Magnetic Fields in Elliptical Galaxies
An observational probe of the fluctuation dynamo action!

Amit Seta
Research School of Astronomy and Astrophysics
Australian National University, Canberra, AU
C. A. Hales (NRAO), L. F. S. Rodrigues (NCL)
10\textsuperscript{th} June 2019
amit.seta@anu.edu.au

New Perspectives on Galactic Magnetism, Newcastle, UK
Outline

• Introduction
• Small-scale magnetic fields in spiral galaxies
• Fluctuation dynamos
• Motivation for studying magnetic fields in elliptical galaxies
• Probe 1: Analytical estimates from the ISM turbulence
• Probe 2: Nonlinear fluctuation dynamo simulations
• Probe 3: Laing–Garrington effect
• Probe 4: Elliptical galaxies in cosmological simulations
• Conclusions and future prospects
ISM is turbulent, supernovae explosions stirs the ISM, driving scale of turbulence $l_0 \sim 100 \text{ pc}$

**Magnetic fields:**
- Fluctuating or turbulent or random or small-scale $b$: correlation length smaller than $l_0$ ($\lesssim 100 \text{ pc}$)
- Mean field or regular or large-scale $B_0$: correlation length greater than $l_0$ (few $\text{kpc}$)

**Dynamo theory:**
- Fluctuation or small-scale dynamo: amplification of a small seed field by random stretching of fieldlines due turbulent velocity; faster: $t_{\text{eddy}} \sim 10^7 \text{ yr}$ at larger scales
- Mean field or large-scale dynamo: requires larger scale features of galaxy, i.e., rotation, velocity shear, density stratification, ...; longer time scales $t_{\text{rot}} \sim 3 \times 10^8 \text{ yr}$
Spiral galaxies: large- & small- scale magnetic fields

M51 (Fletcher et al 2011)
HST + VLA + Effelsberg

$B_0 \approx 5 \mu G$, $b_{\text{rms}} / B_0 \approx 1 - 3$
(Fletcher 2010, Havercorn 2015, Beck 2016)

3C196 (Zaroubi et al 2015)
PLANCK + LOFAR

$B_0 \approx 5 \mu G$, $b_{\text{rms}} / B_0 \approx 1 - 3$

$\rho \propto \int_0^L n_{\text{cre}} B_{\perp}^2 \, dl$, $\Pi \propto \int_0^L n_{\text{cre}} \langle B_{\perp} \rangle^2 \, dl$

$\Pi / I = \langle B_{\perp} \rangle^2 / \langle B_{\perp} \rangle^2 + \langle b_{\perp} \rangle^2$

$\text{RM} \propto \int_0^L n_e B_{\parallel} \, dl$
Different generation mechanisms of small-scale magnetic fields:

- **Tangling of the mean field (TMF):** \( b_{TMF} \)

  \[
  \frac{\partial b_{TMF}}{\partial t} \approx \nabla \times (u_{turb} \times B_0), \quad (b_{TMF})_{\text{rms}} \sim B_0 \sim 5 \mu G
  \]

- **Gaussian or vol. filling**

- **Fluctuation dynamo (FD):** \( b_{FD} \)

  \[ (b_{FD})_{\text{rms}} \approx 0.5 b_{eq} \]

- **Shock compression (SC):** \( b_{SC} \)

  Dependent on the Mach number (\( \sim 1 \); Gaensler et al. 2011), non-Gaussian at scales smaller than the separation of shocks.
Small-scale magnetic fields generation mechanisms

Estimates!

- **Tangling of the mean field (TMF):** $b_{\text{TMF}}$

  \[
  \frac{\partial b_{\text{TMF}}}{\partial t} \approx \nabla \times (u_{\text{turb}} \times B_0), \quad (b_{\text{TMF}})_{\text{rms}} \sim B_0 \sim 5 \mu G
  \]

  Gaussian or vol. filling

- **Fluctuation dynamo (FD):** $b_{\text{FD}}$

  \[
  (b_{\text{FD}})_{\text{rms}} \simeq 0.5 b_{\text{eq}} = 0.5(4\pi \rho u_{\text{turb}}^2)^{1/2} \sim 5 \mu G
  \]

  Sim. + Exp. (Tzeferacos et al 2018)

  Inherently filamentary field, strongly intermittent
Small-scale magnetic fields generation mechanisms

Estimates!

- **Tangling of the mean field (TMF):** $b_{\text{TMF}}$
  
  $$\frac{\partial b_{\text{TMF}}}{\partial t} \approx \nabla \times (u_{\text{turb}} \times B_0), \quad (b_{\text{TMF}})_{\text{rms}} \sim B_0 \sim 5 \mu G$$

  Gaussian or vol. filling

- **Fluctuation dynamo (FD):** $b_{\text{FD}}$
  
  $$(b_{\text{FD}})_{\text{rms}} \sim 0.5 b_{\text{eq}} = 0.5(4\pi \rho u_{\text{turb}}^2)^{1/2} \sim 5 \mu G$$

  Sim. + Exp. (Tzeferacos et al 2018)

  Inherently filamentary field, strongly intermittent

- **Shock compression (SC):** $b_{\text{SC}}$
  
  Dependent on the Mach no. ($\sim 1$; Gaensler et al 2011)

  non-Gaussian at scales smaller than the separation of shocks
Fluctuation dynamos (FD)

Importance of FD

- Seed for mean field dynamo (Ruzmaikin, Shukurov, Sokoloff 1988)
- Field structure important for cosmic rays (Shukurov et al 2017)
Importance of FD

- Seed for mean field dynamo (Ruzmaikin, Shukurov, Sokoloff 1988)
- Field structure important for cosmic rays (Shukurov et al 2017)

**FD theory:** Kazantsev 1968, Zeldovich et al 1990, Kulsrud & Anderson 1992, Subramanian 1999, 2003, Boldyrev & Cattaneo 2004, ...

**FD simulations:** Meneguzzi et al. 1981, Cattaneo 1999, Haugen et al. 2004, Schekochihin et al. 2004, Cho & Ryu 2009, Cattaneo & Tobias 2009, Federrath et al. 2011, Favier & Bushby 2012, Beresnyak 2012, Bhat & Subramanian 2013, Bushby & Favier 2014; Federrath et al. 2014, Sur et al. 2018, ...

**FD experiment:** Tzeferacos et al 2018
**Fluctuation dynamos (FD)**

**Importance of FD**
- Seed for mean field dynamo (Ruzmaikin, Shukurov, Sokoloff 1988)
- Field structure important for cosmic rays (Shukurov et al 2017)

**FD theory:** Kazantsev 1968, Zeldovich et al 1990, Kulsrud & Anderson 1992, Subramanian 1999, 2003, Boldyrev & Cattaneo 2004, ...

**FD simulations:** Meneguzzi et al. 1981, Cattaneo 1999, Haugen et al. 2004, Schekochihin et al. 2004, Cho & Ryu 2009, Cattaneo & Tobias 2009, Federrath et al. 2011, Favier & Bushby 2012, Beresnyak 2012, Bhat & Subramanian 2013, Bushby & Favier 2014; Federrath et al. 2014, Sur et al. 2018, ...

**FD experiment:** Tzeferacos et al 2018

**FD observations:** ???

Magnetic Fields in Elliptical Galaxies
Problem of interest
Signatures of magnetic fields in elliptical galaxies

In spiral galaxies, it is difficult to differentiate between the small-scale field due to tangling of the mean field and fluctuation dynamo action (also in Sun; Karak & Brandenburg 2016)

Difference in structure of two components:
\[ l_0 = 100 \text{ pc}, \quad l_b = (1/3-1/4)l_0 \approx 25 \text{ pc}, \quad \text{requires 1–2 pc resolution, not possible with existing telescopes.} \]

Elliptical galaxies \( \rightarrow \) negligible rotation \( \rightarrow \) conventional mean field dynamo inactive \( \rightarrow \) no mean field \( \rightarrow \) only small-scale random fields \( \rightarrow \) ideal for studying fluctuation dynamos

Motivation:
*If* fluctuation dynamo is inefficient in spirals \( \rightarrow \) weak seed field \( \rightarrow \) mean field dynamo would take longer to amplify
X–ray observations $\rightarrow$ temp $\rightarrow$ sound speed $\rightarrow$ Sedov–Taylor blastwave solution (Type Ia SN rate) $\rightarrow$ negligible turbulence, shock front vel $\approx$ sound speed $\rightarrow$ $l_0 \approx 300 \text{ pc}$ (Moss & Shukurov 1996, with a difference in type of turbulence)

1% SN energy into turbulence $\rightarrow$ $u_{\text{turb}} \approx 2.5 \text{ km s}^{-1}$
P1: Estimates from the ISM turbulence

- X-ray observations → temp → sound speed → Sedov-Taylor blastwave solution (Type Ia SN rate) → negligible turbulence, shock front vel ≈ sound speed → \( l_0 \approx 300 \text{ pc} \) (Moss & Shukurov 1996, with a difference in type of turbulence)

- 1% SN energy into turbulence → \( u_{\text{turb}} \approx 2.5 \text{ km s}^{-1} \)

- temp → Spitzer resistivity \( \eta \) → \( \text{Re}_M = u_{\text{turb}} l_0 / \eta \approx 10^{22} \)
  \( \gg \text{Re}_M^{(\text{crit})} (10^2-10^3) \)
X-ray observations $\rightarrow$ temp $\rightarrow$ sound speed $\rightarrow$ Sedov–Taylor blastwave solution (Type Ia SN rate) $\rightarrow$ negligible turbulence, shock front vel $\approx$ sound speed $\rightarrow$ $l_0 \approx 300$ pc (Moss & Shukurov 1996, with a difference in type of turbulence)

1% SN energy into turbulence $\rightarrow u_{turb} \approx 2.5 \text{ km s}^{-1}$

temp $\rightarrow$ Spitzer resistivity $\eta$ $\rightarrow$ $Re_M = u_{turb}l_0/\eta \approx 10^{22}$

$Re_M^{(\text{crit})} (10^2-10^3)$

$b_{\text{rms}} \approx 0.5 b_{\text{eq}} = 0.5(4\pi \rho u_{turb}^2)^{1/2} \approx 0.2 \mu G$
X–ray observations $\rightarrow$ temp $\rightarrow$ sound speed $\rightarrow$ Sedov–Taylor blastwave solution (Type Ia SN rate) $\rightarrow$ negligible turbulence, shock front vel $\approx$ sound speed $\rightarrow$ $l_0 \approx 300$ pc (Moss & Shukurov 1996, with a difference in type of turbulence)

1% SN energy into turbulence $\rightarrow u_{\text{turb}} \approx 2.5$ km s$^{-1}$

temp $\rightarrow$ Spitzer resistivity $\eta$ $\rightarrow$ $\text{Re}_M = u_{\text{turb}} l_0 / \eta \approx 10^{22}$

$\gg \text{Re}^{(\text{crit})}_M (10^2–10^3)$

$b_{\text{rms}} \approx 0.5 b_{\text{eq}} = 0.5 (4\pi \rho u_{\text{turb}}^2)^{1/2} \approx 0.2 \mu$G

Cooling flow compression in the core (Mathews & Brighenti 1997), $b_{\text{rms}} \approx 1$–$10 \mu$G

Significant in strength!
Solve continuity equation, induction equation, Navier Stokes equation with a prescribed forcing, $b_{\text{rms}} = 1 \mu G$

Calculate $RM = K \int_L n_e b_\parallel dl$ (scarce $n_{\text{cre}}$, weak I)

Parameters: $l_0 = 300\, \text{pc}$, $Re_M \implies l_b \simeq 75\, \text{pc}$, $L = 1.5\, \text{kpc}$

$n_e$ distributions: uniform, King profile, collapse
($n_e(r) = 0.1r^{-1.5} \, \text{cm}^{-3}$; Mathews & Brighenti 2003)
RM fluctuations

\[
RM = K \int n_e b_{||} dl, \quad n_e: \text{uniform and King profile}
\]

(a) 

- Red: \(n_e: \text{constant}\)
- Blue: \(n_e: \text{King profile}\)
- Green dashed: \(N(\sigma = 43.5 \text{ rad m}^{-2})\)
- Magenta dashed: \(N(\sigma = 15.2 \text{ rad m}^{-2})\)
RM fluctuations

\[ \text{RM} = K \int n_e b_{\parallel} \, dl, \quad n_e : \text{uniform and King profile} \]

\[
\sigma_{\text{RM}} = \frac{(2\pi)^{1/4}}{3^{1/2}} K n_e \, b_{\text{rms}} l_b^{1/2} L^{1/2} \simeq 45 \text{ rad m}^{-2}
\]
(Shukurov & Sokoloff 2007)

\[
\sigma_{\text{RM}} = \frac{(2\pi)^{1/4}}{3^{1/2}} K n_e \, b_{\text{rms}} a^{1/2} l_b^{1/2} \left( \frac{\Gamma\left(\frac{3}{2}(\gamma+1)-0.5\right)}{\Gamma\left(\frac{3}{2}(\gamma+1)\right)} \right)^{1/2} \simeq 15 \text{ rad m}^{-2}
\]
(Bhat & Subramanian 2013)
Both $n_e$ and $b$ are important for the RM distribution. 

\[ \sigma_{RM} \not\Rightarrow b_{rms} \]

\[
\star n_e \text{ distribution has to be considered!}
\]
RM distribution, extreme case of cooling flow

\[ n_e \propto b^{3/2}, \ RM = K \int b^{3/2} b_\parallel dl \]

structure of the field also contributes
setting up expectations for RM grid
P3: Laing–Garrington effect

(Garrington et al 1988)

(Magnetic Fields in Elliptical Galaxies)
Assuming both jets have similar intrinsic properties and depolarization is just due to the elliptical galaxy, one can estimate the magnetic field.

\[ \text{DP}_j, \text{DP}_{cj} \rightarrow \text{DP} = \exp(-2\sigma_{\text{RM}}^2(\lambda_1^4 - \lambda_2^4)); \sigma_{\text{RM}_j}, \sigma_{\text{RM}_{cj}} \rightarrow \sigma_{\text{RM}_{\text{ellip}}} \rightarrow b_{\text{rms}} \approx 0.03-0.3 \mu\text{G} \]
Assuming both jets have similar intrinsic properties and depolarization is just due to the elliptical galaxy, one can estimate the magnetic field.

$$DP_j, DP_{cj} \rightarrow DP = \exp(-2\sigma_{RM}^2(\lambda_1^4 - \lambda_2^4)); \sigma_{RM_j}, \sigma_{RM_{cj}} \rightarrow \sigma_{RM_{ellip}} \rightarrow \langle b_{rms} \approx 0.03-0.3 \mu G \rangle$$
GALFORM: semi-analytical model for galaxy formation and evolution (Lacey et al 2016).

Classify galaxy as elliptical if ratio of bulge to total luminosity is $> 0.5$, disk component not selected.

$$b_{\text{rms}} \approx 0.5 b_{\text{eq}} = 0.5 \left(4\pi \rho u_{\text{turb}}^2 \right)^{1/2}$$ and $b_{\text{rms}}$ at half-mass radius.

![Magnetic Fields in Elliptical Galaxies](image-url)
Conclusions and future work

Conclusions:

- Important to study magnetic fields in elliptical galaxies to probe fluctuation dynamos
- Magnetic field strengths are significant, at least in the core
- All four probes give similar answers
- Structure of magnetic fields probed using $\text{RM}$ distribution
- $\sigma_{\text{RM}}$ shouldn’t directly be associated with $b_{\text{rms}}$

Future work:

Ongoing: including $n$ self-consistently

Probe 5: $\text{RM}$ grid (including stacking data)

Probe 6: lensed elliptical galaxies (similar to Mao et al 2017)

Probe 7: fast radio bursts (CHIME, ASKAP, ...)

Magnetic Fields in Elliptical Galaxies
Conclusions and future work

Conclusions:

- Important to study magnetic fields in elliptical galaxies to probe fluctuation dynamos
- Magnetic field strengths are significant, at least in the core
- All four probes give similar answers
- Structure of magnetic fields probed using $\text{RM}$ distribution
- $\sigma_{\text{RM}}$ shouldn’t directly be associated with $b_{\text{rms}}$

Future work:

- Ongoing: including $n_e$ self-consistently
- Probe 5: RM grid (including stacking data)
- Probe 6: lensed elliptical galaxies (similar to Mao et al 2017)
- Probe 7: fast radio bursts (CHIME, ASKAP, ...)

Magnetic Fields in Elliptical Galaxies