Testing discrete symmetries with the cosmic microwave background: current constraints and Planck forecasts

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Abstract. Anisotropy and polarization of the CMB are probing cosmological models with unprecedented precision. The WMAP satellite data are largely consistent with concordance $\Lambda$CDM cosmology. However, intriguing flukes are known to exist that may pinpoint at physics beyond the standard model. Constraining the violations of discrete symmetries in the CMB pattern is a promising mean to investigate these discrepancies.

In this paper we constrain the Parity and CPT symmetries through CMB datasets. We describe the basic formalism, the relevant estimators and the overall analysis strategy. We provide marginal evidence for large scale Parity anomaly in the WMAP data that may be soon confirmed or discarded by the \textit{Planck} satellite. \textit{Planck} is currently measuring CMB anisotropies and their polarization with a level of precision that will remain unparalleled for many years to come. We also show how the CMB can be used to constrain fundamental symmetry violations in the photon sector through the so-called cosmological birefringence phenomenon. Finally, we provide forecasts for \textit{Planck} and we discuss how emission from a specific diffuse foreground component arising within the Solar System needs to be kept under strict control to avoid incurring into false positive detections.

1. Introduction
The \textit{Planck} cosmic microwave background (CMB) anisotropy probe\textsuperscript{1}, the first European and third generation mission after the COsmic Background Explorer (COBE) and Wilkinson Microwave Anisotropy Probe (WMAP) \textsuperscript{2}, represents the state-of-the-art in precision cosmology today \cite{1, 2, 3}. \textit{Planck} is equipped with a 1.5–m effective aperture telescope with two actively-cooled instruments observing the sky in nine frequency channels from 30 GHz to 857 GHz: the Low Frequency Instrument (LFI) operating at 20 K with pseudo-correlation radiometers, and the High Frequency Instrument (HFI) with bolometers operating at 100 mK. The coordinated

\textsuperscript{1} \textit{Planck} (http://www.esa.int/Planck) is a project of the European Space Agency - ESA - with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

\textsuperscript{2} http://lambda.gsfc.nasa.gov/
use of the two different instrument technologies and analyses of their output data will allow optimal control and suppression of systematic effects, including discrimination of astrophysical sources. A summary of the LFI and HFI performance is reported in Table 1. Note that Planck is sensitive to linear polarization up to 353 GHz. The constraints on the thermal behaviour, required to minimize systematic effects, dictated a Planck cryogenic architecture that is one of the most complicated ever conceived for space. Moreover, the spacecraft has been designed to exploit the favourable thermal conditions of the orbit around the second Lagrangian point of the Sun-Earth system. The thermal system is a combination of passive and active cooling: passive radiators are used as thermal shields and pre-cooling stages, active cryo coolers are used both for instrument cooling and pre-cooling [4]. Planck is a spinning satellite. Thus, its receivers will observe the sky through a sequence of (almost great) circles following a scanning strategy aimed at minimizing systematic effects and achieving all-sky coverage for all receivers [5, 6]. The data analysis, its scientific exploitation, and the core cosmology programme of Planck are mostly carried out by two core teams (one for LFI and one for HFI), working in close connection with the Data Processing Centres (DPCs), and closely linked to the wider Planck scientific community, consisting of the LFI, HFI, and Telescope consortia, organized into various working groups. Planck is managed by the ESA Planck science team. Planck will open a new era in our understanding of the universe and of its astrophysical structures [7].

Table 1. Planck performance. The average sensitivity, $\delta T/T$, per FWHM$^2$ resolution element (FWHM is reported in arcmin) is given in CMB temperature units (i.e. equivalent thermodynamic temperature) for 28 months of integration. The white noise (per frequency channel for LFI and per detector for HFI) in 1 sec of integration (NET, in $\mu K \cdot \sqrt{s}$) is also given in CMB temperature units. The other used acronyms are: DT = detector technology, N of R (or B) = number of radiometers (or bolometers), EB = effective bandwidth (in GHz). Adapted from [8, 2] and [3].

| LFI | Frequency (GHz) | 30 | 44 | 70 |
|-----|----------------|----|----|----|
|     | InP DT         | MIC| MIC| MMIC|
| FWHM|                | 33.34| 26.81| 13.03|
| N of R (or feeds) | 4 (2) | 6 (3) | 12 (6) |
| EB  |                | 6 | 8.8 | 14 |
| NET |                | 159 | 197 | 158 |
| $\delta T/T$ [\(\mu K/K\)] (in T) | 2.48 | 3.82 | 6.30 |
| $\delta T/T$ [\(\mu K/K\)] (in P) | 3.51 | 5.40 | 8.91 |
| Frequency (GHz) | 217 | 353 |
| FWHM in T \(\mu K\) (in T) | 4.6 (4.6) | 4.7 (4.6) |
| N of B in T \(\mu K\) (in T) | 4 (8) | 4 (8) |
| EB in T \(\mu K\) (in T) | 72 (63) | 99 (102) |
| NET in T \(\mu K\) (in T) | 91 (132) | 277 (404) |
| $\delta T/T$ [\(\mu K/K\)] in T \(\mu K\) (in T) | 3.4 (6.4) | 14.1 (26.9) |
| $\delta T/T$ [\(\mu K/K\)] in T \(\mu K\) (in P) | 106 | 4243 |

| HFI | Frequency (GHz) | 100 | 143 |
|-----|----------------|-----|-----|
|     | FWHM in T \(\mu K\) (in T) | (9.6) | 7.1 (6.9) |
| N of B in T \(\mu K\) (in T) | (8) | 4 (8) |
| EB in T \(\mu K\) (in T) | (33) | 43 (46) |
| NET in T \(\mu K\) (in T) | 100 (100) | 62 (82) |
| $\delta T/T$ [\(\mu K/K\)] in T \(\mu K\) (in T) | 2.1 (3.4) | 1.6 (2.9) |
| $\delta T/T$ [\(\mu K/K\)] in T \(\mu K\) (in P) | 545 | 857 |
| Frequency (GHz) | 545 | 857 |
| FWHM in T \(\mu K\) (in T) | 4.7 | 4.3 |
| N of B in T \(\mu K\) (in T) | 4 | 4 |
| EB in T \(\mu K\) (in T) | 169 | 257 |
| NET in T \(\mu K\) (in T) | 2000 | 91000 |
| $\delta T/T$ [\(\mu K/K\)] in T \(\mu K\) (in T) | 3.4 (6.4) | 14.1 (26.9) |
| $\delta T/T$ [\(\mu K/K\)] in T \(\mu K\) (in P) | 106 | 4243 |

After the successful launch in May 2009, Planck has already mapped the sky more than twice (at the time of writing this proceedings paper) with the expected behavior and it is planned to complete at least two further all-sky surveys.

The first scientific results have been released on January 2011 [9]. They describe the instrument performance in flight including thermal behaviour [10, 11, 12], the HFI and LFI data analysis pipelines [13, 14], the main astrophysical results about Galactic science [15, 16, 17, 18, 19, 20, 21], extragalactic sources and far-IR background [22, 23, 24, 25, 26, 27], and
Sunyaev-Zel’dovich effects and cluster properties [28, 29, 30, 31, 32], providing to the scientific community the Planck Early Release Compact Source Catalog (ERCSC) [33]. The first publications of the main cosmological implications are expected in early 2013.

The anisotropy pattern of the CMB, measured by WMAP, probes cosmology with unprecedented precision (see [34, 35] and references therein). WMAP data are largely consistent with the concordance Λ cold dark matter (ΛCDM) model, but there are some interesting deviations from it, in particular on the largest angular scales [36]. See also [37] for a critical point of view upon the subject.

A large number of papers dealing with these anomalies have been published in the last years. We briefly list below those that are the most studied: a) lack of power on large angular scales [38, 39]; b) hemispherical asymmetries [40, 41, 42, 43, 44, 45, 46]; c) unlikely alignments of low multipoles [47, 48, 49, 50, 51, 38, 52, 53, 54, 55, 56]; d) non-Gaussianity [46, 57, 58]; e) spots and/or excess of signal [59, 60, 45, 61], possibly linked to non-Gaussianity; f) Parity asymmetry. This anomaly represents one subject of the present paper. It has been suggested in [62] that an estimator built upon the point Parity symmetry might be used as a practical tool for detecting foregrounds. In particular these authors consider whether the observed low CMB quadrupole in temperature could more generally signal odd point-Parity, i.e. suppression of even multipoles. However they claim that WMAP dataset never supports Parity preference beyond the meagre 95% confidence level. Later, [63] found that the Parity symmetry in the temperature map of WMAP 3 and 5 year data is anomalous at the level of 4 out of 1000 in the range $\delta \ell = [2, 18]$. This analysis have been repeated in the WMAP 7 year data confirming the anomaly at same level for a slightly wider range $\delta \ell = [2, 22]$ [64]. We report in this paper that analysis and its extension to polarization [65].

In fact, the CMB polarization pattern can provide information on symmetry-violating physics beyond the standard model. In general, the breakdown of spacetime symmetries is a potential tracer of new physics [66]. Several models exist that predict non-standard $\mathcal{P}$ and $\mathcal{C}\mathcal{P}$ violations (‘$\mathcal{C}$’ standing for charge conjugation), as well as $\mathcal{CPT}$ violations (‘$\mathcal{T}$’ being time reversal) and the related (through the anti-$\mathcal{CPT}$ theorem [67, 68]) breakdown of Lorentz invariance. A number of tests have been suggested and (in many cases) performed, either in terrestrial and orbital laboratories [69, 70] or through cosmological observations [71, 72, 73]. These violations may also be seen as anomalies in the CMB polarization pattern, since its statistical properties are constrained by the assumption of symmetry conservation.

The paper is organized as follows. In Section 2 we describe the basic formalism, the performed analysis, and the relevant symmetry estimators. Current results on symmetry estimators based on WMAP data are given in Section 3 while in Section 4 we focus on the implications for birefringence. The forecasts for Planck about these topics are provided in Section 5. The precise extraction of the cosmological information from microwave observations requires an extremely accurate and efficient data analysis and a careful separation of CMB and astrophysical emissions (see e.g. [74] for a discussion of this topics in the context of the Planck surveys). In Section 6 we focus on a specific foreground component that could be critical for the above topics [75]. Finally, our conclusions are drawn in Section 7.

2. Description of the analysis
2.1. Introduction
All-sky temperature maps, $T(\hat{n})$, are usually expanded in Spherical Harmonics $Y_{\ell m}(\hat{n})$, with $\hat{n}$ being a direction in the sky, namely depending on the couple of angles $(\theta, \phi)$:

$$a_{T,\ell m} = \int d\Omega Y_{\ell m}^* (\hat{n}) T(\hat{n}) ,$$

(1)
where $a_{T,lm}$ are the coefficients of the Spherical Harmonics expansion and $d\Omega = d\theta d\phi \sin \theta$. Under reflection (or Parity) symmetry ($\hat{n} \rightarrow -\hat{n}$), these coefficients behave as

$$a_{T,lm} \rightarrow (-1)^\ell a_{T,lm}. \quad (2)$$

Analogously for polarizations maps, taking into account the usual combination of Stokes parameters ($Q(\hat{n})$ and $U(\hat{n})$)

$$a_{\pm 2,lm} = \int d\Omega Y_{\pm 2,lm}^*(\hat{n})(Q(\hat{n}) \pm iU(\hat{n})), \quad (3)$$

where $Y_{\pm 2,lm}(\hat{n})$ are the Spherical Harmonics of spin 2 and $a_{\pm 2,lm}$ are the corresponding coefficients, it is possible to show that under Parity

$$a_{E,lm} \rightarrow (-1)^\ell a_{E,lm}, \quad (4)$$

$$a_{B,lm} \rightarrow (-1)^{\ell+1} a_{B,lm}, \quad (5)$$

where

$$a_{E,lm} = -(a_{2,lm} + a_{-2,lm})/2, \quad (6)$$

$$a_{B,lm} = -(a_{2,lm} - a_{-2,lm})/2i. \quad (7)$$

Eqs. (2), (4) and (5) show cross-correlations $C_{T B}^\ell = C_{E B}^\ell = 0$.

Further details can be found for example in [76], [77] and explicit algebra is present in the Appendix of [65].

In order to evaluate the angular power spectrum (APS) we adopt the quadratic maximum likelihood (QML) estimator, introduced in [78] and extended to polarization in [79]. Further details can be found in [80].

### 2.2. Angular Power Spectrum Estimation, Data set and Simulations

In order to evaluate the angular power spectrum (APS) we adopt the quadratic maximum likelihood (QML) estimator, introduced in [78] and extended to polarization in [79]. Further details can be found in [80]. Now, we describe the data set that we have considered. We use the temperature ILC map smoothed at 9.8 degrees and reconstructed at HEALPix\(^3\) [81] resolution $N_{side} = 16$, 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\(^4\) for the frequency channels Ka, Q and V as considered by [34] for the low $\ell$ analysis. These frequency channels have been co-added as follows [82]

$$m_{tot} = C_{tot}(C_{Ka}^{-1}m_{Ka} + C_{Q}^{-1}m_{Q} + C_{V}^{-1}m_{V}), \quad (8)$$

where $m_i$, $C_i$ are the polarization maps and covariances (for i=Ka, Q and V) and

$$C_{tot}^{-1} = C_{Ka}^{-1} + C_{Q}^{-1} + C_{V}^{-1}. \quad (9)$$

This polarization data set has been extended to temperature considering the ILC map. We have added to the temperature map a random noise realization with variance of $1\mu K^2$ as suggested in [83]. Consistently, the noise covariance matrix for TT is taken to be diagonal with variance equal to $1\mu K^2$.

\(^3\) http://healpix.jpl.nasa.gov/

\(^4\) http://lambda.gsfc.nasa.gov/
We have also performed Monte-Carlo simulations in order to assess the significance of our results. A set of 10000 CMB + noise sky realizations has been generated: the signal extracted from the WMAP 7 years best fit model, the noise through a Cholesky decomposition of the noise covariance matrix. We have then computed the APS for each of the 10000 simulations by means of BolPol and built two figures of merit as explained in the next subsection.

Two masks are considered: one for T and one for Q and U. Monopole and dipole have been subtracted from the observed Internal Linear Combination (ILC) map through the HEALPix routine remove-dipole [81].

2.3. Estimators
We define the following quantities

\[ C_{X+/-}^{\ell} = \frac{1}{(\ell_{\text{max}} - 1)} \sum_{\ell=2,\ell_{\text{max}}}^{\ell_{\text{max}}} \frac{\ell(\ell + 1)}{2\pi} \hat{C}_{\ell}^{X} \]  

(10)

where \( \hat{C}_{\ell}^{X} \) are the estimated APS obtained with the BolPol code [80] for the power spectrum \( X = \text{TT}, \text{TE, EE and BB} \). The sum is meant only over the even or odd \( \ell \) (and this is represented respectively by the symbol + or −) with \( \ell_{\text{max}} \geq 3 \).

Therefore, two estimators can be built from Eq. (10) as follows: the ratio \( R_{X} \), as performed in [63] or [64],

\[ R_{X} = C_{+}^{X}/C_{-}^{X}, \]  

(11)

and, in analogy to what performed for the hemispherical symmetry in [44], the difference \( D_{X} \)

\[ D_{X} = C_{+}^{X} - C_{-}^{X}, \]  

(12)

of the two aforementioned quantities. In the following, we drop the index \( X \) for \( R \) and \( D \) specifying every time we use them which is the spectrum they refer to.

For our application to WMAP data, both estimators have been considered for the TT spectrum but only the second one for the other spectra (EE, TE and BB). This is due to the unfavorable signal-to-noise ratio of the WMAP data in polarization.

For \( X = \text{TB and EB} \) we simply use the average power

\[ C_{X}^{\ell} = \frac{1}{(\ell_{\text{max}} - 1)} \sum_{\ell=2,\ell_{\text{max}}}^{\ell_{\text{max}}} \frac{\ell(\ell + 1)}{2\pi} \hat{C}_{\ell}^{X}. \]  

(13)

3. Results
In Fig. 1 we show the estimator \( R \) and \( D \) for TT averaged in \( \delta \ell = [2, 22] \) and in \( \delta \ell = [2, 33] \). The probability to obtain a smaller value than the WMAP one is 0.47% for \( R \) in the range \( \delta \ell = [2, 22] \) and 3.17% in the range \( \delta \ell = [2, 33] \). For the \( D \) estimator the probability is 0.63% in the range \( \delta \ell = [2, 22] \) and 3.17% in the range \( \delta \ell = [2, 33] \). The upper left panel of Fig. 1 recovers the same level of anomaly claimed in [64].

In Fig. 2 we plot the percentage related to the WMAP 7 yr Parity anomaly for TT versus \( \ell_{\text{max}} \) in the range \([10, 40]\) for the two considered estimators. As evident there is not a single \( \ell_{\text{max}} \) for which the TT anomaly shows up, but rather a characteristic scale, see also [64]. For the estimator of Eq. (11) the percentage anomaly is well below 1% for almost any choice of \( \ell_{\text{max}} \) in the range \([15, 25]\). As also shown in Fig. 2, the estimator of Eq. (12) follows closely the other estimator although it is slightly less sensitive. Therefore, we find a whole multipole range, rather than a single \( \ell_{\text{max}} \) value, where the WMAP 7 yr Parity anomaly holds. This dims significantly the case for posterior biasing.

Only for \( \ell_{\text{max}} = 21 \) the estimator of Eq. (11) exhibits a percentage which is of the order of 1%.
Figure 1. TT. Counts (y-axis) vs the estimator (x-axis). Upper histograms: Ratio for the range $\delta \ell = [2, 22]$ (left panel) and for the range $\delta \ell = [2, 33]$ (right panel). Lower histograms: Difference for the range $\delta \ell = [2, 22]$ (left panel) and for the range $\delta \ell = [2, 33]$ (right panel). Units for the estimator D are $\mu K^2$. The vertical line stands for the WMAP 7 year value.

Figure 2. TT. Percentage of the WMAP 7 yr value (y-axis) vs $\ell_{\text{max}}$ (x-axis). Blue line is for the ratio and the red line for the difference. This analysis shows that there is no single $\ell_{\text{max}}$ for which the TT anomaly shows up, but rather suggests the existence of a characteristic scale, see also [64].

In Table 2 we provide the results for EE, TE and BB. As mentioned above, only $D$ is considered and computed for the four following multipoles range $\delta \ell = [2, 4]$, [2, 8], [2, 16] and [2, 22]. No anomalies have been found and compatibility with Parity symmetry is obtained.

In Table 3 we provide the results for EB and TB where the estimator $C$ is considered and computed for the same aforementioned four multipoles range. Both the spectra are well consistent with zero. Only the EB spectrum shows a mild anomaly in the range $\delta \ell = [2, 22]$ at the level of 97.7%. This is due to five estimates from $\ell = 18$ to $\ell = 22$ that are systematically larger than zero. When these points are excluded this mild anomaly drops. For example in the range $\delta \ell = [2, 16]$ the probability to obtain a smaller value than the WMAP one is 55.35%. The latter two estimators are shown in Fig. 3.
Table 2. Probabilities (in percentage) to obtain a smaller value than the WMAP 7 yr one.

| D  | δℓ = [2,4] | δℓ = [2,8] | δℓ = [2,16] | δℓ = [2,22] |
|----|-------------|-------------|-------------|-------------|
| EE | 93.09      | 76.21       | 44.27       | 46.61       |
| TE | 56.35      | 38.88       | 24.79       | 22.77       |
| BB | 7.97       | 13.42       | 11.70       | 44.31       |

Table 3. Probabilities (in percentage) to obtain a smaller value than the WMAP 7 yr one.

| C  | δℓ = [2,4] | δℓ = [2,8] | δℓ = [2,16] | δℓ = [2,22] |
|----|-------------|-------------|-------------|-------------|
| TB | 51.78       | 39.42       | 6.71        | 10.55       |
| EB | 62.73       | 69.83       | 55.35       | 97.70       |

Figure 3. EB. Counts (y-axis) vs the estimator C (x-axis). Distribution of C for δℓ = [2,22] (left panel) and δℓ = [2,16] (right panel). Units are μK². The vertical line stands for the WMAP 7 yr data.

4. Birefringence

As shown above, if the physics controlling CMB fluctuations is Parity conserving then the cross spectra $C_{TT}^l$ and $C_{EB}^l$ must vanish due to the different handedness of the $B$ and $(T,E)$ harmonics. Therefore, if the standard cosmological model holds, we should expect no relevant information from $TB$ and $EB$. On the other hand, detection of non-zero primordial $TB$ and/or $EB$ may probe fundamental physics in the early universe, such as the presence of a primordial homogeneous [84] or helical [85, 86] magnetic field which would induce Faraday rotation and non-zero $TB$ correlations. Parity-asymmetric gravity dynamics during inflation may generate a discrepancy among left and right-handed gravitational waves, so that $TB$ and $EB$ are non-zero [87, 88]. Particle physics models with non-standard Parity-violating interactions also predict non-vanishing $TB$ and $EB$ signals [89, 90, 91].

In this section we focus on a class of models that exhibit Parity violations in the photon sector [92]. A Chern-Simons term can be introduced in the effective Lagrangian [72, 73]:

$$\Delta L = -\frac{1}{4} p_\mu \varepsilon^{\mu
u\rho\sigma} F_{\rho\sigma} A_\nu ,$$

where $F^{\mu\nu}$ is the Maxwell tensor and $A^\mu$ the 4-potential. The 4-vector $p_\mu$ may be interpreted as the derivative of the quintessence field or the gradient of a function of the Ricci scalar [93, 94]. In either case a $\mathcal{P}$ violation always arises provided that $p_0$ is non-zero, while $\mathcal{C}$ and $\mathcal{T}$ remain intact. Hence, $\mathcal{CP}$ and $\mathcal{CPT}$ symmetries are also violated, as well as Lorentz invariance, since $p^\mu$ picks up a preferred direction in space-time. The net effect on a propagating photon is to
rotate its polarization direction by an angle $\Delta \alpha$, hence the name “cosmological birefringence”. Historically, the effect has being constrained by measuring polarized light from high redshift radio galaxies and quasars [72, 73, 95, 96, 97, 98, 99]. Obviously, the CMB photons would also be affected and, due to their longer journey, may get a larger rotation. A consequence for the CMB pattern is the mixing of $E$ and $B$ modes: the $TB$ and $EB$ correlations still vanish at last scattering surface, but the observable CMB spectra are distorted as [87, 88, 100]:

\begin{align}
C_l^{TB} &= C_l^{TE} \sin 2\Delta \alpha \quad (14) \\
C_l^{EB} &= \frac{1}{2} (C_l^{EE} - C_l^{BB}) \sin 4\Delta \alpha \quad (15) \\
C_l^{TE} &= C_l^{TE} \cos 2\Delta \alpha \quad (16) \\
C_l^{EE} &= C_l^{EE} \cos^2 2\Delta \alpha + C_l^{BB} \sin^2 2\Delta \alpha \quad (17) \\
C_l^{BB} &= C_l^{BB} \cos^2 2\Delta \alpha + C_l^{EE} \sin^2 2\Delta \alpha. \quad (18)
\end{align}

where the primed quantities are rotated. In [35] a limit $\Delta \alpha = 0.9^\circ \pm 1.4^\circ$ was derived for the multipole range $\delta \ell = [23, 800]$, whereas for $\delta \ell = [2, 23]$ they find $\Delta \alpha = -3.8^\circ \pm 5.2^\circ$. The reason for this distinction is that the low $\ell$ polarization pattern is only influenced by the reionization epoch, which happened at redshift $z \simeq 10$. The primary fluctuations at higher multipoles, on the other hand, can be traced to last scattering at $z \simeq 1100$ so the corresponding angular scales allow for a much longer journey of the CMB photons. A slightly more stringent limit based on QUaD\(^6\) data has been set in [101] as $\Delta \alpha = 0.83^\circ \pm 0.94^\circ \pm 0.5^\circ$, the second error being systematic.

5. Planck Forecast

In this section we discuss how Planck will improve the present constraints on the symmetry violations discussed above. We first take into account the case of the low $\ell$ Parity anomaly. We then discuss briefly the case of birefringence.

5.1. Simulated dataset

We consider the white noise level for 143 GHz channel of Planck. As in [44], we consider the nominal sensitivity of the Planck 143 GHz channel, taken as representative of the results which can be obtained after the foreground cleaning from various frequency channels. The 143 GHz channel has an angular resolution of 7.1′ (FWHM) and an average sensitivity of 6 $\mu$K (11.4 $\mu$K) per pixel - a square whose side is the FWHM size of the beam - in temperature (polarization), after 2 full sky surveys. We assume uniform uncorrelated instrumental noise and we build the corresponding diagonal covariance matrix for temperature and polarization, from which, through Cholesky decomposition we are able to extract noise realizations. For this low noise level we apply the same procedure adopted for the Monte-Carlo simulations in Subsection 2.2.

5.2. Forecasts

From the set of 10000 CMB + noise sky realizations, we find that: the T based estimators (both $R$ and $D$) do not change much since at large scale the APS for T is dominated by cosmic variance and not by the noise. For EE, TE and BB it is possible to consider even the $R$ estimator. See for example Fig. 4 where the $R$ estimator is computed for EE in the range $\delta \ell = [2, 22]$ (left panel) and $\delta \ell = [2, 16]$ (right panel). The standard deviations for the $D$ and $C$ are evaluated in Table 4 for $\delta \ell = [2, 22]$ and compared to the WMAP 7 yr ones.

\(^6\) QUaD stands for “QUEST at DASI”. In turn, QUEST is “Q & U Extragalactic Survey Telescope” and DASI stands for “Degree Angular Scale Interferometer”.

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Table 4. Left Table: standard deviation for the D estimator computed in the range $\delta \ell = [2, 22]$. Right Table: standard deviation for the C estimator computed in the range $\delta \ell = [2, 22]$. Units are $\mu K^2$.

|       | WMAP 7 yr | Planck |
|-------|-----------|--------|
| TT    | 1517.17   | 1509.21|
| TE    | 20.19     | 9.08   |
| EE    | 0.65      | 0.10   |
| BB    | 0.69      | 0.04   |

|       | WMAP 7 yr | Planck |
|-------|-----------|--------|
| TB    | 0.95      | 0.19   |
| EB    | 0.023     | 0.001  |

Figure 4. EE. Counts (y-axis) vs the estimator $R$ (x-axis). Distribution of $R$ for $\delta \ell = [2, 22]$ (left panel) and $\delta \ell = [2, 16]$ (right panel).

The case of birefringence has been investigated in [102] where the expected standard error for Planck in constraining the rotation angle $\alpha$ is given as $\Delta \alpha = 0.057^\circ$. Note however that this error purely considers the noise level. Realistic measurements of $\alpha$ may be affected by systematic errors, especially arising from the uncertainties in the orientation of the polarimeters. The latter need to be properly taken into account [103].

6. Foreground impact

An open possibility is that the detected Parity anomaly in the WMAP data is due to an unknown foreground contribution relevant at large angular scales, i.e. a diffuse foreground component, or to foreground residuals left by an imperfect component separation. Foreground, by definition, is any astrophysical emission rising between us and the last scattering surface. The spectral behaviors of the most relevant Galactic diffuse foreground components (synchrotron, free-free and dust emission) are typically very different from the CMB blackbody behavior. On the other hand, it can not be excluded that diffuse Solar System emission could contribute at low $\ell$'s at WMAP frequencies [49, 38]. Such foreground would exhibit planar symmetry with respect to the ecliptic (or some plane slightly tilted with respect to it). According to (Far) Infra Red (IR) measures, the “classical” Zodiacal Light Emission (ZLE) is the thermal emission of sub-mm Interplanetary Dust Particles (IDPs), with orbital radii within 5 AU, characterized by $a \approx \nu^4$ scaling below 1 THz [104]. If larger IDPs exist, their emission would add to the classical ZLE, producing a signal at mm wavelengths, ranging between about $1/10 \div 10$ times the classical ZLE, with a less steep spectrum, $\approx 1/\nu$, as suggested by several models [105, 106, 107, 108, 109], see left panel of Fig. 5. Such particles can be produced by the erosion of Kuiper Belt Objects (KBOs) due to mutual collisions or by the erosion of incoming interstellar dust and they should be located beyond Jupiter. They would be then colder and possibly larger than the IDPs responsible for the classical ZLE. Impact detectors onboard interplanetary probes reveal that such particles indeed
Figure 5. Left Panel: Comparison of ZLE fluxes compatible with FIRAS data [104] and a set of possible models of KBOE [106] characterized by a different dust grain temperature $T$ and optical depth $\tau$. The black solid line shows the ZLE derived from the best fit model to FIRAS data and extrapolated to lower frequencies. The gray band represents a sketch of the allowed region obtained from the error bars in [104]. The blue dashed lines display four different models of KBOE corresponding to different parameters values. The resulting fluxes, sum of KBOE and ZLE, are represented by the red solid lines. Note that the classical ZLE (estimated on the basis of COBE data) is negligible in practice at WMAP frequencies, whereas KBOE might not be ignored. Right Panel: Parity anomaly of the estimator $r$ as defined in the text with $\ell_{\max} = 22$. The histogram (in red) displays the distribution of $r$ obtained from $10^5$ MC realizations. Vertical lines correspond to the maps considered in this work: the black solid line (on the left) refers to the ILC 7 yr map; colored solid lines refer to the CM; colored dashed lines refer to the WM. Green, blue, and yellow lines are for $H_{KBOE} = 17.5^\circ$, $35^\circ$, and $70^\circ$, respectively.

exist [110], but very little is known about their nature. Motivated by these considerations, the problem of diffuse Solar System emission at cosmological frequencies has been reconsidered [75] by introducing a toy model of emission from the KBO dust particles, that we will call in this paper KBO Emission (KBOE), and evaluating its implications for CMB observations.

To explore the effect of the KBOE on CMB maps we considered a toy model in which the emission is confined within a region of width $H_{\text{wedge}}$, symmetric with respect to the ecliptic plane, with constant brightness inside and zero outside. Owing to the planar and cylindrical symmetry of the model, all the coefficients $a_{\ell,m}$ for the multipole expansion in ecliptic coordinates of the KBOE will be zero except for those with even $\ell$ and $m = 0$. Then, KBOE (and likewise ZLE) will just affect the map components with even $\ell$.

Also the KBOE template we propose in this paper, as well as the standard ZLE, is highly Parity-asymmetric. Therefore it is worth to study its possible impact on the WMAP ILC 7yr map, of course under the assumption that a residual of the kind considered in the current paper, is present in the ILC map.

We consider the same estimator of eq. (11) with $\ell_{\max} = 22$. We have extracted $10^5$ random maps from the best fit model of WMAP 7 yr working at the HEALPix resolution $N_{\text{side}} = 64$ (i.e. all-sky maps of 49152 pixels). We have computed the $R$ estimator for each random map and we have built the probability distribution function (pdf) for $R$, shown in the right panel of Fig. 5. Note that the pdf for $R$ does not peak around the value 1, but at slightly larger values since for the chosen $\ell$-range there are more terms at numerator than in the denominator. Vertical lines in right panel of Fig. 5 represent the values of $R$ for the considered maps. Black vertical line (on left) stands for the WMAP 7 yr ILC map. The probability to have this value is as low as
0.91% \(^7\). When we remove our KBOE template from the maps we have the colored vertical lines. Green, blue, and yellow lines stand for \(H_{\text{KBOE}} = 17.5^\circ, 35^\circ,\) and \(70^\circ\), respectively. Colored solid lines refer to a Cold Model (CM), characterized by \(T = 30\text{K}\) and \(\tau = 3 \times 10^{-7}\), colored dashed lines refer to a Warm Model (WM), characterized by \(T = 60\text{K}\) and \(\tau = 3 \times 10^{-8}\) (see left panel of Fig. 5 for their spectral behaviors). Note that the probability associated to the green line (i.e. CM and \(H_{\text{KBOE}} = 17.5^\circ\)) is 77.1% and the probability associated to the blue line (i.e. CM and \(H_{\text{KBOE}} = 35^\circ\)) is 10.6%. The Parity anomaly is removed when these templates are properly taken into account. In the definition of the Parity estimator in the current paper we adopted \(\ell_{\text{max}} = 22\), just for simplicity and since for that \(\ell_{\text{max}}\) value the anomaly is remarkable. However, as shown in [64, 63, 65], in the WMAP TT spectrum there is a whole multipole range, rather than a single \(\ell_{\text{max}}\) value, where the WMAP 7 yr Parity anomaly holds. This dims significantly the case for posterior biasing.

We finally remark that the inclusion of a KBOE component in the analysis could also significantly alleviate the problem of lack of power at large angular scales, reflecting itself in both the TT angular power spectrum and the two-points angular correlation function [75].

7. Conclusions

The Planck satellite is measuring CMB anisotropies and their polarization with a level of precision that will remain unparalleled for many years to come. The results derived from the Planck dataset will set a benchmark for precision cosmology. In this paper we have focused on fundamental information that the CMB may reveal about the breaking of fundamental discrete symmetries in the early universe. We have reviewed the present constraints, due to WMAP, for the cases of a hinted low resolution Parity anomaly as well as for cosmic birefringence. For the latter, the QUaD dataset has provided the most stringent limits to date. We have also presented Planck forecasts. Planck may be able to confirm or deny the existence of the low resolution Parity anomaly. Moreover, it is expected to greatly improve the knowledge of the polarization pattern of the CMB. Planck will also probe photon birefringence, improving the present constraints by over an order of magnitude. Through its wide frequency coverage and improved foreground cleaning Planck will be also capable to detect subdominant foreground components and in particular those that might impact the analyses about discrete symmetries, such as the Solar System diffuse emission considered in this review.

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\(^7\) This value is slightly larger than what quoted in [64] that is 0.86%. This might be due to the details of the MC, like number of simulations, resolutions of maps and the considered FWHM.
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