Primordial magnetic fields and the CMB

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Outline

The magnetic universe

- Magnetic fields are **ubiquitous**.

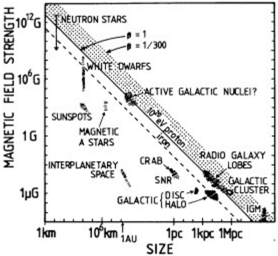


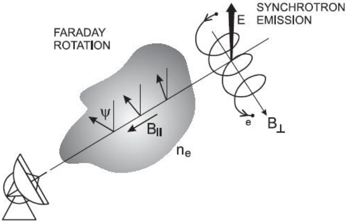
Figure 1 Size and magnetic field strength of possible sites of particle acceleration. Objects below the diagonal line cannot accelerate protons to 10^{20} eV.

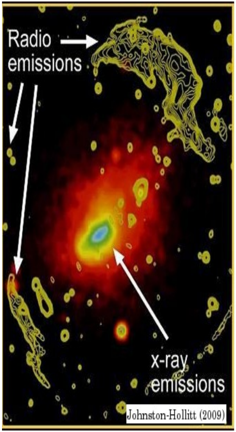
Hillas, 1984

- Why can not they come from the early Universe?

Detecting cosmic magnetic fields

- Optical, infrared, and sub-mm polarization of dust grains.
- Zeeman effect.
- Synchrotron emission.
- Faraday rotation.





(Abell 3667)

Generating early magnetic fields

Proposals:

- Inflation (Turner & Widrow 1988).
- Reheating (Calzetta & Kandus 2002).
- Cosmic strings (Vachaspati 1991).
- Cosmic defects (Hollenstein et al. 2008).
- Phase transitions (Hogan 1983): EW and QCD.
- Dynamo mechanisms (Semikoz & Sokoloff 2004).
- Vorticity (Harrison 1969).

Description of a PMF distribution

- Two-point correlation function in the Fourier space:

$$\langle B_i^*(\mathbf{k}) B_j(\mathbf{k'}) \rangle = (2\pi)^3 \delta^{(3)}(\mathbf{k}-\mathbf{k'})(P_{ij} P_B(k) - i\epsilon_{ijl} \hat{k}_l P_H(k)). \tag{1}$$

- P_B is the power spectrum of the magnetic field for the symmetric part is:

$$P_B(k) = A_B k^{n_B} = \frac{(2\pi)^{n_B+5}}{2k_\lambda^{n_B+3}} \frac{B_\lambda^2}{\Gamma\left(\frac{n_B}{2}+\frac{3}{2}\right)} k^{n_B} (\text{for } k < k_D). \tag{2}$$

- P_H is the power spectrum for the helical part:

$$P_H(k) = A_H k^{n_H} = \frac{(2\pi)^{n_H+5}}{2k_\lambda^{n_H+3}} \frac{H_\lambda^2}{\Gamma\left(\frac{n_H}{2}+2\right)} k^{n_H} (\text{for } k < k_D). \tag{3}$$

with $k_\lambda = 2\pi/\lambda$, B_λ the strength of the magnetic field smoothed on a comoving scale λ by convolving with a Gaussian kernel ($f_\lambda = N exp(-x^2/2\lambda^2)$).

Constraints on PMF

PMF have implications for:

- nucleosynthesis: $< B_0 > \leq 3 \times 10^{-7}$ G (Grasso & Rubenstein 1995) or an updated value $< B_0 > \leq 1.5 \times 10^{-6}$ G (Kawasaki & Kusakabe 2012).
- large-scale structure formation through:
  - thermal-SZ effect: $B_0 \lesssim 10^{-8}$ G (e.g. Tashiro et al. 2012).
  - Lyman-α forest: $B_0 \sim 10^{-6} - 10^{-9}$ G (Oren & Wolfe 1995, Pandey et al. 2012).

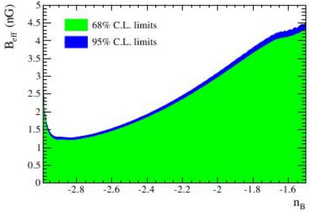


Figure 6. Effective magnetic field limits from Lyα data for different values of n_B.

Figure: Kahniashvili et al. 2013

Constraints on PMF (cont.)

- matter power spectrum: $B_0 \sim 1.5 - 4.5 \times 10^{-9}$ G and $n_B \in (-3, -1.5)$ (Kahniashvili et al. 2013).

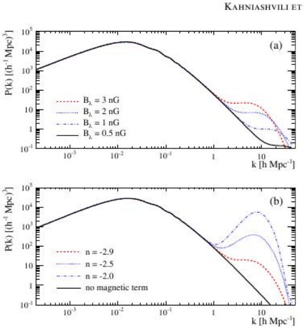


Figure 1. Magnetic field matter power spectra for $n_B = -2.9$ with different values of B_λ (a) and for $B_\lambda = 3$ nG with different values of n_B (b).

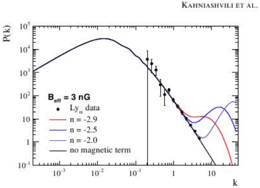


Figure 5. Magnetic field matter power spectra for different values of n_B and data points from Croft et al. (2002).

- CMB in temperature and polarization.

Effects on CMB

Source of scalar, vector, and tensor metric perturbations:

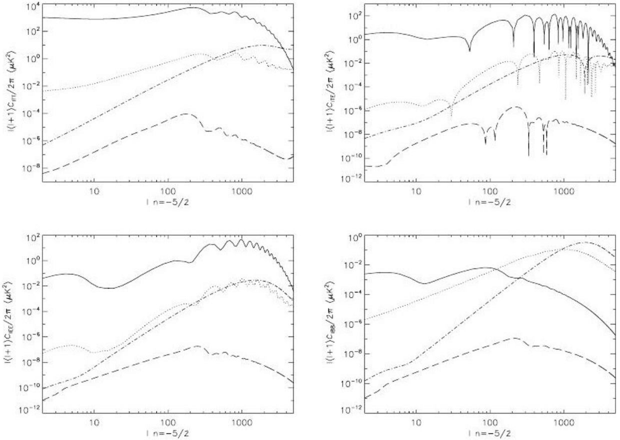


Figure: Paoletti et al. 2009

Effects on CMB (cont.)

- Non-gaussianity (Brown & Crittenden 2005).
- Faraday rotation of the polarization plane (Kosowsky & Loeb 1996).
- Alfvèn waves (Durrer et al. 2004).
- Influence on Reionization (Sethi & Subramanian 2005).

Effects on CMB polarization

- E-modes are partially converted into B-modes (Kanhniashvili et al. 2009, Pogosian et al. 2012) and vice versa (Ruiz-Granados et al. in preparation):

$$C_\ell^{BB} \propto C_\ell^{EE} C_\ell^{\phi} \tag{4}$$

$$C_\ell^{EE} \propto -C_\ell^{BB} C_\ell^{\phi} \tag{5}$$

  The power spectrum of the polarization angle is:

$$C_\ell^{\phi} \propto \frac{1}{\nu_0^4} \frac{B_\lambda^2}{\Gamma(n_B+3/2)} \left(\frac{\lambda}{\eta_0}\right)^{n_B+3} \int_0^{x_D} dx x^{n_B} j_\ell^2(x). \tag{6}$$

- Faraday rotation (FR) is expected to mix all polarization modes.

FR results for WMAP polarization

WMAP5 and *instantaneous* recombination:

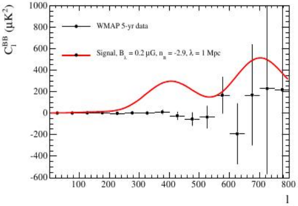


Figure: Kahniashvili et al. 2009

WMAP7 and *non-instantaneous* recombination:

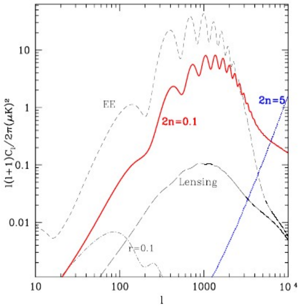


Figure: Pogosian et al. 2011

Results from WMAP9 polarization

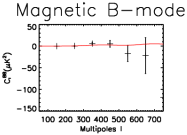
What's new?

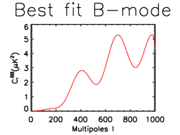
- Exploration on r (0, 0.01, 0.05 and 0.1) and convolution scale λ.
- E-modes coming from magnetic contribution.

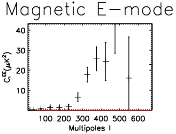
Summary of results (Ruiz-Granados et al. in prep.)

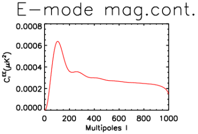
ν (GHz)	$B_\lambda(68\%, 95\%)$ (nG)	$n_B(68\%, 95\%)$	$\lambda(68\%, 95\%)$ (Mpc)	χ^2
41	$< 40.23, < 212.43$	$< -1.05, < 1.29$	$< 15, < 25$	1.6148
61	$< 75.34, < 386.31$	$< -0.98, < 1.36$	$< 100, < 200$	1.6116
94	$< 172.31, < 259.25$	$< -1.29, < 0.87$	$< 270, < 350$	1.6137

For all frequencies, r=0.1 is favoured.

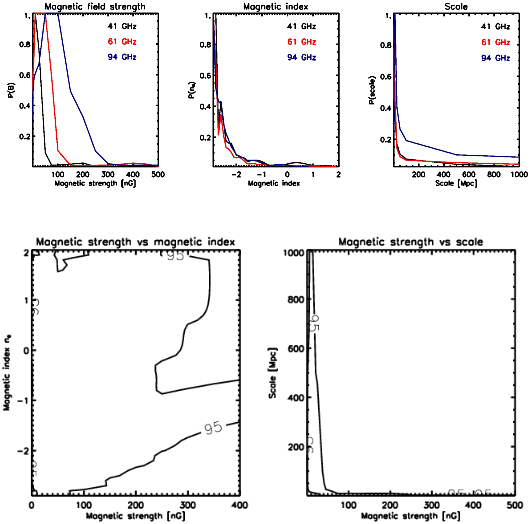

Magnetic B−mode


Best fit B−mode


Magnetic E−mode


E−mode mag.cont.

Results from WMAP9 polarization (cont.)



Constraints on PMF

Planck WG 4.1

- UGR (Granada) E.Battaner (PI), E. Florido, B. Ruiz-Granados.
- INAF (Bolonia) F. Finelli, D. Paoletti.
- IAS (Paris) J. Aumont.
- CEFCA (Teruel) C. Hernández-Monteagudo.
- LPSC (Grenoble) J. Macías-Pérez.
- IFCA (Santander) E. Martínez-González.
- INFN (Padua) S. Matarrese.
- NBI (Copenague) P. Naselsky, J. Kim.
- SISSA(Trieste) F. Paci.
- IAC (La Laguna) R. Rebolo, J.A. Rubiño-Martín.
- AST (Cambridge) V. Stoliarov.

Constraints from the temperature power spectra

(Planck 2013 results XVI)

- Magnetic scalar and tensor modes contributes at intermediate and large scales mainly.
- Magnetic vector mode peaks at $\ell = 2000 - 3000$ (small scales).

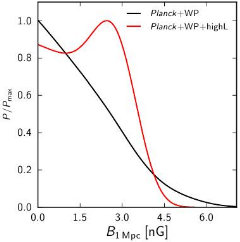


Fig. 37. Constraints on the PMF amplitude obtained with *Planck*+WP (red line) and *Planck*+WP+highL (black line).

Planck+WMAP constraints: $B_0 < 4.1 \times 10^{-9}$ G and $n_B < 0$ (95% C.L.).
Planck+WMAP+highℓ : $B_0 < 3.4 \times 10^{-9}$ G and $n_B < 0$ (95% C.L.).

Constraints from Alfvèn waves

(Planck 2013 results XXIII)

- PMF produce statistical anisotropy signatures breaking isotropy.
- PMF with a coherence length comparable to the present day horizon induce Alfvèn waves in the early Universe.
- Their imprints on the CMB could be recognized via Doppler effect and Sachs-Wolfe effect (Durrer et al. 1998, Kim & Naselsky 2009).
- Alfvèn waves produce specific correlations in temperature (Kahniashvili et al. 2008).

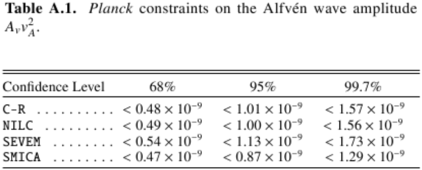
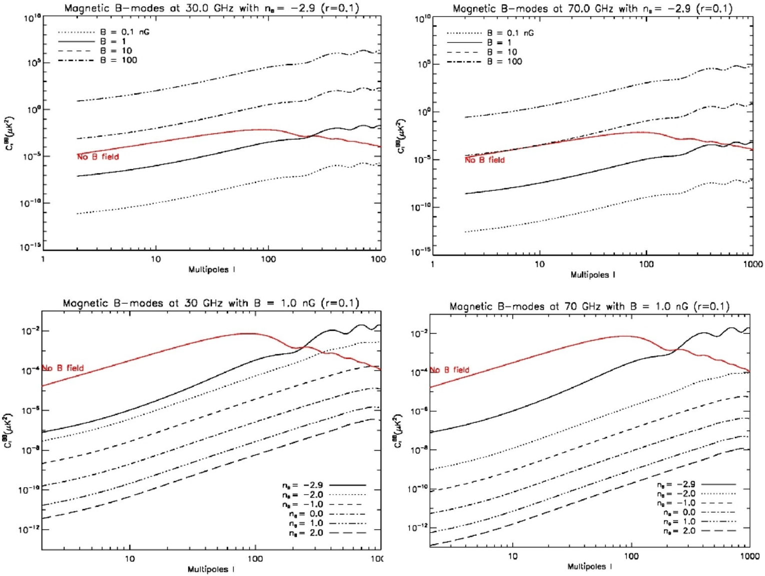


Table A.1. *Planck* constraints on the Alfvén wave amplitude $A_v v_A^2$.

Confidence Level	68%	95%	99.7%
C-R	$< 0.48 \times 10^{-9}$	$< 1.01 \times 10^{-9}$	$< 1.57 \times 10^{-9}$
NILC	$< 0.49 \times 10^{-9}$	$< 1.00 \times 10^{-9}$	$< 1.56 \times 10^{-9}$
SEVEM	$< 0.54 \times 10^{-9}$	$< 1.13 \times 10^{-9}$	$< 1.73 \times 10^{-9}$
SMICA	$< 0.47 \times 10^{-9}$	$< 0.87 \times 10^{-9}$	$< 1.29 \times 10^{-9}$

Simulations for magnetic B-modes

coming from FR



Conclusions

- The detection of PMF would open new fields in the physics of the early Universe and on the formation of large-scale structure.
- Strengths of $B_0 \lesssim 10^{-8}$ G are constrained by combining all the methods.
- Faraday rotation of the CMB polarization plane is an independent and powerful tool for detecting PMF.
- Primordial Faraday rotation will be distinguishable from other contributions to the B-mode (as lensing or gravitational waves) due to its frequency dependence.
- Planck polarization results would be an unique opportunity to improve our knowledge of the Universe and enrich its physics.

Thank you very much.