Constraints on primordial magnetic fields with *Planck* 2015

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Abstract

We present the constraints on Primordial Magnetic Fields (PMFs) derived using the *Planck* 2015 data presented in Planck Collaboration et al. (2015). Since PMFs leave several imprints on the Cosmic Microwave Background (CMB) anisotropies, the CMB represents one of the best laboratory to investigate and constrain their nature. PMFs affect the CMB angular power spectra (APS) in temperature and polarization with their contribution to cosmological perturbations, via Faraday rotation and through the heating of matter caused by the damping. Moreover, PMFs modelled as stochastic background have a fully non-Gaussian contribution to the CMB anisotropy. Overall, *Planck* constrains the amplitude of PMFs to less than a few nanogauss. In particular, individual limits coming from the analysis of the CMB APS, using the *Planck* likelihood, are $B_{1\,\mathrm{Mpc}} < 4.4$ nG (where $B_{1\,\mathrm{Mpc}}$ is the comoving field amplitude at a scale of 1 Mpc) at 95 % CL, assuming zero helicity, and $B_{1\,\mathrm{Mpc}} < 5.6$ nG when we consider a maximally helical field. For nearly scale-invariant PMFs we obtain $B_{1\,\mathrm{Mpc}} < 2.0$ nG, and $B_{1\,\mathrm{Mpc}} < 0.9$ nG when the impact of PMFs on the ionization history of the Universe is included in the analysis. From the analysis of magnetically-induced non-Gaussianity we obtain three different values, corresponding to three applied methods, all below 5 nG with the strongest being $B_{1\,\mathrm{Mpc}} < 2.8$ nG for nearly scale-invariant fields. Together, these results comprise a comprehensive set of constraints on the existence of PMFs with *Planck* data.

1 Introduction

Magnetic fields are ubiquitous in our Universe, they are observed in large scale structures like galaxies and clusters. Recent high-energy data seems to be compatible also with cosmological magnetic fields not associated with structures. The origin of large-scale magnetic fields is strongly debated, one hypothesis is that these are remnants of primordial fields generated in the early Universe. In addition, several early-Universe scenarios predict the generation of cosmological magnetic fields, either during inflation, during phase transitions, or via other physical processes. Therefore, PMFs may provide the seeds to generate large scale magnetic fields, but they may also provide a new observational window to the early Universe (for a review see Durrer & Neronov 2013).

The most widely used model of PMFs is a stochastic background modelled as a fully inhomogeneous component of the cosmological plasma (the contributions at the homogeneous level are negligible), with the energy momentum tensor components (quadratic in the fields) on the same footing as cosmological perturbations. Within this model, PMFs leave several signatures in the CMB temperature and polarization anisotropy patterns: on the CMB power spectra in temperature and polarization by magnetically-induced perturbations; on the polarization power spectra by the Faraday rotation; on CMB non-Gaussianities with the related non-zero magnetically-induced bispectra. In the magnetohydrodynamical (MHD) limit, the evolution of the magnetic field with time is simply dilution with cosmic expansion $B(k,\tau) = B(k)a(\tau)^{-2}$, where $a(\tau)$ is the scale factor and τ the conformal time.

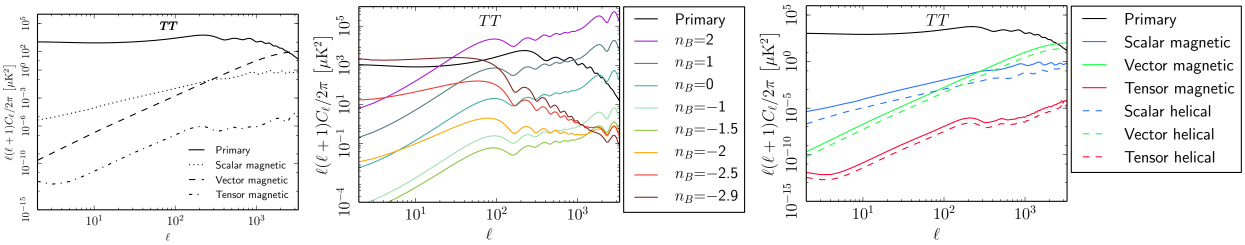

Figure 1: Magnetically-induced CMB APS. The first panel is the comparison between different modes. The second panel is the variation of the magnetically-induced APS with the spectral index. The third panel is the comparison between a maximally helical and non-helical PMFs.

2 Constraints from the magnetically-induced perturbations

PMFs source all types of cosmological perturbations, i.e., scalar, vector, and tensor perturbations, with different initial conditions. We focus on the compensated (Giovannini, 2004; Finelli, Paci, & Paoletti, 2008) and passive (Lewis, 2004; Shaw & Lewis, 2010) initial conditions, that are both independent on the generation mechanism of the fields. We model the PMFs with a power law power spectrum for both non-helical and helical part $P_B(k) = A_B\, k^{n_B}$, $P_H(k) = A_H\, k^{n_H}$. Magnetically-induced perturbations survive the Silk damping but are suppressed on smaller scales by radiation viscosity. We model this suppression with a sharp cut-off in the PMFs power spectrum, at the scale $k_{\rm D}$ (Subramanian & Barrow, 1998). The amplitude of PMFs may be expressed with the convention to smooth over a comoving scale of $\lambda = 1\,$Mpc, $B_\lambda^2 = \int_0^\infty \frac{dk\,k^2}{2\pi^2}\, e^{-k^2\lambda^2} P_B(k) = \frac{A_B}{4\pi^2\lambda^{n_B+3}}\,\Gamma\left(\frac{n_B+3}{2}\right)$.

We refer to the treatment of magnetically-induced perturbations presented in Lewis (2004), Finelli, Paci, & Paoletti (2008), Paoletti, Finelli, & Paci (2009), Shaw & Lewis (2010) and Ballardini, Finelli, & Paoletti (2015). In the first panel of Fig.1 we show the impact of magnetically-induced, scalar, vector and tensor perturbations on the CMB anisotropy temperature APS. We note that the dominant contribution is given by vector mode on small angular scales. The shape of the magnetically-induced power spectra strongly depends on the source of the magnetically induced perturbations: the PMF energy momentum tensor (EMT) components. These components are a white noise for indices $n_B > -3/2$ and are $\propto k^{2n_B+3}$ for $-3 < n_B < -3/2$. This behaviour is reflected on the CMB APS shown in Fig.1 for the passive tensor mode. The addition of a maximally helical component to the fields leads to a reduction of the amplitude of the magnetically-induced spectra as is shown in the comparison of the third panel of Fig.1. We used an extension to the public MCMC `cosmomc` code developed to include PMF contribution (Paoletti & Finelli, 2011, 2013) to derive the constraints on PMF amplitude. In particular, with the *Planck* 2015 likelihood we obtain $B_{1\,\rm Mpc} < 4.4\,$nG (4.5 nG when including high ell polarization) at 95% CL as shown in Fig.2, we also note the strong degeneracy between the amplitude and the spectral index, we have $B_{1\,\rm Mpc} < 2.0\,$nG for nearly scale-invariant PMFs . The maximally helical PMF have a weaker constraint, $B_{1\,\rm Mpc} < 5.6\,$nG at 95% CL due to the lower amplitude of the magnetically-induced APS. The results of a joint analysis *Planck*-BICEP 2/KECK array are $B_{1\rm Mpc} < 4.7\,$nG at 95% CL, compatible with *Planck* alone case.

PMFs are dissipated via two additional effects, which take place in the magnetized plasma, after recombination: ambipolar diffusion and MHD turbulence. The dissipation injects magnetic energy into the plasma, heating it and thereby modifying the optical depth of recombination, with an impact on the primary CMB power spectra (Kunze & Komatsu, 2015; Chluba et al., 2015). This effect leads to $B_{1\,\rm Mpc} < 0.9\,$nG for nearly scale-invariant PMFs with *Planck* 2015 likelihood.

3 Constraints from non-Gaussainities

PMFs modelled as a stochastic background have a non-Gaussian contribution to CMB anisotropies since the components of the energy momentum tensor are quadratic in the fields and therefore approximately follow a χ^2 statistics (Brown & Crittenden, 2005). PMFs generate non-zero higher-order statistical moments and CMB

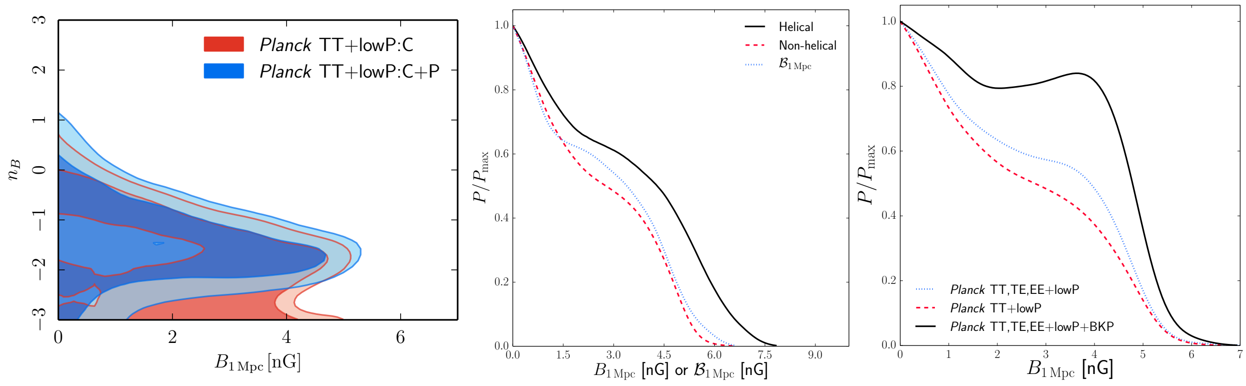

Figure 2: Constraints on PMFs amplitude with the *Planck* 2015 likelihood. We show the constraints on non-helical PMFs, the results for a maximally helical PMFs and the results of the joint analysis of *Planck*-BICEP2/Keck, respectively in the first, second and third panel.

non-Gaussianities give complementary constraints on PMF amplitude. We present three different methods for constraining PMFs using non-Gaussianity measurements all involving the bispectrum and focused on the nearly scale invariant PMFs.

We derive the constraints from the passive-tensor bispectrum. In the case of nearly scale-invariant fields the magnetically-induced bispectrum is amplified in the squeezed-limit configuration with $\ell_1 \ll \ell_2 \approx \ell_3$, as a consequence of the local-type structure of the magnetically-induced gravitational wave. The resultant bispectrum is given by a non-factorizable combination of ℓ-modes (Shiraishi et al., 2011, 2012) and its amplitude can be connected to the amplitude of the fields: $A_{\rm bis}^{\rm MAG} = \left(\frac{B_{1\,\rm Mpc}}{3\,\rm nG}\right)^6 \left[\frac{\ln(\tau_\nu/\tau_B)}{\ln(10^{17})}\right]^3$ where τ_ν and τ_B are the neutrino decoupling time and the PMFs generation time. In order to constrain the non-factorizable magnetically-induced bispectrum, we use the optimal estimator called separable modal methodology (see Shiraishi, Liguori, & Fergusson 2015 for auto-bispectra and Fergusson 2014 for cross-bispectra). With the foreground-cleaned `SMICA` temperature map, we obtain $B_{1\,\rm Mpc} < 2.8\,\rm nG$ at 95% CL, assuming $\tau_\nu/\tau_B = 10^{17}$.

We derive the constraints also using the passive scalar modes and the estimation of the expansion coefficients c_L of the three point correlation function of the magnetically-induced curvature perturbation (Shiraishi et al., 2013): $\langle \zeta(\vec{k}_1)\,\zeta(\vec{k}_2)\,\zeta(\vec{k}_3)\rangle = (2\pi)^3\delta^{(3)}(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)\sum_L c_L \Big(P_L(\hat{\vec{k}}_1 \cdot \hat{\vec{k}}_2)\,P_\zeta(k_1)\,P_\zeta(k_2) + 2\,\text{perm.}\Big)$, where c_0 is related to the local-form $f_{\rm NL}$ as $c_0 = 6/5 f_{\rm NL}^{\rm local}$ and P_L is the Lth order Legendre polynomial. The Legendre coefficients are related to the PMF amplitude as: $c_1 \approx -0.9\left(\frac{B_{1\,\rm Mpc}}{\rm nG}\right)^2\left(\frac{\mathcal{B}_{1\,\rm Mpc}}{\rm nG}\right)^4$ and $c_2 \approx -2.8\times10^{-3}\left(\frac{B_{1\,\rm Mpc}}{\rm nG}\right)^6$. We do not consider a possible helical component ($\mathcal{B}_{1\,\rm Mpc}$) in this analysis. We estimate c_2 from `SMICA`, `NILC`, `SEVEM`, and `Commander` foreground-cleaned maps, assuming again $\tau_\nu/\tau_B = 10^{17}$. The constraints for all the maps are at the level of few nG with the strongest one coming from `SMICA`: $B_{1\,\rm Mpc} < 4.5\,\rm nG$ at 95% CL.

Finally we use the compensated bispectrum with a semi-analytical technique for the scalar mode. We compute an effective $f_{\rm NL}$ based on the comparison between the bispectrum and the power spectrum, and derive the constraints on the amplitude of the PMFs. The analysis is based on the treatment presented by Caprini et al. (2009). The temperature anisotropy on large angular scales depends on the PMF energy density, therefore, the magnetically induced bispectrum depends on the three point correlation function of the PMF energy density:$\langle\rho_B(\vec{k})\,\rho_B(\vec{q})\,\rho_B(\vec{p})\rangle$. In Caprini et al. (2009) it is presented an approximation for this three point correlation function from which it is possible to derive the bispectrum. Once computed the bispectrum, it is possible to estimate an effective $f_{\rm NL}^{\rm eff}$ to be compared with the measurements. For the nearly scale-invariant case we have: $f_{\rm NL}^{\rm eff} \approx \frac{3\pi^9\,\alpha^3}{36\,\mathcal{A}^2}\,\frac{n_B(n_B+3)^2}{2n_B+3}\,\frac{\langle B^2\rangle^3}{\rho_{\rm rel}^3} = 1851\,\frac{n_B(n_B+3)^2}{2n_B+3}\left(\frac{\langle B^2\rangle}{(10^{-9}\,\rm G)^2}\right)^3$. With *Planck* 2015 measurements the constraints on the amplitude of the nearly scale invariant fields is $B_{1\,\rm Mpc} < 3\,\rm nG$ at 95% CL.

4 Faraday rotation

The presence of PMFs at the CMB last scattering surface induces a rotation of the polarization plane of the CMB photons, the Faraday Rotation (FR), which induces a B-mode polarization from the E-mode. The generation of magnetically-induced B-modes through FR of E-modes is described by (Kosowsky et al., 2005): $C_\ell'^{BB} = N_\ell^2 \sum_{\ell_1 \ell_2} \frac{(2\ell_1+1)(2\ell_2+1)}{4\pi(2\ell+1)} N_{\ell_2}^2 \, K(\ell,\ell_1,\ell_2)^2 \, C_{\ell_2}^{EE} \, C_{\ell_1}^{\alpha} \left(C_{\ell_1 0 \ell_2 0}^{\ell 0}\right)^2$, where $N_\ell = (2(\ell-2)!/(\ell+2)!)^{1/2}$ is a normalization factor, $K(\ell,\ell_1,\ell_2) = -1/2\,(L^2 + L_1^2 + L_2^2 - 2L_1L_2 - 2L_1L + 2L_1 - 2L_2 - 2L)$ with $L \equiv \ell(\ell+1)$, $L_1 \equiv \ell_1(\ell_1+1)$, $L_2 \equiv \ell_2(\ell_2+1)$, and $C_{\ell_1 0 \ell_2 0}^{\ell 0}$ is a Clebsch-Gordan coefficient.

The power spectrum of the rotation angle is strongly dependent on the observed frequency ν_0 :$C_\ell^\alpha = \nu_0^{-4} C_\ell^\Phi$, and the rotation power spectrum s given by: $C_\ell^\Phi \approx \frac{9\ell(\ell+1)}{(4\pi)^3 e^2} \frac{B_{1\,\mathrm{Mpc}}^2}{\Gamma(n_B+3/2)} \left(\frac{\lambda}{\tau_0}\right)^{n_B+3} \int_0^{x_\mathrm{D}} dx\, x^{n_B}\, j_\ell^2(x)$ with $x_\mathrm{D} = \tau\, k_\mathrm{D}$. We use the observed *Planck* E-mode spectrum $C_\ell'^{EE}$ at 70 GHz as a proxy for the primordial one, C_ℓ^{EE} to calculate predicted B-mode spectra to be compared with the observed one. By using the EE information at 70 GHz for $\ell < 30$, provided by the low-ℓ likelihood, we obtain $B_{1\,\mathrm{Mpc}} < 1380$ nG at 95% CL.

Planck 2015 data provide a set of complementary constraints on PMFs, from the CMB APS to the non-Gaussianities to the Faraday rotation. Overall *Planck* 2015 constrains PMFs amplitude at the level of the nanoGauss.

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