Magnetic Field in Galaxies and clusters

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Plan

- Observing galactic and cluster B: **Radio crucial**
- The fluctuation dynamo, Young galaxies/Old clusters
- The large scale galactic dynamo

http://ned.ipac.caltech.edu/level5/March08/Subramanian/frames.html
Measuring B fields: Synchrotron Radiation

Faraday Rotation gives \( B_{\parallel} \)

\[ \Delta \phi = \lambda^2 \times RM = \lambda^2 \times K \int n_e \mathbf{B} \cdot d\mathbf{l} \]

\[ K = 0.81 \text{ rad m}^{-2} (\mu G)^{-1} (\text{pc})^{-1} \text{ cm}^{-3} \]

Synchrotron polarization gives \( B_{\perp} \)

\[ \mathbf{E} \propto \mathbf{n} \times \left[ (\mathbf{n} - \mathbf{\beta}) \times d\mathbf{\beta} / dt \right] \propto d\mathbf{\beta} / dt \]
Galactic Magnetic Fields: Observations

- Synchrotron polarization and Faraday rotation probe B fields.
- M51 at 6 cm (Fletcher and Beck)
- Few \( \mu \)G mean Fields coherent on 10 kpc scales
- Correlated with optical spiral
Why are optical and magnetic spirals correlated?
Edge on Galaxies: NGC4631

Halo magnetic fields
Cumulative FRM distributions for sightlines with and without strong Mg II absorption line systems.

Cluster Radio halos

Chandra (X-Ray)-GMRT (235 Mhz): Giant radio halo in RXC J2003.5-2323

Cluster Magnetism: Observations

Radio halos and Faraday Rotation probe cluster B fields

Hydra Cluster $B \sim 7 \mu G$ coherent on 3 kpc scale

Cluster Magnetism: Observations


Statistical RM study

$B \sim 5(l/10\text{kpc})^{-1/2} \mu\text{G}$

How are cluster fields generated/maintained against turbulent decay?
Fluctuation/Small scale turbulent dynamo

- Turbulence common: Stars, galaxies, galaxy clusters: leads to Random Stretching + "Flux freezing" ⇒ Growth of $B$
- Cancellation (Eyink, 2011) and Resistance limits growth.
- Random $B$ grows if $R_M = vL/\eta > R_{crit} \sim 30 - 100$ (Kazantsev 1967)
  Eigenmode solutions of form: $\Psi(r) \exp(2\Gamma t) = r^2 \sqrt{\eta T} M_L$
  $$-\Gamma \Psi = -\eta_T \frac{d^2 \Psi}{dr^2} + U_0(r) \Psi$$
- Growing modes if there are bound states in potential $U_0(r)$.
- Growth rate fast $\sim \epsilon v/L$ ($10^7$ yr: Galaxies; $10^8$ yr clusters).
  Field intermittent: Eddy scale $L$, to "resistive" scale $\sim L/R_m^{1/2} \ll L$
- How does it saturate? Important for young galaxy/cluster/IGM Faraday RM and mean field dynamos?
Simulations by Pallavi Bhat, 2012, $P_m = \nu/\eta = 1$

\[ k^{-5/3} \quad \text{and} \quad k^{3/2} \]

\[ M(k) \quad \text{and} \quad K(k) \]
The fluctuation dynamo

Generated $\mathbf{B}$ intermittent (Pallavi Bhat, 2012)
RMS Faraday RM $\sigma_{RM}$ by shooting lines of sight through the simulation box. Normalize by $\sigma_0 = K n_e (B_{rms}/\sqrt{3}) \sqrt{Ll}$

$\sigma_{RM} \approx 0.4 - 0.5 \sigma_0$ for various $R_m$ and $P_m$ explored. Rare structures contribute $< 20\%$ to $\sigma_{RM}$
Kazantsev with Helicity: Tunneling?

- **Fluctuation dynamo → bound state problem** (Kazantsev, 1967)
- **Helicity of turbulence allows ‘tunneling’ to larger scales than** $L$ (Subramanian, PRL, 1999; Brandenburg, Subramanian, A&A Lett, 2000)

For $\dot{M}_L \approx 0$, $\dot{H} \approx 0$ → $-\eta_T (d^2 \Psi / dr^2) + \Psi \left[U_0 - (\alpha^2(r)/\eta_T(r))\right] = 0$,

$r \gg L$, $M_L(r) = \bar{M}_L(r) \propto r^{-3/2} J_{\pm 3/2}(\mu r)$.

\[
\Gamma = E = 0
\]

\[
2 \eta_T / r^2 - \alpha_0^2 / \eta_T
\]

\[
r > L
\]
Helically forced turbulent dynamos

Axel Brandenburg, 2001....2012; $k_f = 15$

- **Rapid growth in kinematic stage conserving magnetic helicity.**
- **Further Slow Growth on resistive timescale (dissipating small-scale helicity)**
- Can be understood in terms of magnetic helicity conservation; (Field and Blackman, 2002).
Supernovae Drive Helical turbulence
Galactic Shear and $\alpha$ effect

Kinematic Limit?

Helicity (links) conservation? Competing Fluctuation dynamo?
Consider flow with large-scale velocity $\bar{V}$ and a 'turbulent' stochastic velocity $v$.

$$V = \bar{V} + v, \quad \mathbf{B} = \bar{\mathbf{B}} + \mathbf{b}: \text{Mean + Stochastic fields}$$

Average can be volume average over 'intermediate' scales or ensemble average.

Averages satisfy Reynolds rules:

$$\bar{V}_1 + \bar{V}_2 = \bar{V}_1 + \bar{V}_2, \quad \bar{V} = \bar{V}, \quad \bar{V} \cdot \bar{v} = 0, \quad \bar{V}_1 \cdot \bar{V}_2 = \bar{V}_1 \cdot \bar{V}_2,$$

$$\frac{\partial \bar{V}}{\partial t} = \frac{\partial \bar{V}}{\partial t}, \quad \frac{\partial \bar{V}}{\partial x_i} = \frac{\partial \bar{V}}{\partial x_i}.$$

Average now the induction equation.
**Turbulent Mean-Field Dynamo**

- \( \mathbf{V} = \overline{\mathbf{V}} + \mathbf{v}, \mathbf{B} = \overline{\mathbf{B}} + \mathbf{b} \): Mean + Stochastic fields
- Mean satisfies DYNAMO equation, with \( \overline{\mathbf{E}} = \overline{\mathbf{V}} \times \mathbf{b} \):

\[
\frac{\partial \overline{\mathbf{B}}}{\partial t} = \nabla \times (\overline{\mathbf{V}} \times \overline{\mathbf{B}} + \overline{\mathbf{E}} - \eta (\nabla \times \overline{\mathbf{B}}));
\]

- The stochastic small-scale field satisfies:

\[
\frac{\partial \mathbf{b}}{\partial t} = \nabla \times (\overline{\mathbf{V}} \times \mathbf{b} + \mathbf{V} \times \overline{\mathbf{B}} - \eta \nabla \times \mathbf{b}) + \mathbf{G}
\]

- Here \( \mathbf{G} \) is the "pain in neck" nonlinear term in \( \mathbf{v} \) and \( \mathbf{b} \).

\[
\mathbf{G} = \nabla \times (\mathbf{v} \times \mathbf{b})' = \nabla \times [\mathbf{v} \times \mathbf{b} - \overline{\mathbf{v}} \times \overline{\mathbf{b}}]
\]

- Finding \( \overline{\mathbf{E}} = \overline{\mathbf{V}} \times \mathbf{b} \) is a closure problem:

\[
\overline{\mathbf{E}} = \alpha \overline{\mathbf{B}} - \eta_{turb} (\nabla \times \overline{\mathbf{B}})
\]
The kinematic limit of $\bar{\mathcal{E}}$

For short correlation times ($\tau_{\text{cor}}$), neglect $G$, also assume statistical isotropy of the random $\mathbf{v}$:

$$\bar{\mathcal{E}} = \mathbf{v} \times \int_0^t dt' (\partial \mathbf{b} / \partial \tau) = \mathbf{v}(t) \times \int_0^t dt' [ - \mathbf{v}(t') \cdot \nabla \bar{\mathbf{B}} + \bar{\mathbf{B}} \cdot \nabla \mathbf{v}(t') ]$$

$$\bar{\mathcal{E}}_i = \int_0^t \left[ \epsilon_{ijk} v_j(t) v_{k,p}(t') \bar{B}_p(t') + \epsilon_{ijp} v_j(t) v_{l}(t') \bar{B}_{p,l}(t') \right] dt' ,$$

So: $\bar{\mathcal{E}} = \alpha \bar{\mathbf{B}} - \eta_t \nabla \times \bar{\mathbf{B}}$, where

$$\alpha = -\frac{1}{3} \int_0^t \mathbf{v}(t) \cdot \mathbf{\omega}(t') \ dt' \approx -\frac{1}{3} \tau_{\text{cor}} \overline{\mathbf{v}} \cdot \overline{\mathbf{\omega}} ,$$

$$\eta_t = \frac{1}{3} \int_0^t \mathbf{v}(t) \cdot \mathbf{v}(t') \ dt' \approx \frac{1}{3} \tau_{\text{cor}} \overline{\mathbf{v}}^2 ,$$

$$\partial \bar{\mathbf{B}} / \partial t = \nabla \times \left( \overline{\mathbf{V}} \times \overline{\mathbf{B}} + \alpha \overline{\mathbf{B}} - (\eta_t + \eta)(\nabla \times \overline{\mathbf{B}}) \right) ;$$
Mean-Field Dynamo: Galactic

- Galactic Shear generates $B_\phi$ from $B_r$
- Supernovae drive HELICAL turbulence (Due to Rotation + Stratification)
- Helical motions generate $B_r$ from $B_\phi$
- Mean field satisfies dynamo equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} + \mathbf{E} - \eta (\nabla \times \mathbf{B})) ;$$

$$\mathbf{E} = \mathbf{u} \times \mathbf{b} = \alpha \mathbf{B} - \eta_{turb} (\nabla \times \mathbf{B})$$

$$\alpha = -\frac{\tau_{corr}}{3} \langle \mathbf{u} \cdot \omega \rangle \quad \eta_{turb} = \frac{\tau_{corr}}{3} \langle \mathbf{u}^2 \rangle$$

- Exponential growth of $\mathbf{B}$, $t_{growth} \sim 10^9$ yr

RSS, 1988
A revised picture for $\alpha$-effect

$\mathcal{E}$ transfers helicity: Oppositely signed WRITHE AND TWIST Helicities

Lorentz force of small-scale twist Helicity grows to cancel kinetic $\alpha$
Nonlinear saturation of helical dynamos

- $\overline{E}$ transfers helicity between small-large scales
- Small scale current helicity grows to cancel kinetic $\alpha$
- Nonlinear $\alpha = -(\tau/3)\langle v \cdot \omega \rangle + (\tau/3\rho)(4\pi/c)\langle j \cdot b \rangle \to 0$?
- Catastrophic quenching of dynamo?

Need to get rid of small scale helicity, by Helicity fluxes? (Blackman & Field; Kleeorin et al).
But what is gauge invariant helicity density and flux?


$$\frac{\partial h}{\partial t} + \nabla \cdot F = -2\overline{E} \cdot \overline{B} - 2\eta(4\pi/c)\overline{j} \cdot \overline{b}$$

Large scale dynamos need helicity fluxes
Effect of $\alpha$-quenching in galaxy

Effect of advective flux in galaxy

Galactic outflows and magnetic spiral

Winding up Spiral with enhanced outflow along spiral (Chamandy, Shukurov, KS, 2014)

10.250 Gyr

Questions

- When do the first fields arise?
- How do they evolve with redshift in galaxies and the IGM?
- Dynamos required to amplify/maintain fields.
- Fluctuation dynamo saturation?
- Galaxy cluster plasma nearly collisionless...how to treat?
- For mean field dynamos: $\alpha, \eta_t$ at large $R_m$?
- How do MFD’s saturate; helicity fluxes?
- Is an Early universe field needed? Is it inevitable?

SKA will be crucial to probe the Magnetic Universe.