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The Planck mission: From first results to cosmology

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Summary. — *Planck* is an ESA satellite launched in May 2009, whose main objective is to image the anisotropies of the Cosmic Microwave Background Radiation and their linear polarizartion with unprecedented sensitivity, angular resolution and frequency leverage. *Planck* is providing high-quality data to be mined for decades to come. Planck results have been released starting January 2011 ("early results") and February 2012 ("intermediate results") and are limited to Galactic and extragalactic science. The first cosmological data products are awaited for early 2013. *Planck* has a wide list of scientific targets. Here we focus on constraining constraints about parity-violating models that go beyond Maxwell's electromagnetism. We focus first on the *in vacuo* cosmological birefringence angle that constraints the rotation of the polarization plane of last scattered background photons. The latter can be non-null only if there is a parity-violating coupling in the Maxwell Lagrangian. We also discuss the so-called parity anomaly claimed in the anisotropy intensity spectrum of the WMAP data (Kim and Naselsky, 2010). We describe the basic formalism, the relevant estimators and the overall analysis strategy. We finally forecast the capabilities of Planck in tightening the present constraints.

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1. – Introduction

The statistical properties of the Cosmic Microwave Background (hereafter, CMB) pattern may be used to constrain parity (P) symmetry. Parity violations arise in several models: as modification of electromagnetism [1-3] (hence deviations from the particle physics Standard Model) or as modification of the standard picture of the Inflationary mechanism (where P is broken due to primordial gravitational waves). In the latter case, we refer to chiral gravity [4-7] and in the former we generally talk of cosmological birefringence. Both of these classes of models predict non-vanishing cross-correlations between E and B modes and T and B modes. However, chiral gravity induces such correlations at the CMB last scattering surface whereas cosmological birefringence induces them by rotating the polarization plane during the CMB photon journey from its last scattering to us [8]. We focus here only on cosmic birefringence case, reporting mainly findings from [9]. In addition, we review the claimed P anomaly found at large angular scaless in the anisotropy intensity (temperature or "TT") spectrum of the WMAP data, first claimed by Kim and Naselsky in 2010 [10-13]. The latter is dubbed a parity anomaly in view of an observed discrepancy (in power) among even and odd multipoles, which behave differently under P transformation (see sect. **2**, below). However, there is no sound theoretical framework that could explain such a mismatch. it is commonly use such terminology, *i.e.* TT parity anomaly. It is not known yet whether the effect arises due to fundamental physics or it is due to some spurious sources, *i.e.* instrumental systematics or poorly removed astrophysical foregrounds [14]. If the effect is indeed due to fundamental physics, its appearance at large angular scales naturally suggests the possibility that a P-violating mechanism is involved during an early phase of the universe. Other explanations exist: for a more conservative approach see [11] where it is assumed that the early universe evolution obeys the standard inflationary mechanism, and concluded that we must then live in a special location of the universe. Translational invariance would thus be violated for scales larger than $\sim 4\,\mathrm{Gpc}$ leading some 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 unit vector or direction on the sky, completely specified by a couple of angles (θ, ϕ). The quantities $a_{T,\ell m} = \int \mathrm{d}\Omega\, Y^{\star}_{\ell m}(\hat{n})\, T(\hat{n})$, are coefficients of the spherical harmonics expansion, and $\mathrm{d}\Omega = \mathrm{d}\theta \mathrm{d}\phi \sin\theta$. Under reflection (or P) symmetry ($\hat{n} \to -\hat{n}$), these coefficients behave as $a_{T,\ell m} \to (-1)^{\ell}\, a_{T,\ell m}$. Analogously, for polarization, one may consider the linear polarization maps(1) ($Q(\hat{n})$ and $U(\hat{n})$). The latter are not scalar, but rather components of a rank-two tensor [15] and are decomposed by the appropriate spin harmonics:

$$a_{\pm 2,\ell m} = \int \mathrm{d}\Omega\, Y^{\star}_{\pm 2,\ell m}(\hat{n})\, (Q(\hat{n}) \pm iU(\hat{n})), \tag{1}$$

where $Y_{\pm 2,\ell m}(\hat{n})$ are precisely Spherical Harmonics of spin 2 and $a_{\pm 2,\ell m}$ are the corresponding coefficients. It is then useful to introduce new coefficients as linear combinations of the previous:

$$a_{E,\ell m} = -(a_{2,\ell m} + a_{-2,\ell m})/2, \tag{2}$$

$$\text{and} \quad a_{B,\ell m} = -(a_{2,\ell m} - a_{-2,\ell m})/2i. \tag{3}$$

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(1) Due to the polarization dependence of the Compton cross section the CMB does not display circular polarization, at least in a standard scenario. Hence we do not consider the Stokes parameter V in what follows.

These have opposite behaviors under a P transofrmation:

$$a_{E,\ell m} \to (-1)^{\ell}\, a_{E,\ell m}, \tag{4}$$

$$a_{B,\ell m} \to (-1)^{\ell+1}\, a_{B,\ell m}. \tag{5}$$

If P is conserved, by combining the previous transformation one immediately derives that the cross-correlations $C_\ell^{TB} = \langle a^\star_{T,\ell m} a_{B,\ell' m'} \rangle$ and $C_\ell^{EB} = \langle a^\star_{E,\ell m} a_{B,\ell' m'} \rangle$ must vanish. Further details can be found in [15, 16] and explicit algebra is set forth in the Appendix of [12].

3. – Cosmological birefringence

The CMB is a powerful probe of cosmological birefringence and, hence, of the parity behavior of the electromagnetic 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. For other cosmological observations about the Cosmological Birefringence effect see [1, 2, 18, 19].

For instance, the presence of a primordial homogeneous [20] or helical [21] magnetic field would induce Faraday rotation and non-zero TB correlations. Parity-asymmetric gravity dynamics during inflation could cause unbalance in left and right-handed gravitational waves, which impacts TB and EB [4]. In general, models in high energy physics with non-standard parity-violating interactions also predict TB and EB signals different from zero [8]. A popular model for which parity is broken in the photon sector is the Chern-Simons perturbation to the Maxwell Lagrangian [1]:

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

where $F^{\mu\nu}$ is the Maxwell tensor and A^μ the four-potential. The four-vector p_μ can be interpreted in several ways, *e.g.*, the derivative of the quintessence field or the gradient of a function of the Ricci scalar [22]. In any case a P violation always arises provided that the timelike component of p_μ does not vanish. C and T symmetries are then unbroken so CP and CPT are not conserved. Given that p^μ selects a preferred direction in spacetime, Lorenz invariance cannot be preserved.

Historically, the effect has been first constrained by measuring polarized light from high redshift radio galaxies and quasars [1, 2, 19, 23], see [24] for an analysis on ultraviolet polarization of distant radio galaxies. Recent polarization oriented CMB observations [25-28] 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 [26, 29-31].

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 [4,29,32,33](2). The polarization rotation can be parametrized by the angle α, namely the birefringence angle, that, in the limit of constant α, impacts the angular power spectra of CMB anisotropies as follows [4,29,32,33]:

$$C_\ell^{TE,obs} = C_\ell^{TE}\cos(2\alpha), \tag{6}$$

$$C_\ell^{TB,obs} = C_\ell^{TE}\sin(2\alpha), \tag{7}$$

$$C_\ell^{EE,obs} = C_\ell^{EE}\cos^2(2\alpha) + C_\ell^{BB}\sin^2(2\alpha), \tag{8}$$

$$C_\ell^{BB,obs} = C_\ell^{BB}\rangle\cos^2(2\alpha) + C_\ell^{EE}\sin^2(2\alpha), \tag{9}$$

$$C_\ell^{EB,obs} = \frac{1}{2}\left(C_\ell^{EE} + C_\ell^{BB}\right)\sin(4\alpha). \tag{10}$$

The WMAP team [26], 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% CL. Our constraint, obtained at low resolution [9] and considering the same estimator that has been used in [31], reads $\alpha = -1.6^\circ \pm 1.7^\circ\,(3.4^\circ)$ at 68% (95%) CL for $\Delta\ell = 2-47$. Considering $\Delta\ell = 2-23$ we obtain $\alpha = -3.0^\circ{}^{+2.6^\circ}_{-2.5^\circ}$ at 68% CL and $\alpha = -3.0^\circ{}^{+6.9^\circ}_{-4.7^\circ}$ at 95% CL. This is the same multipole range considered by the WMAP team at low resolution in [26] (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% CL. In [39] it is claimed that the improvement expected for the Planck satellite [40] in terms of sensitivity [41] is around 15. Almost the same number is obtained in [9]. Both 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. We define the following quantities:

$$C_{+/-}^{X} \equiv \frac{1}{(\ell_{max}-1)}\sum_{\ell=2,\ell_{max}}^{+/-}\frac{\ell(\ell+1)}{2\pi}\hat{C}_\ell^{X}, \tag{11}$$

where $\hat{C}_\ell^X$ are the estimated APS obtained with *BolPol* for the power spectrum $X = TT$, TE, EE and BB. The sum is meant only over the even or odd ℓ and this is represented respectively by the symbol $+$ or $-$. Therefore, two estimators can be built from eq. (11): the "ratio" $R^X = C_+^X/C_-^X$ (see [10-12]) and the "difference" $D^X = C_+^X - C_-^X$, (see [12, 42]), 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.

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(2) See [34, 35] 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 [36-38] as examples of non-isotropic birefringence effect.

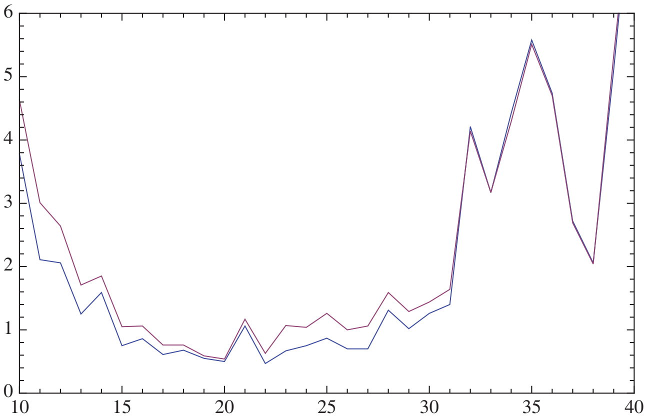

Fig. 1. – TT. Percentage of the WMAP 7 year value (y-axis) *vs.* ℓ_{max} (x-axis). The blue line is for the ratio and the red line for the difference.

In fig. 1 we plot the percentage related to the WMAP 7 year P anomaly 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 $[16, 32]$. We confirm the previously reported P anomaly in TT in the range $\Delta\ell = [2, 22]$ at $> 99.5\%$ CL. 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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