TESTS OF FUNDAMENTAL SYMMETRIES THROUGH THE CMB: FROM WMAP TO PLANCK

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We review some constraints about Parity violating models that go beyond the Maxwell electromagnetism. The observable, that is already considered as a standard tracer of such violations, is the in vacuo Cosmological Birefringence angle that can be obtained from the Angular Power Spectra of the Cosmic Microwave Background (henceforth CMB) pattern. This angle, that represents the rotation of the polarization plane that a CMB photon experiences traveling from the last scattering surface to us, is different from zero only if there is a Parity violating coupling in the Maxwell Lagrangian. We also review the claimed Parity anomaly found at large scales of the TT spectrum of the WMAP data by Kim and Naselsky in 2010. We finally forecast the capabilities of Planck in tightening the present constraints.

1 Introduction

The observed properties of the Cosmic Microwave Background (henceforth CMB) pattern can be used to constrain Parity (P) symmetry. P violations arise in many models, as modification of electromagnetism[1,2,3](hence deviations from the Standard Model of Particle Physics) or as modification of the standard picture of the Inflationary mechanism (where P is broken for primordial gravitational waves). In the latter case, we refer to Chiral Gravity [4,5,6,7] and in former we generally talk of Cosmological Birefringence. Both of these classes of models predict cross-correlations between E and B modes and T and B modes different from zero. However Chiral Gravity induces such correlations at the CMB last scattering surface whereas the Cosmological Birefringence effect induces them by rotating the primordial polarization during the CMB photon journey from the last scattering to us [8].

In this proceeding, we focus on the Cosmic Birefringence case reporting mainly from [9]. Moreover we review the claimed P anomaly found at large scales of the TT spectrum of the WMAP data by Kim and Naselsky in 2010 [10,11,12,13]. Since, up to our knowledge, there is no P violating model capable to explain such deviation from the expected cosmological standard model, the reader might find the use of the “P violation” term in this context not proper. However since such anomaly highlights a difference in the even and odd multipoles (that behave differently under P transformation, see Section 2), it is commonly use such terminology, i.e. TT P anomaly. It is not known yet if this come from fundamental physics or it is due to some spurious effect, like systematics or foreground not removed [14]. Supposing it is due to fundamental physics, since it shows up in the WMAP temperature map at large angular scales one may naturally think about the possibility that a P violating mechanism is responsible for such an effect during the early universe evolution. For a more conservative approach see [11] where under the hypothesis that the early universe evolution is unchanged from the standard inflationary mechanism, it is concluded that we live in a special location of the universe, such that translational invariance is violated for scales larger than 4 Gpc leading to a sort of breaking of the Copernican principle.

2 Parity symmetry in CMB

All-sky temperature maps, $T(\hat{n})$, are usually expanded in terms of Spherical Harmonics $Y_{\ell m}(\hat{n})$, with $\hat{n}$ being a direction in the sky, namely depending on the couple of angles (θ, ϕ), $a_{T,\ell m} = \int d\Omega\, Y^{\star}_{\ell m}(\hat{n})\, T(\hat{n})$, where $a_{T,\ell m}$ are the coefficients of the Spherical Harmonics expansion and $d\Omega = d\theta d\phi \sin\theta$. Under reflection (or P) symmetry ($\hat{n} \rightarrow -\hat{n}$), these coefficients behave as $a_{T,\ell m} \rightarrow (-1)^{\ell}\, a_{T,\ell m}$. Analogously for polarizations maps, taking into account the usual combination of Stokes parameters ($Q(\hat{n})$ and $U(\hat{n})$) one obtains $a_{\pm 2,\ell m} = \int d\Omega\, Y^{\star}_{\pm 2,\ell m}(\hat{n})\,(Q(\hat{n}) \pm iU(\hat{n}))$, where $Y_{\pm 2,\ell m}(\hat{n})$ are the Spherical Harmonics of spin 2 and $a_{\pm 2,\ell m}$ are the corresponding coefficients. It is possible to show that under P, $a_{E,\ell m} \rightarrow (-1)^{\ell}\, a_{E,\ell m}, \quad a_{B,\ell m} \rightarrow (-1)^{\ell+1}\, a_{B,\ell m}$, where $a_{E,\ell m} = -(a_{2,\ell m} + a_{-2,\ell m})/2$ and $a_{B,\ell m} = -(a_{2,\ell m} - a_{-2,\ell m})/2i$. If P is conserved, combining the previous transformation one immediately derives that the cross-correlations $C_{\ell}^{TB} = C_{\ell}^{EB} = 0$. Further details can be found for example in [15,16] and explicit algebra is present in the Appendix of [12].

3 Cosmological Birefringence

The CMB is a powerful probe for constraining the Cosmological Birefringence angle (and therefore exploring possible P violations of Maxwell Lagrangian) for two main reasons. First, it is generated in the early universe, when the physics at the stake was not obviously identical to present. Secondly, the long look-back time of CMB photons may render tiny violations to the electromagnetic Lagrangian observable, since such effects usually accumulate during propagation. CMB polarization arises at two distinct cosmological times: the recombination epoch ($z \sim 1100$) and the reionization era ($z \sim 11$ or less [17]). When the CMB field is expanded in spherical harmonics, the first signal mostly shows up at high multipoles, since polarization is generated through a causal process and the Hubble horizon at last scattering only subtends a degree sized angle. The later reionization of the cosmic fluid at lower redshift impacts the low ℓ instead. These two regimes need to be taken into account when probing for cosmological birefringence, since they can be ascribed to different epochs and, hence, physical conditions.

Recent polarization oriented CMB observations [18,19,20,21] have been capable to measure TB and EB correlations, other than TT, TE and EE correlations. While no detection has been claimed to date, polarization data have been used to derive constraints on the birefringence angle [19,22,23,24].

In the limit of constant birefringence angle, α, the angular power spectra of CMB anisotropies, assuming $C_{\ell}^{TB} = C_{\ell}^{EB} = 0$, are given by [4,22,25,26] [a],

$$C_{\ell}^{TE,obs} = C_{\ell}^{TE} \cos(2\alpha)\,, \quad (1)$$

$$C_{\ell}^{TB,obs} = C_{\ell}^{TE} \sin(2\alpha)\,, \quad (2)$$

$$C_{\ell}^{EE,obs} = C_{\ell}^{EE} \cos^2(2\alpha) + C_{\ell}^{BB} \sin^2(2\alpha)\,, \quad (3)$$

[a] See [27,28] as an example of computation that takes into account the time dependence of α in a specific model of pseudoscalar fields coupled to photons. See [29,30,31] as examples of non-isotropic birefringence effect.

$$C_\ell^{BB,obs} = C_\ell^{BB}\rangle \cos^2(2\alpha) + C_\ell^{EE} \sin^2(2\alpha)\,, \quad (4)$$

$$C_\ell^{EB,obs} = \frac{1}{2}\left(C_\ell^{EE} + C_\ell^{BB}\right) \sin(4\alpha)\,. \quad (5)$$

The WMAP team [19], using a Markov Chain Monte Carlo (MCMC) method, at high ℓ (from 24 to 800) find $\alpha^{\mathrm{WMAP}\,7yr} = -0.9^\circ \pm 1.4^\circ$ at 68% C.L.. Our constraint, obtained at low resolution [9] and considering the same estimator that has been used in [24], reads $\alpha = -1.6^\circ \pm 1.7^\circ$ (3.4°) at 68% (95%) C.L. for $\Delta\ell = 2-47$. Considering $\Delta\ell = 2-23$ we obtain $\alpha = -3.0^{\circ}{}^{+2.6^\circ}_{-2.5^\circ}$ at 68% C.L. and $\alpha = -3.0^{\circ}{}^{+6.9^\circ}_{-4.7^\circ}$ at 95% C.L.. This is the same multipole range considered by the WMAP team at low resolution in [19] (the only other result available in the literature at these large angular scales) where with a pixel based likelihood analysis they obtain $\alpha^{\mathrm{WMAP}\,7yr} = -3.8^\circ \pm 5.2^\circ$ at 68% C.L.. In [32] it is claimed that the improvement expected for the Planck satellite [33] in terms of sensitivity [34] is around 15. Almost the same number is obtained in [9]. Both the forecasts are provided considering just the nominal sensitivity whereas the uncertainties coming from the systematic effects are not taken into account.

4 TT Parity anomaly

The starting consideration for this analysis is that CMB physics does not distinguish between even and odd multipoles [10,11]. Therefore the power contained in even and odd multipoles must be statistically the same. For this reason we define the ratio $R^X = C_+^X/C_-^X$, as in [10,11,12] and the difference $D^X = C_+^X - C_-^X$, , as in [12,35], where $C_\pm^X$ is the band power average contained in the even (+) or odd (-) multipoles with X standing for one of the six CMB spectra. See [13] for other estimators. In Fig. 1 we plot the percentage related to the WMAP 7 year P anomaly

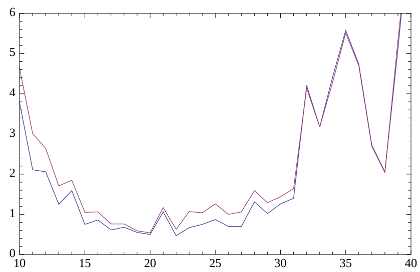

Figure 1: TT. Percentage of the WMAP 7 year value (y-axis) vs ℓ_{max} (x-axis). Blue line is for the ratio and the red line for the difference.

for TT versus ℓ_{max} in the range $10-40$ for the two considered estimators. As evident there is not a single ℓ_{max} for which the TT anomaly shows up, but rather a characteristic scale in the ℓ range $[15, 25]$. We confirm the previously reported P anomaly in TT in the range $\Delta\ell = [2, 22]$ at $> 99.5\%$ C.L.. Planck will not improve the signal-to-noise ratio in this range for the TT spectrum, since it is already cosmic variance dominated in the WMAP data. However Planck has a wider frequency coverage and this will improve the component separation layer in the data analysis pipeline. Moreover Planck is observing the sky with a totally different scanning strategy and this represents a benefit from the systematic effects analysis point of view.

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[b] http://lambda.gsfc.nasa.gov/
[c] http://healpix.jpl.nasa.gov/