Galactic dynamo action from small to large scales

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Outline

1. Large-scale magnetic structures in spiral galaxies
2. Meso-scale magnetic structures: reversals, magnetic arms, etc.
3. Small-scale magnetic structures in the ISM: intermittency, magnetic filaments and ribbons
1. Large-scale magnetic structures in spiral galaxies

- Azimuthal structure
- Vertical structure
- Radial structure

1.1. Azimuthal structure

Observed: predominance of axisymmetric structures, azimuthal Fourier mode \( m = 0 \).

Prediction of dynamo theory: \( m = 0 \) dominates (strong differential rotation).

Distortions:
\( m = 2 \) (spiral arms),
\( m = 1 \) (overall asymmetries), … … …

Fletcher et al. 2010: fitting polarization angles, \( \lambda = 3, 6, 20 \) cm
This disc, $h/r \ll 1$, dynamo modes:

\[
\frac{B_r}{B_\phi} \simeq -\frac{l}{h} \left| \frac{d \ln \Omega}{d \ln r} \right|^{1/2}.
\]

Magnetic pitch angle:

\[
p = \arctan \left( \frac{B_r}{B_\phi} \right) \simeq -\left(10^\circ - 20^\circ\right), \text{ as observed.}
\]

Vertical magnetic field:

\[
\frac{B_z}{B_\phi} \simeq (h/r)^{1/2} \lesssim 0.3, \text{ on average.}
\]

\[
B_z \simeq 0.3 \mu\text{G} \text{ near the Sun (Mao et al. 2010).}
\]

\[
B_z \simeq B_r, B_\phi \text{ near reversals and at } h \simeq r.
\]

$h \equiv 0.5\text{–}1 \text{ kpc}, \quad r \equiv 10 \text{ kpc}, \quad l \equiv 0.1 \text{ kpc (turbulent scale)}$
1.2. Vertical structure

Quadrupolar symmetry in the main part of the disc:
\[ B_\phi(z) = B_\phi(-z), \quad B_r(z) = B_r(-z), \quad B_z(z) = -B_z(-z). \]

Dynamo theory:
faster decay of dipolar modes \(\rightarrow\) predominance of quadrupolar symmetry.

Distortions (e.g., north-south asymmetry in the Milky Way).

Confirmed observationally for the Solar vicinity of the Milky Way.
\( \alpha \omega \)-dynamo in a thin disc embedded in a poorly conducting halo, with random seed field (A. Brandenburg, from Beck et al., *Ann. Rev. Astron. Astrophys*. 1996)

\[ t = 8.1 \text{ Gyr} \]
Axisymmetric field structure near a reversal

\[ B_r \ll B_z < B_\phi \]

or

\[ B_r, B_\phi \ll B_z \]
Simple analytical solution for $\alpha\omega$-dynamo in a thin disc in vacuum  
(Shukurov & Sokoloff 2008, Dynamos, Elsevier, p. 251)

$$B_r \approx R_\alpha C_0 \left[ \cos \frac{\pi z}{2} + \frac{3}{4\pi^{3/2}} \sqrt{-D} \cos \frac{3\pi z}{2} \right],$$

$$B_\phi \approx -2C_0 \sqrt{-\frac{D}{\pi}} \cos \frac{\pi z}{2}, \quad B_z \approx 0.$$

Accuracy better than 10% in galactic discs

+ radial dependence: $\vec{B} = Q(r)\vec{B}(z; r)$ (flared disc)

$$R_\alpha \approx 3\frac{l\Omega}{v}, \quad R_\omega \approx 3\frac{h^2}{lv} r \frac{d\Omega}{dr}, \quad D = R_\alpha R_\omega \approx 9r\Omega \frac{d\Omega}{dr} \frac{h^2}{v^2}.$$

$v \equiv 10$ km/s (turbulent velocity), $C_0 =$ arbitrary constant
1.3. Radial structure

Large-scale dynamo controlled by magnetic helicity conservation (Shukurov et al., MNRAS, 2006):

- differential rotation, $\Omega(r, z)$,
- helicity of interstellar turbulence, $\alpha \simeq l^2 \Omega/h \simeq 0.5$ km/s,
- gas outflow from the disc, $R_U = U_z h/\beta \simeq 0.2–2$.

$U_z = \text{mass-averaged outflow velocity}, \quad U_z = V_z \rho_{\text{hot}}/\langle \rho \rangle \simeq 0.1–1$ km/s,
$\beta \equiv \frac{1}{3} l \nu \equiv 10^{26}$ cm$^2$/s turbulent magnetic diffusivity.
Steady-state large-scale magnetic field (Sur et al., MNRAS 2007) due to helicity advection:

\[ B^2 \approx \frac{8\pi}{C} R_U D_{\text{crit}} \rho v^2 \approx (1\mu G)^2, \]

\[ C = 2(h/l)^2 \approx 50, \]

\[ D \approx (\Omega h/v)^2 \approx 10, \] the dynamo number near the Sun,

\[ D_{\text{crit}} \approx 8, \] critical dynamo number

Dependence of \( B \) on SFR, disc-halo connection, winds, galactic evolution, etc.

\[ \rho_{\text{hot}} V_z^2 = \xi S, \quad S = \text{SFR} \quad \Rightarrow \quad B \propto S^{1/4} \]

(IF all other relevant parameters are independent of SFR)
2. Meso-scale magnetic structures

2.1. Axisymmetric reversals

Poezd et al. (1993): thin-disc dynamo, random seed field: numerous reversals, nonlinear effects can preserve some of them for a long time in the Milky Way, but not in M31.

Positions of reversals:

\[ r^2 \gamma \left( \frac{1}{r} + 2 \frac{B_0'}{B_0} \right) + \frac{1}{2} r^2 \gamma' = 0 \]
Localised reversals?

Bykov et al. (1997): long-lived region of reversed magnetic field near the corotation radius.

Rotation curve and spiral structure of M51
Observational picture

• The only firmly established reversal of the large-scale magnetic field is the Sagittarius-arm one (Simard-Normandin & Kronberg, Nature 1979).

• All models with more reversals do not meet even basic statistical criteria. Likewise, it is not possible to decide what is the global azimuthal symmetry (ASS vs BSS) (Men et al. A&A, 819, 2008; Farrar et al. 2009).

• Nature of the problems: deriving $B$ from $\int_0^L n_e B_\parallel ds$, need for a VERY careful statistical treatment
Deducing the global structure from noisy data
Multiple reversals?

\[ \text{RM}(L) = \int_0^L n_e B_{\parallel} \, dl \]
Random magnetic field:

\[ \sigma_{RM} = K n_e b (2dL)^{1/2} \simeq 55 \text{ rad m}^{-2} \frac{n_e}{0.03 \text{ cm}^{-3}} \frac{b}{5 \mu \text{G}} \left( \frac{d}{100 \text{ pc}} \right)^{1/2} \left( \frac{L}{1 \text{ kpc}} \right)^{1/2} \]
3. Small-scale magnetic structures in the multi-phase ISM

- Interstellar magnetic field ≠ a quasi-homogeneous Gaussian random vector field.

- Interstellar shocks, multi-phase structure, ...

- A quasi-homogeneous, weaker magnetic background from the tangling of the large-scale magnetic field by turbulence.

Further details in:

More importantly: **fluctuation dynamo** produces intermittent magnetic fields even in a homogeneous medium.

Magnetic filaments (+ ribbons & sheets?), $\langle B \rangle = 0$

- $B_{\text{max}} \approx B_{\text{eq}} = (4\pi \rho)^{1/2} v \approx 5\,\mu\text{G}.$
- Length $\approx l \approx 50$–100 pc.
- **Low volume filling factor**, $\langle B^2 \rangle \approx 0.1 B_{\text{max}}^2$.
- **Kinematic stage**: magnetic energy max at $l_\eta = l R_m^{-1/2}$.
- **Nonlinear, statistically steady state**: controversial
  - **folds** at $l_\eta = l R_m^{-1/2} \approx 10^{-7}$ pc (???) (Schekochihin et al. 2004) or
  - **thicker structures** $l_\eta,\text{cr} = l R_{m,\text{cr}}^{-1/2} \approx 10$ pc (Subramanian 1999).
Simulations of the fluctuation dynamo: magnetic isosurfaces, $B^2 = \text{const}$

Haugen et al., PRE 2004

$\left(1024\right)^3$


$\left(256\right)^3$

Wilkin et al., PRL 2007

$\left(128\right)^3$
Implications

- Power spectrum & structure/correlation function are not suitable tools to describe intermittent magnetic fields (intense flux ropes separated by extended regions with relatively weak magnetic field).

- Magnetic field estimates from synchrotron intensity can be strongly affected (underestimated random magnetic field).

- Cosmic ray propagation can be strongly affected by magnetic intermittency. No models available of cosmic ray propagation in such magnetic fields.

- Locally anisotropic magnetic fields are less efficient in cosmic ray scattering (> $10^2$–$10^3$ GeV) (Chandran 2000).