Power asymmetries in the cosmic microwave background temperature and polarization patterns

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ABSTRACT

We test the asymmetry of the cosmic microwave background anisotropy jointly in temperature and polarization. We study the hemispherical asymmetry, previously found only in the temperature field, with respect to the axis identified by Hansen et al. To this extent, we make use of the low-resolution Wilkinson Microwave Anisotropy Probe 5-yr temperature and polarization maps and our implementation of an optimal power spectrum estimator. We consider two simple estimators for the power asymmetry and we compare our findings with Monte Carlo simulations which take into account the full noise covariance matrix. We confirm an excess of power in temperature angular power spectrum in the Southern hemisphere at a significant level, between 3σ and 4σ depending on the exact range of multipoles considered. We do not find significant power asymmetry in the gradient (curl) component EE (BB) of polarized angular spectra. Furthermore, cross-correlation power spectra, i.e. TE, TB, EB, show no significant hemispherical asymmetry. We also show that the cold spot found by Vielva et al. in the Southern Galactic hemisphere does not alter the significance of the hemispherical asymmetries on multipoles which can be probed by maps at resolution Nside = 16. Although the origin of the hemispherical asymmetry in temperature remains unclear, the study of the polarization pattern could add useful information on its explanation. We therefore forecast by Monte Carlo the Planck capabilities in probing polarization asymmetries.

Key words: methods: numerical – methods: statistical – cosmology: observations – cosmology: theory – cosmic microwave background.

1 INTRODUCTION

Great attention has been devoted to a hemispherical power asymmetry in the intensity pattern of the cosmic microwave background (CMB) as seen by Wilkinson Microwave Anisotropy Probe (WMAP; Dunkley et al. 2009; Hinshaw et al. 2009). Such asymmetry has been originally found in WMAP 1-yr release and appears to lay on an axis nearly orthogonal to the ecliptic plane (Eriksen et al. 2004; Hansen, Banday & Gorski 2004). It has been confirmed in the WMAP 3- and 5-yr release (Eriksen et al. 2007; Hansen et al. 2009; Hoftuft et al. 2009) and it is present in the COBE data as well, although with lower significance. The temperature power spectra of the opposing hemispheres are inconsistent at 3σ to 4σ depending on the range of multipoles considered. The asymmetry has been detected in low-resolution maps (Eriksen et al. 2004), both in angular and multipoles space, but it extends to much smaller angular scales in the multipole range δℓ = [2, 600] (Hansen et al. 2009). It is unclear whether this hemispherical asymmetry is primordial or due to unknown residual foreground/systematics.

Although several groups have performed different and independent investigations on the CMB temperature pattern, the joint analysis of the CMB temperature and polarization pattern has not been performed yet. The information encoded in the polarization pattern may turn out extremely useful to clarify the presence of the hemispherical asymmetry shedding light on its origin. Low-resolution WMAP 5-yr maps in (T, Q, U) with relative noise covariance matrices are publicly available: these public maps have allowed a re-analysis by a quadratic maximum likelihood (QML) estimator of the low multipole angular power spectrum in temperature and polarization (Gruppuso et al. 2009).

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In this paper, we address the issue of hemispherical asymmetry by estimating the power spectrum in the two hemispheres by using the QML: our application of QML in this context is novel and extremely useful since the aggressive masking needed to reduce residual foreground contamination might be even more problematic for polarization than for temperature (Bunn et al. 2003; Smith & Zaldarriaga 2009).

Our main aim is to test whether other asymmetries in full temperature–polarization pattern are present around the most recently determined axis defined by the direction ($\theta = 107^\circ$, $\phi = 226^\circ$; Hansen et al. 2009), where $\theta$ and $\phi$ are the Galactic colatitude and longitude, respectively.

This paper is organized as follows. In Section 2 we describe our methodology by reviewing the algebra of the QML estimator. We also discuss the data set used and introduce the $R$ and $D$ estimators, the ratio and the difference of the power in the two hemispheres, respectively. In Section 3 we discuss our results including the related Monte Carlo uncertainties based on 1000 simulations. We discuss Planck predicted performances in probing the hemispherical asymmetries in Section 5, while in Section 6 we draw our main conclusions.

2 DESCRIPTION OF THE ANALYSIS

2.1 Angular power spectra estimation

In order to evaluate the angular power spectra, we use the BoltPol code, a QML estimator. The QML formalism was introduced in Tegmark (1997) and extended to polarization in Tegmark & de Oliveira-Costa (2001). In this section we describe the essence of the method. Further details can be found in Gruppuso et al. (2009) where BoltPol has been applied to WMAP 5-yr low-resolution data.

Given a map in temperature and polarization $x$ (T, Q, U), the QML provides estimates $\hat{C}_\ell^X$ – with $X$ being one of TT, EE, TE, BB, TB, EB – of the angular power spectrum as

$$\hat{C}_\ell^X = \sum_{\ell'} \left( F^{-1} \right)^{X\ell'}_{\ell'\ell} \left[ x_l \mathbf{E}_\ell^X x - \text{tr} \left( \mathbf{N} \mathbf{E}_\ell^X \right) \right],$$

where the Fisher matrix $F^{X\ell'}_{\ell\ell'}$ is defined as

$$F^{X\ell'}_{\ell\ell'} = \frac{1}{2} \text{tr} \left[ \mathbf{C}^{-1} \frac{\partial \mathbf{C}}{\partial \hat{C}_{\ell'}^X} \mathbf{C}^{-1} \right],$$

and the $\mathbf{E}_\ell^X$ matrix is given by

$$\mathbf{E}_\ell^X = \mathbf{C}^{-1} \frac{\partial \mathbf{C}}{\partial \hat{C}_{\ell'}^X} \mathbf{C}^{-1},$$

with $\mathbf{C} = \mathbf{S}(C_X^X) + \mathbf{N}$ being the global covariance matrix (signal plus noise contribution)\(^1\) and $C_X^X$ is a fiducial power spectrum.

Although an initial assumption for a fiducial power spectrum $C_X^X$ is needed, the QML method provides unbiased estimates of the power spectrum contained in the map regardless of the initial guess:

$$\langle \hat{C}_\ell^X \rangle = \hat{C}_\ell^X,$$

where the average is taken over the ensemble of realizations or, in a practical test, over Monte Carlo realizations extracted from $C_X^X$.

On the other hand, the covariance matrix associated to the estimates,

$$\left\langle \Delta \hat{C}_\ell^X \Delta \hat{C}_{\ell'}^X \right\rangle = (F^{-1})_{\ell\ell'},$$

does depend on the assumption for the fiducial power spectrum $C_X^X$: the closer the guess to the true power spectrum is the closer are the error bars to minimum variance. According to the Cramer–Rao inequality, equation (5) tells us that the QML has the smallest error bars. We thus call the QML an ‘optimal’ estimator.

2.2 Data set and simulations

In this section we describe the data set that we have considered and the corresponding simulations we have produced to analyse it. We use the temperature Internal Linear Combination (ILC) map smoothed at 9.8 and reconstructed at healpix\(^2\) (Gorski et al. 2005) resolution $N_{\text{side}} = 16$, the foreground cleaned low-resolution maps and the noise covariance matrix in $(Q, U)$ publicly available at the Legacy Archive for Microwave Background Data Analysis (LAMBDA) website.\(^3\) We have added to the temperature map a random noise realization with variance of 1 $\mu$K\(^2\), as suggested in Dunkley et al. (2009). Consistently, the noise covariance matrix for TT is taken to be diagonal with variance equal to 1 $\mu$K\(^2\).

To perform the analysis, we have built the masks for the two hemispheres defined by the direction ($\theta = 107^\circ$, $\phi = 226^\circ$; Hansen et al. 2009) and combined them with the Galactic WMAP 5-yr low-resolution temperature and polarization mask. Maps and covariances for the two sky regions (namely north and south) have been consistently tailored to the produced masks (see Fig. 1).

To assess the significance of the power asymmetries found in the data, our results have been tested against Monte Carlo simulations. A set of 1000 CMB+noise sky realizations has been generated: the signal was generated from the WMAP 5-yr best-fitting model, the noise through a Cholesky decomposition of the global $(T, Q, U)$ noise covariance matrix. We then computed the angular power spectra for each of the 1000 simulations using BoltPol and built two figures of merit as explained in the next subsection.

2.3 Estimators

We define the following quantities:

$$c_{N/S}^X \equiv \frac{1}{(\ell_{\text{max}} - 1)} \sum_{\ell=2,\ell_{\text{max}}} (\ell + 1) \frac{2\pi}{2\gamma} \hat{C}_\ell^{X,N/S},$$

where $\hat{C}_\ell^{X,N}$ and $\hat{C}_\ell^{X,S}$ are the estimated angular power spectra obtained with BoltPol observing only the Northern (‘N’) and the Southern (‘S’) hemisphere, respectively, outside the Galactic plane. As above, $X$ runs over the spectral types.

Two estimators can be built as follows: the ratio $R^X$, as performed in Eriksen et al. (2004),

$$R^X = \frac{\hat{C}_\ell^{X,N}}{\hat{C}_\ell^{X,S}},$$

and the difference $D^X$,

$$D^X = \hat{C}_\ell^{X,N} - \hat{C}_\ell^{X,S},$$

of the two aforementioned quantities. In the following, we will drop the index $X$ for $R$ and $D$ specifying only the spectrum we refer to.

\(^1\) Note that, in principle, it is possible to include in this matrix residuals from foreground subtraction. This is the case for the WMAP foreground reduced covariance matrix we employ hereafter.

\(^2\) http://healpix.jpl.nasa.gov/

\(^3\) http://lambda.gsfc.nasa.gov/
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For our application to WMAP data, both estimators have been considered for TT, while only the $D$ estimator has been applied to the other spectra (EE, TE, BB, TB and EB), because of unfavourable signal-to-noise ratio of the WMAP data in polarization.

3 RESULTS

The six angular power spectra TT, EE, TE, BB, TB and EB are presented in Figs 2 and 3. Our results for TT, shown in the upper panel of Fig. 2, are consistent with those obtained by Eriksen et al. (2004).

In Fig. 4, we show the $R$ estimator distribution for the range $\ell = 2$–40. For this estimator we obtain that the probability of having the WMAP value is as low as 0.2 per cent, which agrees with the results by Eriksen et al. (2004). In Table 1 the probability of obtaining the WMAP value for the $D$ estimator is computed for the following four multipoles ranges: 2–8, 2–16, 2–32 and 2–40. See Fig. 5 for the full empirical (Monte Carlo) probability distribution functions. Note that the $R$ and $D$ estimator detect a comparable level of anomaly in the multipole range 2–40.

In Table 2, we provide results for polarization and cross-spectra. As mentioned above, only $D$ is considered and computed for the four aforementioned multipoles range. The estimator $R$, in fact, is not well defined any time the denominator $C_X$ approaches to zero, which might be the case for highly noisy spectra. Although Table 2 does not show any significant deviation from the symmetry for polarization and cross-spectra, it is none the less worth noting the behaviour of EE in the range $\ell = 2$–16 (see also Fig. 6), for which the probability of having the WMAP value is as low as 3.5 per cent, and of BB.

Figure 1. Mollweide projection of the observed Northern (red) and Southern (blue) hemisphere at $N_{side} = 16$. The (light blue) circle in the Southern hemisphere corresponds to the region of the cold spot, whereas the light grey region corresponds to the WMAP low-resolution Galactic mask for temperature (upper panel) and polarization (lower panel).

Figure 2. QML estimates for TT (upper panel), EE (middle panel) and TE (lower panel) from WMAP 5-yr $N_{side} = 16$ maps. Solid (blue) line is for the angular power spectrum of the Southern hemisphere (blue region of Fig. 1), whereas dotted (red) line is for the Northern hemisphere (red region of Fig. 1). Dashed line shows the WMAP 5-yr best fit, taken as fiducial power spectrum for the analysis. For reference, we also show the error bars of the QML computed from a Monte Carlo of 1000 sky realizations of the Northern hemisphere with the global $(T, Q, U)$ noise covariance matrix (error bars from the Monte Carlo on the Southern hemisphere are basically undistinguishable from the ones plotted).

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Figure 3. As in Fig. 2, but for BB, TB and EB (from top to bottom).

Figure 4. TT. Number counts (y-axis) versus $R$ (x-axis) for the range $\Delta \ell = [2, 40]$. The vertical line stands for the WMAP 5-yr data. The probability to obtain a smaller value than the WMAP one is 99.8 per cent.

Table 1. Probabilities (in per cent) to obtain a smaller value than WMAP low-resolution data for TT angular power spectrum and the $D$ estimator.

| $D$ | $\Delta \ell = 2$–8 | $\Delta \ell = 2$–16 | $\Delta \ell = 2$–32 | $\Delta \ell = 2$–40 |
|-----|---------------------|---------------------|---------------------|---------------------|
| TT  | 86.2                | 96.9                | 99.8                | 99.1                |

in the range $\ell = 2$–8 where the probability decreases to 2.2 per cent. Moreover, an unexpected statistics seems to show up for TE in the range 2–40 where the probability of having the WMAP value is 0.5 per cent. However, this mainly comes from the multipoles between 32 and 40, which are close to the threshold of reliability of the QML on $N_{\text{side}} = 16$ maps.

We also report on the possible contribution to the north–south power asymmetry given by the cold spot found by Vielva et al. (2004) (see also Cruz et al. 2005, 2007). By masking out the cold spot (see light blue spot of Fig. 1) with a circle of radius $8^\circ$ – a conservative choice compared to its size of $5^\circ$ – we have not found any significant deviation from the $C_\ell$ obtained without masking it out. This might be due to the fact that the low resolution of our

Table 2. Probabilities (in per cent) to obtain a smaller value than WMAP low-resolution data.

| $D$ | $\Delta \ell = 2$–8 | $\Delta \ell = 2$–16 | $\Delta \ell = 2$–32 | $\Delta \ell = 2$–40 |
|-----|---------------------|---------------------|---------------------|---------------------|
| TE  | 59.9                | 16.9                | 75.6                | 99.5                |
| EE  | 5.4                 | 3.5                 | 28.8                | 34.3                |
| BB  | 97.8                | 79.5                | 71.9                | 81.0                |
| TB  | 80.9                | 54.1                | 42.8                | 91.7                |
| EB  | 61.3                | 54.6                | 74.4                | 21.8                |
the direction reported in Hansen et al. (2009), see Table 1 and Fig. 5. Considering the same axis, we have extended such analysis to the other spectra (TE, EE, BB, TB and EB) considering only the estimator \( D \), defined in equation (8), because the noise level of \( WMAP \) permits the use of \( R \) (see equation 7) only for TT.

Since our implementation of the QML (Gruppuso et al. 2009) is capable of handling the full noise covariance matrix in \( (T, Q, U) \), the analysis of the present paper is joint for temperature and polarization. The information encoded in CMB polarization is complementary to the temperature and is important to test for possible asymmetries in polarization (see for instance Dvorkin, Peiris & Hu 2008 for the description of the polarization field in models that break statistical isotropy locally through a modulation field). We confirm the TT anomalies that have been already reported by several groups. Our analysis of polarized and cross-spectra does not show significant anomalies, as from Table 2.

The origin of these hemispherical asymmetries is still unknown. They can be primordial or due to some residual foreground or systematic effect. For instance, in Li et al. (2009) an anomalous correlation between temperature and observation number has been claimed to be present in the \( WMAP \) 5-yr data, potentially impacting the large-scale pattern of CMB maps (including the power asymmetry) has been recently claimed (Bernui 2009), especially in the

5 DISCUSSIONS AND CONCLUSIONS

Using an optimal power spectrum estimator, we have confirmed the power asymmetry for TT found by Eriksen et al. (2004) along
polarization sector where the properties of the cold spot are still unclear (Vielva et al. 2010).

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