Primordial Magnetic Fields

Richard Shaw
Kavli Institute for Cosmology, Cambridge

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Galaxies (1-10 µG)
Clusters (0.1-3 $\mu$G)
Origins

- Unsolved problem
- Difficult to produce fields within a galaxy
- Must amplify seed fields (via adiabatic contraction, dynamo) from either
  - Pre-galactic Astrophysical process (AGN, Biermann Battery)
  - Early Universe Mechanism (our focus)
Early Universe Origins

- Inflationary mechanisms (acausal)
- Can give scale invariant fields. Coherent fields in Galaxies, Clusters, Superclusters
- Also produce potential CMB signature
- Problem: naturally inflation produces tiny fields, $B \sim 10^{-100} G$ needs a mechanism to break conformal symmetry.
Primordial Magnetism

• Universe is a good conductor so field is frozen in

• Field \( B^i(x^j, \tau) = B^i(x^j)/a(\tau)^2 \) defining comoving field

• Contribute to energy-momentum tensor

\[
T^0_0 = -\frac{1}{8\pi a^4} B^2(x),
\]
\[
T^i_j = \frac{1}{4\pi a^4} \left( \frac{1}{2} B^2(x) \delta^i_j - B^i(x) B_j(x) \right).
\]
Primordial Magnetism

- Define a density and anistropic stress perturbation via
  \[ T_0^0 = -\rho \gamma \Delta B, \]
  \[ T_j^i = p \gamma (\Delta_B \delta^i_j + \Pi_B^i_j), \]

- Perturbations are constant in time

- As \( \Delta_B \propto B^2(x^i) \), perturbation is manifestly non-gaussian
Early Evolution

• We imagine magnetic fields are produced at time $\tau_B$ prior to neutrino de-coupling $\tau_\nu$

• At this time photons, neutrinos, and baryons tightly bound by interactions

• Combined fluid has zero anisotropic stress.

• The net total stress sources gravitational potentials
Early Evolution

- Magnetic density perturbation is generated compensated to conserve energy.
- Initially stress cannot be compensated.
- Comoving curvature grows logarithmically

\[ \zeta(\tau) = \zeta(\tau_B) - \frac{1}{3} R_{\gamma B} \Pi_B \log \left( \frac{\tau}{\tau_B} \right) \]

- After \( \tau_\nu \), decoupled neutrino stress grows. Total anisotropic stress quickly zero.
• When anisotropic stress compensated three types of perturbation present

- Passive, Adiabatic-like, mode with curvature

\[ \zeta(\tau) \propto \Pi_B \log(\tau_v/\tau_B) \]

- Compensated magnetic stress mode (with all non-zero anisotropic stresses), amplitude \( \Pi_B \)

- Compensated density mode (contains all non-zero density perturbation), with amplitude \( \Delta_B \)
Vectors and Tensor Perturbations

- Tensor perturbations, two modes
  - Passive mode: \( H^{(2)} \propto R_\gamma \Pi_B^{(2)} \log (\frac{\tau_\nu}{\tau_B}) \)
  - Compensated mode: \( \Pi_B^{(2)} \)

- Vector perturbations
  - Compensated mode: \( \Pi_B^{(1)} \)
  - No passive mode as vector mode
Statistics

• Magnetic field statistics gaussian with

\[ \langle B_i(k) B_j^*(k') \rangle = (2\pi)^3 \delta(k - k') \frac{P_{ij}(\hat{k})}{2} P_B(k) \]

• Power spectrum  

\[ P_B(k) = Ak^{n_B} \]

• Amplitude set by variance  

\[ B_\lambda^2 \] at 1 Mpc

• Statistics of \( \Delta_B \), \( \Pi_B \) are not independent.

• We treat diffusion damping of magnetic field with evolving perturbations (see Subramanian and Barrow 1997)
$B_\lambda = 4.7\text{nG}$
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$\lambda = 4.7 \text{nG}$
Kojima et al. 2008

$\ell(l+1)C_\ell / (2\pi) \ [\mu K^2]$

$\ell$

EE mode
Constraints (in progress)

- We can see the constraints will come from:
  - Small scale CMB (compensated vector)
  - Large scale CMB (passive tensor)
  - Small scale Matter power (scalar compensated)

- Other constraints:
  - Contribution to SZ (Tashiro et al, 2009).
  - Nucleosynthesis (Caprini and Durrer, 2002)
Constraints (in progress)

• For proper constraints need to sample full parameter space of 6 standard params, plus

  • Magnetic amplitude: \( B_\lambda \)
  • Magnetic spectral index: \( n_B \)
  • Field production time: \( \log_{10} (\tau_\nu / \tau_B) \)

• Datasets: CMB (WMAP, ACBAR, CBI), Lyman alpha, SZ (SPT)

• CMB only, and CMB with SDSS has been done (Yamazaki et al. 2006, 2010)
Preliminary: CMB only
Conclusions

• Origin of cosmic magnetic fields is an unsolved problem

• CMB on its own provides some constraint on the magnetic fields

• Adding small scale matter power (Lya, SZ) will improve this