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^{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

Introduction

- ISM is turbulent, supernovae explosions stirs the ISM, driving scale of turbulence $l_0 \sim 100\,\mathrm{pc}$

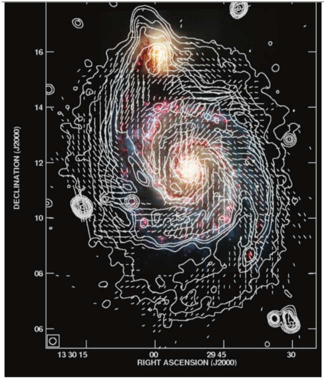
Magnetic fields:

- Fluctuating or turbulent or random or small-scale $\mathbf{b}$: correlation length smaller than l_0 ($\lesssim 100\,\mathrm{pc}$)
- Mean field or regular or large-scale $\mathbf{B}_0$: correlation length greater than l_0 (few kpc)

Dynamo theory:

- Fluctuation or small-scale dynamo: amplification of a small seed field by random stretching of fieldlines due turbulent velocity; faster: $t_{\mathrm{eddy}} \sim 10^7\,\mathrm{yr}$ 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 $t_{\mathrm{rot}} \sim 3 \times 10^8\,\mathrm{yr}$

Spiral galaxies: large- & small- scale magnetic fields



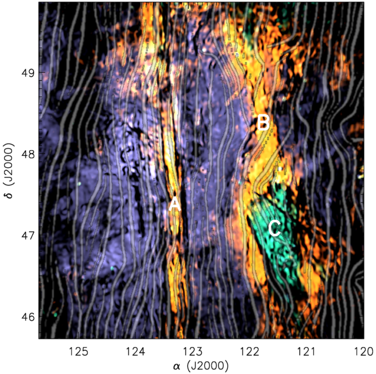
M51 (Fletcher et al 2011)

HST + VLA + Effelsberg

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

(Fletcher 2010, Haverkorn 2015, Beck 2016)

- $\mathrm{I} \propto \int_0^L n_{\rm cre} B_\perp^2 \mathrm{d}l$, $\mathrm{PI} \propto \int_0^{\rm L} \mathrm{n_{cre}} \langle \mathrm{B}_\perp \rangle^2 \mathrm{dl}$
- $\mathrm{PI/I} = \langle \mathrm{B}_\perp \rangle^2 / \langle \mathrm{B}_\perp \rangle^2 + \langle \mathrm{b}_\perp \rangle^2$
- $\mathrm{RM} \propto \int_0^L n_{\rm e} B_\parallel \mathrm{d}l$



3C196 (Zaroubi et al 2015)

PLANCK + LOFAR

Small-scale magnetic fields generation mechanisms
Estimates!

- **Tangling of the mean field (TMF)**: $\mathrm{b}_{\mathrm{TMF}}$

$$\frac{\partial \mathbf{b}_{\mathrm{TMF}}}{\partial t} \approx \nabla \times (\mathbf{u}_{\mathrm{turb}} \times B_0)\,, (\mathbf{b}_{\mathrm{TMF}})_{\mathrm{rms}} \sim B_0 \sim 5\,\mu\mathrm{G}$$

Gaussian or vol. filling

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

$$\underbrace{(\mathbf{b}_{\mathrm{FD}})_{\mathrm{rms}} \simeq 0.5\, b_{\mathrm{eq}}}_{\text{Sim. + Exp. (Tzeferacos et al 2018)}} \quad = 0.5(4\pi\rho u_{\mathrm{turb}}^2)^{1/2} \sim 5\,\mu\mathrm{G}$$

Inherently filamentary field, strongly intermittent

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- **Shock compression (SC)**: $\mathrm{b_{SC}}$
  Dependent on the Mach no. (~ 1; Gaensler et al 2011)
  non-Gaussian at scales smaller than the separation of shocks

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Importance of FD

- Seed for mean field dynamo (Ruzmaikin, Shukurov, Sokoloff 1988)
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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, ...

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FD observations: ???

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:
$l_0 = 100\,\mathrm{pc}, l_b = (1/3\text{–}1/4)l_0 \simeq 25\,\mathrm{pc}$, requires $1\text{–}2\,\mathrm{pc}$ resolution, not possible with exisiting telescopes.

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

Motivation:
If fluctuation dynamo is inefficient in spirals $\longrightarrow$ weak seed field $\longrightarrow$ mean field dynamo would take longer to amplify

P1: Estimates from the ISM turbulence

- X–ray observations $\longrightarrow$ temp $\longrightarrow$ sound speed $\longrightarrow$ Sedov–Taylor blastwave solution (Type Ia SN rate) $\longrightarrow$ negligible turbulence, shock front vel $\approx$ sound speed $\longrightarrow$ $l_0 \approx 300\,\mathrm{pc}$ (Moss & Shukurov 1996, with a difference in type of turbulence)
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- Cooling flow compression in the core (Mathews & Brighenti 1997), $b_{\mathrm{rms}} \approx 1\text{–}10\,\mu\mathrm{G}$

Significant in strength!

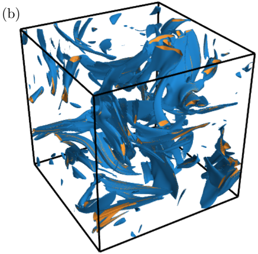
P2: Fluctuation dynamo: numerical simulations

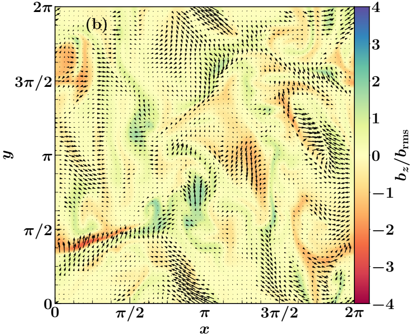
Solve continuity equation, induction equation, Navier Stokes equation with a prescribed forcing, $b_{\rm rms} = 1\,\mu{\rm G}$

Calculate ${\rm RM} = K \int_L n_{\rm e} b_{||} {\rm d}l$ (scarce $n_{\rm cre}$, weak I)

Parmeters: $l_0 = 300\,{\rm pc}$, Re$_{\rm M}$ $\implies$ $l_b \simeq 75\,{\rm pc}$, $L = 1.5\,{\rm kpc}$

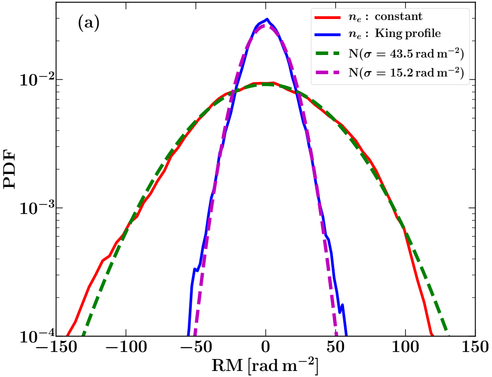
$n_{\rm e}$ distributions: uniform, King profile, collapse ($n_{\rm e}(r) = 0.1 r^{-1.5}\,{\rm cm}^{-3}$; Mathews & Brighenti 2003)





RM fluctuations

$\mathrm{RM} = K\int n_{\mathrm{e}} b_{\|} \mathrm{d}l$, n_{e} : uniform and King profile



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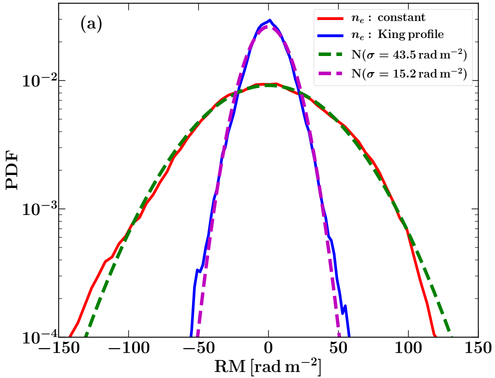


$$\sigma_\mathrm{RM} = \frac{(2\pi)^{1/4}}{3^{1/2}} K n_\mathrm{e}\, b_\mathrm{rms} l_b^{1/2} L^{1/2} \simeq 45\,\mathrm{rad\,m^{-2}}$$

(Shukurov & Sokoloff 2007)

$$\sigma_\mathrm{RM} = \frac{(2\pi)^{1/4}}{3^{1/2}} K n_\mathrm{e}\, b_\mathrm{rms} a^{1/2} l_b^{1/2} \left(\frac{\Gamma(\frac{3}{2}(\gamma+1)-0.5)}{\Gamma(\frac{3}{2}(\gamma+1))} \right)^{1/2} \simeq 15\,\mathrm{rad\,m^{-2}}$$

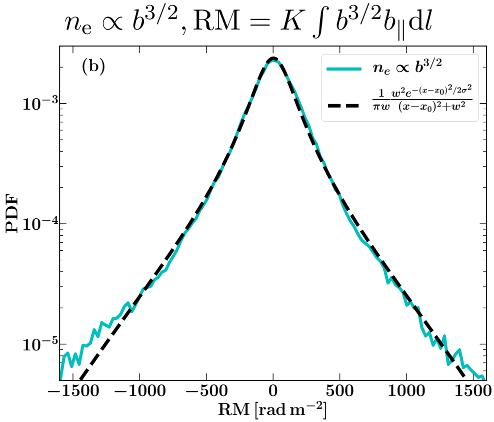
(Bhat & Subramanian 2013)

Both n_e and b are important for the RM distribution

$$\sigma_\mathrm{RM} \Longrightarrow b_\mathrm{rms}$$

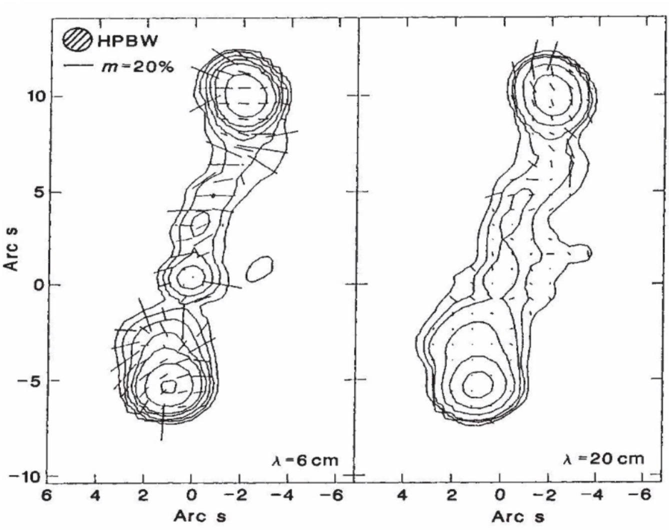
⋆ n_e distribution has to be considered!

RM distribution, extreme case of cooling flow



- structure of the field also contributes
- setting up expectations for RM grid

P3: Laing–Garrington effect



(Garrington et al 1988)

Magnetic fields in hosts, data from Garrington et al 1991

Assuming both jets have similar intrinsic properties and depolarization is just due to the elliptical galaxy, one can estimate the magnetic field.

$$\mathrm{DP_j},\ \mathrm{DP_{cj}} \longrightarrow \mathrm{DP} = \exp(-2\sigma^2_{\mathrm{RM}}(\lambda_1^4 - \lambda_2^4));\, \sigma_{\mathrm{RM_j}},\ \sigma_{\mathrm{RM_{cj}}} \longrightarrow \sigma_{\mathrm{RM_{ellip}}} \longrightarrow b_{\mathrm{rms}} \approx 0.03\text{–}0.3\,\mu\mathrm{G}$$

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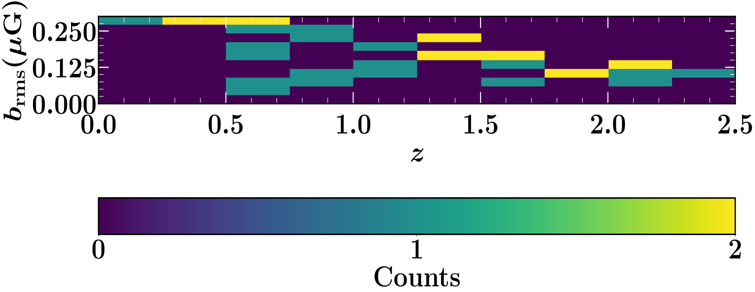
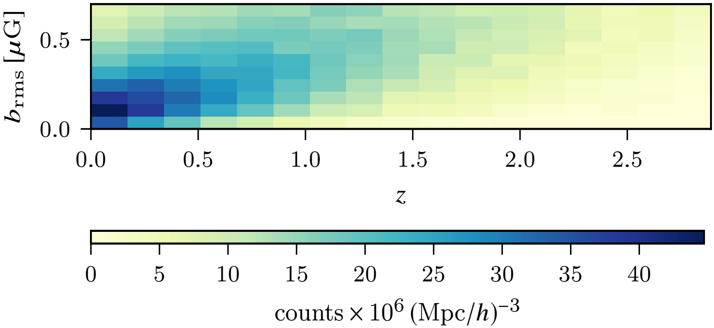


P4: Cosmological simulations

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



Conclusions and future work

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

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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, ...)