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1 PMF Theory

1.1 Biermann Batteries

The large-scale magnetic fields we see need to have had some initial seed field, but of course this raises the question: Where did the seed field come from? The most popular model for seed magnetic field generation from zero initial conditions is the 'Biermann battery' proposed by Biermann in 1950. Biermann batteries form in highly ionised environments such as the plasma shortly after the Big Bang. Within the plasma, ions are drawn to regions of lower density and lower temperature. Since the constituents of the plasma - protons and electrons - have different masses they flow at different rates resulting in a net flow of charge. If this flow of current forms a loop, then by Faraday's law of induction, a magnetic field is produced by the battery.

The magnetic field produced by the Biermann battery is described by:

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{U} \times \vec{B} - \eta \nabla \times \vec{B}) - \frac{ck_b}{e} \frac{\nabla n_e}{n_e} \times \nabla T \quad (1)$$

The final term, $\nabla n_e \times \nabla T$ is the source term describing the Biermann battery effect. In order for this term to be non-zero and hence to have a Biermann battery, gradients of the electron density and the temperature must be non-parallel.

Biermann batteries are also predicted to occur at later times in the Universe

- Infalling ionised hydrogen in galaxies
- diagram of Biermann battery

1.2 Other Methods of PMF Generation

- QCD
- Inflation
- I really need to read up on this stuff.

1.3 Effect of PMFs on the Cosmic Microwave Background

If PMFs have a field strength 1nG then their signatures will be detectable in the CMB B-mode polarisation power spectrum. Just as extragalactic magnetic fields Faraday rotate radio and X-ray signals, PMFs would induce Faraday rotation on CMB polarisation. The net effect is that a fraction of E-mode polarisation would be transformed into B-mode polarisation.

- PMF polarisation power spectrum
- Measurable quantity, $A_p m f \propto B_1 \text{mpc}^4$
- previous constraints from PLANCK and POLARBEAR (transplant from intro)
- How distinguish effects of pmfs from primordial gravity waves
- Neat.

1.4 Other effects of PMFs

see lit review or talk for:

- large scale structure: Ω_8
- plot of matter power spectrum for different pmf strengths
- PMFs interact with charged baryons through Lorentz force
- interfere with distribution of mass
- non-linear effect hard to gauge:
- BBN
- early energy density budget is modified, expansion rates change
- freeze-out times for nucleosynthesis change
- changes in H and He abundances.
- Weak constraints, Yamazaki in 2012 cites $B_1 mpc < 1.5 \mu G$, which isn't very telling.

1.5 Cosmic Birefringence

Measuring a conversion of E-mode power to B-mode power consistent with expected PMF effects doesn't strictly confirm the existence of PMFs. PMFs are not the only mechanism that could rotate the polarisation of

- Birefringent materials have different refractive indices for left and right circular polarisation - harkens back to faraday rotation
- Space may be intrinsically birefringent
- Hint of new physics: New pseudoscalar coupling between photons and dark energy: Quintessence models.
- Can be quantified in terms of an effective primordial magnetic field