Primordial magnetic fields: Origins and Constraints

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Summary

- The universe is magnetized.
- Early Universe Generation
- Magnetic signals in the CMB
- Primordial fields and early structure formation
- Astrophysical batteries and dynamos

K. Subramanian, Magnetic fields in the early universe, AN, 2010, 331, 110
Magnetic fields are ubiquitous in the universe:

- **Galaxies:** $B \sim 10 \mu G$, ordered on 10 kpc scales + random component
- **Clusters of Galaxies:** few $\mu G$ strengths on $\sim 10$ kpc scales
- **Equally strong $B$ in Young $z \sim 1 - 2$ galaxies** ([Bernet et al. 2008](#))
- **Even in the IGM?** ($B \geq 3 \times 10^{-16}$ Gauss; Mpc scales)

How do such large scale fields arise?

How can One Constrain/Detect Primordial B fields?
Synchrotron polarization and Faraday rotation probe B fields.

- M51 at 6 cm (Fletcher and Beck)
- Few μG mean Fields coherent on 10 kpc scales
- Correlated with optical spiral
- How do such large scale galactic fields arise?
Constraints on B in the universe

Neronov and Vovk, Science, 328, 73 (2010)
Origin: Dynamos? Primordial?

- **Turbulent Dynamos**: Seed field + amplification by motions (turbulence/shear).
  - Turbulence amplifies fluctuations faster than mean field.
  - Can turbulent dynamos generate sufficiently coherent fields?

- **Primordial magnetic fields**: Origin in an early universe phase transition: Inflation, Electroweak, QCD.
  - Provide Seed for dynamo? Help induce coherence?
  - Inflation: Strength? EW/QCD transitions: Scale?

- **Detecting relic B fields** can probe early universe physics?

- **Flux freezing**: On large scales $B(t)a^2(t) = \text{constant}$, So $B(z) = B_0(1+z)^2$

- $B_0 \sim 10^{-9}G$ on galactic scales, interesting for Galaxy formation + galaxy/cluster $B$? ($\rho_B = \rho_\gamma$ implies $B \sim 3\mu G$).
Primordial fields versus Dynamos?
Primordial fields origin during Inflation?

(Turner and Widrow, 1988; Ratra 1992; Gasperini et al. 1995)

- Rapid expansion $\rightarrow$ vacuum fluctuations amplified and stretched to long wavelength "classical" fluctuations

- Negligible charge density breaks flux freezing.

- BUT Need to break conformal invariance of ED (Couple to inflaton, dilaton, curvature invariants, axion, charged scalars ..)

- EM wave amplified from vacuum fluctuations

- After reheating $E$ shorted out and $B$ frozen in.

\[
\frac{d\rho_B}{d \ln k} = \left( \frac{C(\gamma)}{2\pi^2} \right) H^4 (-k\eta)^{4+2\gamma} \approx \left( \frac{9}{4\pi^2} \right) H^4 
\text{ (for } \gamma = -2) 
\]

\[
B_0 \approx 5 \times 10^{-10} \text{G} \left( \frac{H}{10^{-5} M_{pl}} \right) 
\]

- Exponentially sensitive to parameters, as need $B \sim 1/a^\varepsilon$

- Need huge growth of 'charge': a Problem? (Demozzi et al, 2009)
From Electroweak/QCD Phase transition?

- Correlation scale usually tiny: $H^{-1} \sim 1 \text{ cm (EW)}$ or $\sim 10^4 \text{ cm}$
- QCD phase transition or comoving $R_H \sim 100\text{AU}/0.1 \text{ pc}$
  Generates decaying MHD turbulence increasing coherence scale.

- Unless Helicity generation/Conservation leads to Inverse Cascade (Brandenburg et al, PRD 96, Banerjee & Jedamzik, 2004)

- Magnetic Helicity $H = \int_V A \cdot B \, dV$, $\nabla \times A = B$
  $A$ is vector potential, $V$ is closed volume

- Measures links and twists in $B$

- Helicity is nearly conserved even when energy dissipated

- Helicity generation during EW baryogenesis: $H/V \sim n_b/\alpha!$
  (Vachaspati, 2001; Copi et al 2008; Diaz-Gil et al, 2008)

- $B \sim 5 \times 10^{-12} (L/1\text{kpc})!$ (BJ,05): $L$ quite uncertain.
Inverse cascade of helical $B$

(Christensson, Hindmarsch, Brandenburg, 2001; Brandenburg 2001)

- Assuming helicity conservation, $H \sim LB^2 \sim LE \sim \text{constant}.$
- So $\frac{dE}{dt} \sim E/(L/v) \sim \frac{E^{5/2}}{H} \rightarrow L \propto B^{-2} \propto t^{2/3}$ (Sim. $L \propto t^{1/2}$).
Probing Early Universe B

- \( B^2/(8\pi \rho_{rad}) \sim 10^{-7} B_{-9}^2 \). Here \( B_{-9} = B_0/(10^{-9} G) \)

- Magnetic stress ⇒ metric perturbations, including Grav. Waves

- Lorentz force \( \mathbf{J} \times \mathbf{B}/c \Rightarrow \) almost incompressible motions


- Survives damping for \( L_A > (V_A/c)L_{Silk} \ll L_{Silk} \)

- CMB signals from metric and velocity perturbations

- Post recombination: \( n_{rad}/n_b \gg 1 \Rightarrow \) compressible motions ⇒ seeds \( \delta \rho/\rho \Rightarrow \) First Structures

- B field Dissipation → Ionization, Heating, Molecules

  Coherent primordial nG fields potentially detectable
Vector Mode anisotropies

- Semianalytics by KS, JDB, PRL 1998
  TRS, KS, PRL 2001
  KS, TRS, JDB, 2003

- CAMB code, Lewis, PRD 2004
CMB signals: scalar+Tensor + Vector

\[ B_\lambda = 4.7 \mu G, \; n \sim -3, \; \text{Including passive component,} \; \text{Shaw & Lewis, PRD, 2010} \]
Magnetic stresses quadratic in $B \rightarrow$ Magnetically induced CMB signals non-Gaussian even at lowest order!

Due to scalar passive mode, on large angular scales,
\[ l_1(l_1 + 1)l_3(l_3 + 1)b_{l_1 l_2 l_3} \sim 6 - 9 \times 10^{-16}, \text{ for } B_0 \sim 3 \text{ nG}, \text{ nearly scale invariant magnetic spectrum.} \]
(Trivedi, KS, Seshadri, PRD, 2010)

Signal scales as $B_0^6$ and one gets upper limit $B_0 < 1 - 2 \text{ nG}$, just from scalar SW contribution

Potentially stronger limit from non-Gaussianity of magnetically induced Tensor modes (Shiraishi et al. 2011)

Lots still need to be calculated and compared to data!
Structure formation signals

- Extra power in the matter power spectrum on small scales (Gopal, Sethi, 2003)

- First dwarf galaxies form at high $z > 10$ even for $B \sim 0.1nG$, but for masses larger than magnetic and thermal Jeans mass.

- B field induced first structures — Reionization? (Sethi, KS 2005, Tashiro, Sugiyama, 2006; Schleicher, Banerjee, Klessen, 08).

- Influence formation of first structures through catalyzing Molecule formation (Sethi, Nath, KS 2008; Schleicher et al 2009)

- Probe through redshifted HI 21 cm signals (Tashiro, Sugiyama, 06; Schleicher, Banerjee, Klessen, 09; Sethi, KS 09)
Structure formation signals

Extra power in the matter power spectrum on small scales
Gopal, Sethi, JAA, 2003; 3 nG, $n = 0, -1, -2, -2.9$; LCDM
Even $B = 0.1nG$ can induce $10^6 M_\odot$ dwarf galaxy collapse at high $z > 15$ causing early re-ionization (Sethi, KS MN, 2005)
Global 21 cm signals from reionization

HI global signal only seen in emission in magnetised models

Sethi, KS, 2009; 0, 0.5, 1 nG
HI correlation signals from reionization

Both ionization and density inhomogeneities contribute

Sethi, KS, 2009; 0.5, 1, 3 nG
Astrophysical “seed” field mechanisms

- Astrophysical Batteries using positive/negative charge asymmetry

- Biermann Batteries: \( \mathbf{E}_{\text{Bier}} = -\nabla p_e/e_n + ... \)

\[
(\partial \mathbf{B}/\partial t) = -c \nabla \times \mathbf{E}_{\text{Bier}} = -(ck/e_n) \nabla n_e \times \nabla T_e
\]

- If \( \mathbf{E}_{\text{Bier}} \) has a curl then from Faraday, \( \mathbf{B} \) can be generated

- Re-Ionization fronts: \( B < 10^{-19} \) G (Subramanian et al 1994, Gnedin et al, 2000), Structure formation Shocks (Kulsrud et al, 1997)

- During recombination: \( B_0 \sim 10^{-30} \) G at MPc (Gopal & Sethi, 2005; Mattarrese et al, 2005); \( B_0 \sim 10^{-21} \) G at pc (Ichiki et al 2007)

- Seed fields from first supernovae and AGN outflows

Need Dynamos to explain observed fields and maintain against decay
Final Thoughts?

- Universe is full of magnetic fields!

- Origin from the early universe phase transitions?

- Need Compelling generation mechanism or Observations

- Primordial fields will leave signatures in the CMB, Structure formation.

- Redshifted 21 cm signals detectable with upcoming radio telescopes for $B_0 \sim 0.5 \text{ nG}$

- Other Probes: Radio RM s (SKA) and High energy CRs

- Dynamos certainly needed to maintain fields BUT Need to understand their saturation better
THANK YOU!