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FOREGROUNDS CONTAMINATION IN CMB POLARIZATION DATA: IMPLICATIONS FOR CMB B-MODE POLARIZATION MEASUREMENTS WITH PLANCK

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Abstract. We analyze the possibility of detection of the Cosmic Microwave Background (CMB) B-mode polarization by the Planck experiment for the ΛCDM cosmological model with tensor contribution to primordial perturbation given by currently favored ratio of tensor to scalar perturbations, $0.016 < r < 0.16$. The cosmological B-mode polarization is compared with models for the systematic noise induced by the galactic and extragalactic foregrounds in the Planck polarization channels. We have obtained that the 70 GHz channel have the lowest foregrounds induced noise level and, for the considered class of cosmological models, can detect the cosmological B-mode polarization at 3σ level for a tensor to scalar ratio $r > 0.08$. For greater tensor contributions, also the 100 GHz, 143 GHz and 44 GHz channels will be able to detect the CMB B-mode polarization.

This work has been done on behalf of the Planck-LFI activities.

Key words: cosmic microwave background, early Universe, polarization, foregrounds.

1. INTRODUCTION

The Cosmic Microwave Background is a key cosmological probe of the early Universe. Apart from determining the origin of the Large Scale Structure (LSS) in the Universe, the cosmological parameters and the ionization history of the Universe, the CMB anisotropies may probe the gravitational wave background, which, if exists, will be the next important test of the inflation theory.

The existence of the CMB temperature anisotropy implies the existence of polarization anisotropy, both being generated by the same mechanisms. Temperature fluctuations are generated by perturbations in the gravitational potential which lead directly to fluctuations by the gravitational redshifting of CMB photons and drive acoustic oscillations of the primordial plasma. The resulted temperature fluctuations are of the same order of magnitude as the metric perturbations. The polarization is the effect of Compton scattering of the radiation possessing a nonzero quadrupole moment, which is possible only very near the surface of the last scattering, when the photons begin to decouple from electrons and generate a quadrupole moment through free streaming. Since at this epoch the available number of free electrons is reduced, the level of polarization against the temperature fluctuations is only about 10%.

The CMB polarization field can be described by two components: the curl-free component, of even parity, named "E-mode" and the curl component, of odd parity, named "B-mode". While the E-mode polarization is generated both by scalar and tensor perturbations, the B-mode polarization is only generated by tensor perturbations, being a direct probe of the inflationary epoch.

The amplitude of B-mode polarization fluctuations, directly related to the ratio r of the amplitudes of tensor to scalar perturbations generated during inflation, is expected to be extremely weak compared to the total amplitude of CMB temperature fluctuations and about an order of magnitude smaller then the E-mode fluctuations amplitude. For this reason, the detection of the B-mode polarization due to tensor perturbations is very closely related to few confusion factors like the experimental performances, the goodness of foreground subtraction and the correct separation between the E and B modes.

In this paper we are focused on the foreground subtraction errors for the future Planck CMB polarization measurements and we analyze the possibility of detection of the B-mode polarization by the Planck experiment in the context of current limits on the ratio of tensor to scalar primordial perturbations and knowledge of the polarized galactic and extragalactic foregrounds.

2. POLARIZED FOREGROUNDS IN THE PLANCK EXPERIMENT

The expected level of the polarized signal for foreground emission, supposed to be the same, on average, for the E- and B-mode polarization, depends on the observing frequency and on the angular scale.

The main CMB polarized foregrounds are the galactic synchrotron and dust emission and the extragalactic sources such the radio sources and the dusty galaxies. The galactic free-free emission is expected to be negligible polarized.

The synchrotron radiation, emitted by the free electrons in the spiral motion in the galactic magnetic field, can be up to 75% polarized and is the most important CMB foreground at frequencies below 70 GHz. Following [1, 2], we model the power spectrum of polarized synchrotron at frequency ν:

$$C_l^{S,P} = A^S \left(\frac{\nu}{\nu_0}\right)^{2\alpha_S} \left(\frac{l}{l_0}\right)^{\beta_S}, \tag{1}$$

adopting the value $\beta_S = -3$ [3] for the spectral index and $\alpha_S = -3$ [4]. Like in [5], we take the reference frequency $\nu_0 = 30\,\text{GHz}$ and the reference multipole $l_0 = 300$, in order to use the DASI upper limit [6] for the synchrotron amplitude $A_S = 0.91\mu\text{K}^2$.

The thermal (vibrational) emission from galactic dust particles, which is important mainly at frequencies above 70 GHz, have a polarization degree up to 4-5% in the galactic plane, with several clouds of few square degrees polarized more than 10%, as shown by the Archeops polarization measurements [7]. As in [5], we model the dust polarized signal at frequency ν as:

$$C_l^{D,P} = p^2 A^D \left(\frac{\nu}{\nu_0}\right)^{2\alpha_D} \left(\frac{l}{l_0}\right)^{\beta_D} \left[\frac{e^{h\nu_0/KT} - 1}{e^{h\nu/KT} - 1}\right]^2, \tag{2}$$

taking the parameters' values $\alpha_D = 2.2$ [4], $T = 18\text{K}$, constant across the sky, the reference frequency $\nu_0 = 94\text{GHz}$, and the Archeops upper limit for the polarization fraction $p = 5\%$ at the reference multipole order $l_0 = 900$. For the B-mode polarization dust power spectrum we have adopted $\beta_D = -1.4$ [8, 5]. We set the normalization amplitude A_D using the intensity normalization $I_\nu = 1\text{MJy/sr}$ at $\nu = 3000\text{GHz}$ [9], extrapolated to 94 GHz and converted into thermodynamic temperature.

For modeling the contribution of extragalactic sources to the polarization measurements of Planck experiment, we have used the evolutionary model of [10] which predictions for the number counts of radio sources at cm and mm wavelengths have been confirmed by a number of surveys between 15 and 44 GHz [11]. Following [11], we have calculated the polarization power spectrum of the extragalactic point sources as:

$$C_l^{PS,P} = \int_{-Q_c}^{Q_c} n(Q) Q^2 \mathrm{d}Q, \tag{3}$$

where Q_c is the lowest value of polarization intensity for sources that can be individually detected and removed from polarization maps. The differential sources counts for polarization is expressed as:

$$n(Q) = \frac{1}{\pi} \int_0^{U_c} \frac{\mathrm{d}U}{\sqrt{Q^2 + U^2}} \int_0^{\infty} \frac{n(S) P\left(\sqrt{Q^2 + U^2} / S\right)}{S} \mathrm{d}S. \tag{4}$$

In the above equation, *S*, respectively *Q* and *U* are the total intensity respectively polarization Stokes parameters, and *n*(S) is given by the model of [10]. The probability distribution for the polarization degree, $P(p) = 100P(\Pi)$, where $p = \sqrt{Q^2 + U^2} / S$, has been calculated using the NVSS polarization measurements at 1.4 GHz, extrapolated to Planck polarization frequencies.

The polarization power spectra of the foregrounds described above have been estimated at Planck's polarization frequencies, namely 30, 44, 70, 100, 143, 217 and 353 GHz, using, for the point sources power spectra, the threshold $S_c =$ 0.23, 0.25, 0.24, 0.19, 0.13, 0.12 and 0.18 Jy respectively for the frequency channels listed above [12] and taking $Q_c = \sqrt{2} S_c$.

Figure 1 presents the polarization power spectra of the three considered foregrounds at 70 GHz frequency, modeled as described above.

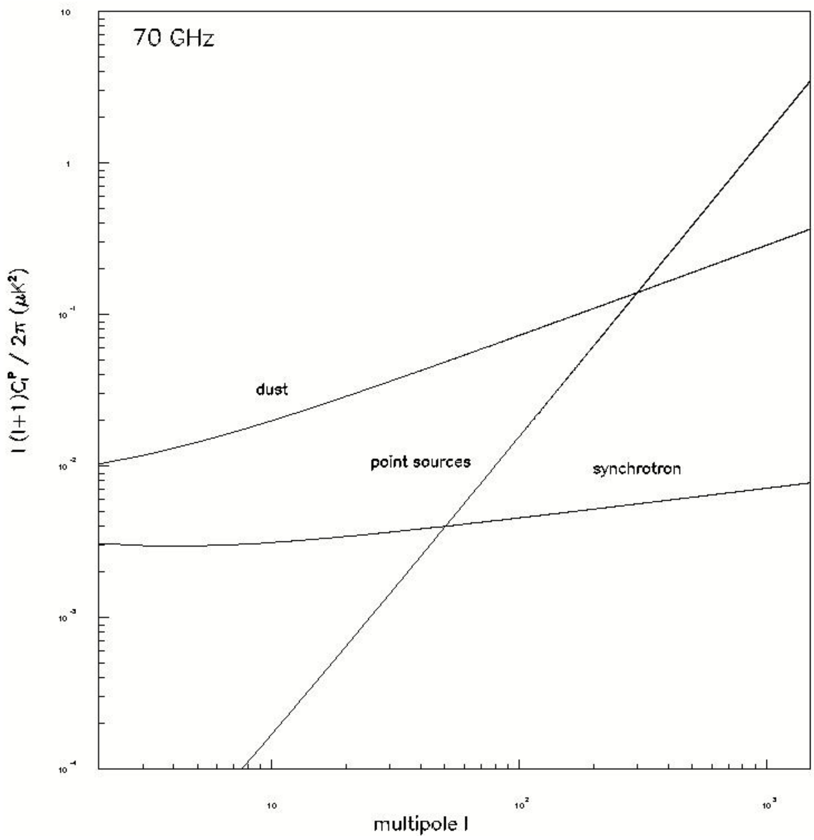

Fig. 1 – Estimated polarization power spectra at 70 GHz for CMB foregrounds (from up down at low multipoles: dust, synchrotron and extragalactic point sources).

3. THE CMB B-MODE POLARIZATION

Inflation is the most currently favored scenario which explains the initial conditions for structure formation and for CMB temperature anisotropies. Inflation generically predicts a mixture of scalar and tensor primordial metric perturbations, generated by quantum fluctuation of the scalar field that drive inflation, which grow during the period of exponential expansion of the Universe, until their wavelengths become larger than the Hubble radius, when they frozen. When the perturbations reenter the horizon in the matter domination era, they seed the inhomogeneities which generate structure upon gravitational collapse. The CMB anisotropies are fingerprints of these perturbations at the last scattering surface.

A number of inflationary predictions, like the Gaussian, adiabatic and nearly scale invariant spectrum of primordial fluctuations are in excellent agreement with the CMB anisotropy measurements, the most recent provided by WMAP [13, 14, 15].

The CMB B-mode polarization power spectrum, predicted by the inflation theory for models with a tensor component of the metric perturbations, is characterized by a peak around the multipole $l = 90$, corresponding to the angular scale of the horizon at the recombination epoch. The amplitude of the power spectrum is proportional to the ratio of tensor to scalar primordial perturbations parameter, which is related to the energy scale of inflation. The attempt to detect the CMB B-mode polarization anisotropies will be the next powerful confirmation of the inflation.

From the analysis of CMB temperature anisotropy data released by WMAP, only upper limits to tensor contributions were obtained. The WMAP-5 years temperature data give the constraint $r < 0.43$ [15]. A recent analysis of available CMB data (WMAP-3 years, ACBAR, CBI2 and BOOMERANG03) combined with LSS data from SDSS, in the framework of trinomial new inflation models, gives the first lower limit for the ratio of tensor to scalar initial perturbations $r > 0.016$ [16]. For the class of trinomial new inflation models there exists also a theoretical upper limit for the tensor to scalar ratio $r < 0.16$ [16].

The next space mission dedicated to CMB temperature and polarization anisotropies measurements is the ESA's Planck mission, which will be launched in May 2008. The Planck experiment will have the advantage of a wide frequency coverage, high angular resolution and low instrumental noise, the combination of these characteristics offering an excellent chance to provide very accurate E-mode polarization measurements and, maybe, to detect the cosmological B-mode polarization.

For the purpose of investigating the possibility of detection of CMB B-mode polarization by Planck experiment, we assume for the cosmological parameters of the ΛCDM model the current values preferred by the data, considering that the tensor to scalar ratio value is in the interval $0.016 < r < 0.16$, specific to trinomial new inflation models.

4. THE CMB B-MODE POLARIZATION VERSUS FOREGROUNDS FOR PLANCK EXPERIMENT

In this work, we have estimated the foregrounds residuals for the Planck polarization channels, assuming that 1% of the polarized foregrounds, at the power spectra level, contribute to the systematic noise of the CMB B-mode polarization power spectra. The polarization power spectra for the considered foregrounds (synchrotron, dust and point sources) have been estimated as is described Section 2. We have compared the residuals with the theoretical CMB B-mode polarization power spectra, for the ΛCDM cosmological models with the ratio of tensor to scalar primordial perturbations $0.016 < r < 0.16$. The theoretical CMB power spectra were calculated using the CAMB code [17] and setting the other cosmological parameters at the latest reported best-fit values [15]: the baryonic matter fraction $\Omega_b h^2 = 0.0227$, the dark matter fraction $\Omega_c h^2 = 0.1099$, the ratio of the (approximate) sound horizon to the angular diameter distance $\theta_* = 0.0104$, the optical depth $\tau = 0.087$, the cosmological constant energy density $\Omega_\Lambda = 0.7435$, the amplitude of curvature perturbations at k = 0.002/Mpc $\Delta_R{}^2 = 2.41 \times 10^{-9}$, and the scalar spectral index $n_s = 0.963$.

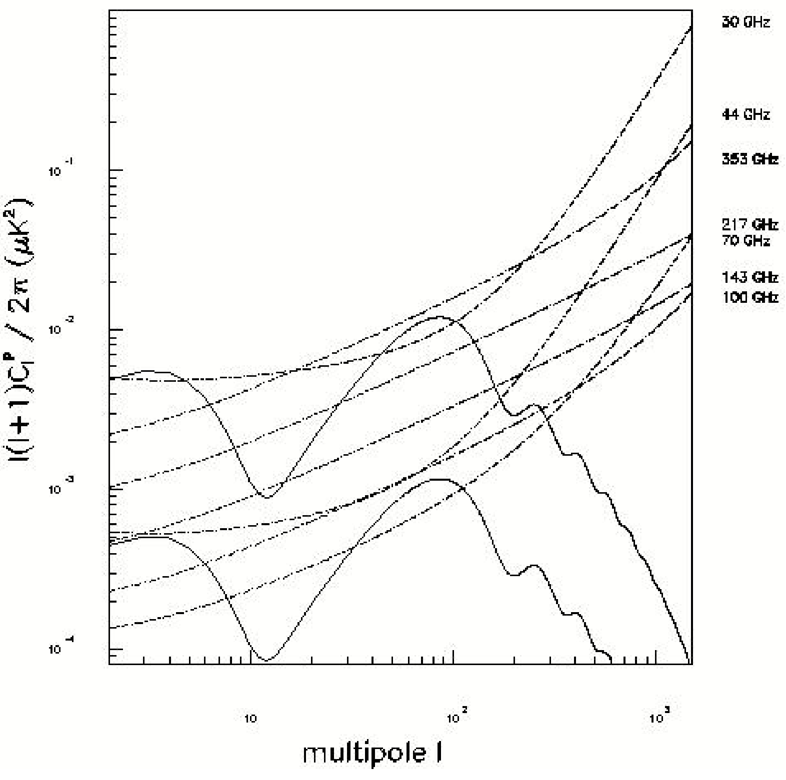

Fig. 2 – Theoretical CMB B-mode polarization power spectra corresponding to the cosmological parameters listed in the text and for the limits of the assumed interval for the ratio r of tensor to scalar perturbations (lower continuous line for $r = 0.016$ and upper continuous line for $r = 0.16$). With dot-dashed lines are plotted the total foreground residuals (assuming 1% subtraction error) for the Planck's frequencies, as is indicated in the right side of the graphic.

In Fig. 2 are plotted the theoretical CMB B-mode polarization power spectra obtained for the cosmological parameters listed above, for the limits of the interval for the ratio r of tensor to scalar perturbations (lower continuous line for $r = 0.016$ and upper continuous line for $r = 0.16$). The total foreground residuals assuming 1% subtraction error, for the Planck's frequencies are plotted with dot-dashed lines, the corresponding frequencies of each line being indicated in the right side of the picture.

It can be seen in Fig. 2 that the 70 GHz frequency channel have the lowest foregrounds residual and therefore have the best chance to detect the B-mode polarization. Considering a signal to noise ratio $S/N = 3$ at the map level, the B-mode polarization can be detected in the multipole range $2 < l < 8$ and $29 < l < 118$ by the 70 GHz channel, for the upper limit of the tensor to scalar ratio $r = 0.16$. For the same detection threshold, also the 100 GHz frequency channel can detect the B-mode polarization for the upper limit of the tensor to scalar ratio for the multipoles $2 < l < 6$, the 143 GHz channel for $2 < l < 4$, and the 44 GHz channel for $l = 3, 4$. For the lower limit of the tensor to scalar ratio $r = 0.016$, the detection threshold for the B-mode polarization for the 70 GHz frequency channel is $S/N = 1$ and the corresponding multipole range is $2 < l < 7$ and $33 < l < 111$. Considering a detection threshold S/N=3 at the map level, the 70 GHz channel can detect the B-mode polarization for the considered cosmological model parameters if the tensor to scalar ratio is $r > 0.08$.

5. CONCLUSIONS

In this paper we have considered the CMB B-mode polarization of the currently preferred ΛCDM cosmological model with a tensor contribution to the primordial metric perturbations described by a tensor to scalar ratio $0.016 < r < 0.16$, as reported by a new analysis of CMB and LSS data [16]. In the context of this class of inflation models, we have analyzed the limits of detection for the B-mode polarization by Planck experiment imposed by foregrounds contamination.

Considering an 1% residual error from the subtraction of the galactic synchrotron and dust emission and of the extragalactic point sources contribution from the Planck B-mode polarization data, we have obtained that the cosmological B-mode polarization of the ΛCDM best-fit cosmological model with a tensor to scalar ratio $r = 0.16$ can be detected by the Planck 70 GHz, 100 GHz , 143 GHz and 44 GHz polarization channels at the *S*/*N*=3 detection threshold. The largest multipole range for which the signal to noise ratio is greater then 3 at the map level is corresponding to the 70 GHz channel, because at this frequency the foregrounds contamination is minimum. For this frequency, the cosmological signal is more than 3 times the foregrounds noise at the map level for a tensor to scalar ratio $r > 0.08$.

We conclude that there are good chances for Planck experiment to detect the cosmological B-mode polarization, and therefore to confirm the inflation theory and the existence of gravitational waves, if the systematic noise induced by the incomplete subtraction of galactic and extragalactic foregrounds will not exceeds the 1% level in the polarization power spectra.

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