\rho}}{\delta \theta} \approx 400 \mu G$$

$\rightarrow B \sim 80$ times higher than in the diffuse ISM ($\sim 5 \mu G$, Crutcher 2007)

$G_0 = 150$

$n = 4 \times 10^3 \text{cm}^{-3}$

$B = 400 \mu G$

$P_{mag} / k = 5 \times 10^7 \text{cm}^{-3} K$

$B_{pos} \leftrightarrow \text{PDR = //}$

$G_0$ – intensity of the incident FUV field (in terms of the average ISRF)
Magnetic fields in PDRs: Omega Nebula M17

Direct measurements of $B$ in PDRs via Zeeman effect observations (give $\vec{B}_{\text{line-of-sight}}$ only):
e.g. $B_{\text{los, max}} = 750 \mu G$ in PDR of M17 (Brogan & Troland 2001)

**Magnetic field is dynamically important** – it must be taken into account to understand the structure of PDRs (Abel et al. 2004, Pellegrini et al. 2007, 2009)

\[
\begin{align*}
G_0 &= 8 \times 10^4 \\
\frac{n}{P_{\text{mag}}/k} &= (1 - 160) \times 10^6 cm^{-3} K \\
B_{\text{pos}} &\leftrightarrow PDR = ?
\end{align*}
\]
The Ophiuchi region as seen by Planck
Magnetic fields in PDRs: L1721

$\rightarrow B_{pos}$ from Planck sub-mm observations of dust polarized emission.

No effect from the star on $B$.

Habart et al. (2001)

$G_0 = 8$

$n = 3 \times 10^3 \text{ cm}^{-3}$

$B = ?$

$P_{mag} / k = ?$

$B_{pos} \leftrightarrow PDR = \perp$
Magnetic fields in PDRs: L204

Zeeman effect observations (Heiles 1988):

\[ B_{\text{los, max}} = 9 \mu G \]

→

\( B_{\text{pos}} \) studies (near-IR and optical polarization of dust extinction):
McCutcheon et al. (1986), Cashman & Clemens (2014)

\[
\begin{align*}
G_0 & = 30 \\
n & = 1 \times 10^3 \text{ cm}^{-3} \\
B & = 12 \mu G \\
P_{\text{mag}} / k & = 4 \times 10^4 \text{ cm}^{-3} K \\
\rightarrow P_{\text{pos}} & \leftrightarrow PDR = \perp
\end{align*}
\]
How is the **magnetic field** affected by **massive stellar feedback**?

→ Field lines are dragged with the gas (frozen-in condition)
Analytical model: the magnetized Strömgren shell

- Radial expansion of the gas:
  - uniform and spherical structure
  - using conservation of mass

\[
r_{\text{final}} = f(r_{\text{initial}})
\]

- Frozen-in condition:
  - start from a uniform \( \mathbf{B}_0 \)
  - field lines follow the gas \( \mathbf{A}(r) = (\nabla r_0) \cdot \mathbf{A}_0(r_0) \) (Parker 1970)

\[
\mathbf{B}(r) = \left( \frac{r_0}{r} \right)^2 \mathbf{B}_0 \mathbf{e}_r + \frac{r_0}{r} \frac{dr_0}{dr} \left( B_{0\theta} \mathbf{e}_\theta + B_{0\phi} \mathbf{e}_\phi \right)
\]

(Previous analytical and numerical studies: e.g. Ferrière et al. 1991, Krumholz et al. 2007, Arthur et al. 2011)
Analytical model: the magnetized Strömgren shell

Planck intermediate results. XXXIV. (2015): The magnetic field structure in the Rosette Nebula

The field is most compressed perpendicular to $\vec{B}_0$.

Along $\vec{B}_0$, $B = B_0$ at the outer surface and $B$ decreases inwards.

**Note:** Exact $B / B_0$ ratios depend on $r_{\text{final}} = f(r_{\text{initial}})$ - the way that matter has expanded – this particular example applies to the Rosette Nebula.
Magnetic fields in PDRs

Under which conditions does the **magnetic field dominate in the PDR?** (ignoring turbulent pressure)

\[ P_{th}^{H II} + P_{rad} = P_{th} + P_{mag} \iff n_e T_e + \frac{L}{4\pi d^2 c} = nT + \frac{B^2}{8\pi} \]

\[ B = \frac{100}{\sqrt{2.9 \times 10^6}} \left( n_e T_e + 376G_0 - nT \right)^{1/2} \]

with \( G_0 = \frac{L_{FUV}}{4\pi d^2} \),

\( T = 20K, T_e = 7000K \)

and \( n_e \) given by the Strömgren solution (density-size relation).

Simple diagnostic to **test with observations** → relative orientation between PDR and \( \vec{B} \)

\( (G_0, n) \): Habart et al. (2011), Pilleri et al. (2012), Pellegrini et al. (2007, 2009)
Future observations

Looking for the signatures of magnetic field compression...

\[ G_0 = 3 \times 10^3 \]

NGC 7023

S. Sellgren et al. (1992); 3.2 x 3.2

2.1 \( \mu \)m image

H - band \( B_{\text{pos}} \)

SOFIA (HAWC+)

IRAM 30m (NIKA2)

ALMA
Summary

★ Depending on the physical conditions ($G_0, n$):

→ magnetic fields are dragged by the expansion of matter in massive star forming regions (by radiation pressure + ionized gas pressure)

→ field lines are compressed in PDRs

→ magnetic pressure increases and may become comparable to the gas pressure

Magnetic fields should be taken into account in the dynamical evolution of PDRs, as they may influence their structure.
Thank you