Polarized Foregrounds Power Spectra vs CMB

Carlo Baccigalupi*, Gianfranco De Zotti†, Carlo Burigana** and Francesca Perrotta†

*SISSA/ISAS, Via Beirut 2-4, 34014 Trieste, Italy
†Osservatorio Astronomico di Padova, Vicolo dell’Osservatorio 5, 35122 Padova, Italy
**ITeSRE-CNR, Via Gobetti, 101, I-40129 Bologna, Italy

Abstract. We briefly review our work about the polarized foreground contamination of the Cosmic Microwave Background maps. We start by summarizing the main properties of the polarized cosmological signal, resulting in “electric” (E) and “magnetic” (B) components of the polarization tensor field on the sky. Then we describe our present understanding of sub-degree anisotropies from Galactic synchrotron and from extra-Galactic point sources. We discuss their contamination of the cosmological E and B modes.

INTRODUCTION

Several ongoing or planned experiments are designed to reach the sensitivities required to measure the expected linear polarization of the Cosmic Microwave Background (CMB), see e.g. [1]. The forthcoming space missions MAP and PLANCK aim at obtaining full sky high resolution maps of Cosmic Microwave Background (CMB) anisotropies, up to several arcminute resolution (see e.g. [2, 3]; MAP webpage: http://map.gsfc.nasa.gov/; PLANCK webpage: http://astro.estec.esa.nl/SA-general/Projects/Planck/).

They will also probe the polarization of the CMB radiation. MAP has polarization sensitivity in all channels. The current design of instruments for the PLANCK mission provides good sensitivity to polarization at all LFI (Low Frequency Instrument) frequencies (30–100 GHz) as well as at three HFI (High Frequency Instrument) frequencies (143, 217 and 545 GHz).

While there is a very strong scientific case for CMB polarization measurements (cf., e.g., [4] and references therein), they are very challenging both because of the weakness of the signal and because of the contamination by foregrounds that may be more polarized than the CMB.

In this paper, we begin by giving a description of the key features and meaning of the polarized CMB component. The latter is usually described in terms of the angular power spectra of two components of the CMB polarization signal, namely electric (E) and magnetic (B) modes (see [5] for an extensive treatment). Then we summarize the main results of our recent work [6] on the diffuse Galactic synchrotron polarized emission, focusing on sub-degree anisotropies. These results have been obtained by analyzing the existing high resolution data in the radio band: the Parkes and Effelberg surveys at 2.4 and 2.7 GHz [9] along the Galactic plane, and the medium latitude data at 1.4 GHz [10]. Moreover we present some preliminary results on the power spectrum of polarized emission from extragalactic radio sources obtained exploiting data from the NVSS survey ([7]; http://www.cv.nrao.edu/~jcondon/nvss.html). In the last Section we give some concluding remarks.

COSMOLOGICAL POLARISATION MODES: ELECTRIC AND MAGNETIC TYPE

We give here only the basic features of the current description of the cosmological polarized signal. A detailed treatment can be found, e.g., in [5].

Given two orthogonal axes $i, j$ in the plane perpendicular to the photon propagation direction $\hat{n}$, the $2 \times 2$ linear polarization tensor $I_{ij}$ is represented by the Stokes parameters $Q$ and $U$, with $Q = (I_{11} - I_{22})/4$, $U = I_{12}/2$. It is convenient to define the complex quantities $Q \pm iU$, which transform like a definite spin state under rotation by an
angle $\psi$ around $\hat{n}$:

$$(Q \pm iU) \rightarrow e^{\pm 2i\psi}(Q \pm iU).$$

These quantities can be expanded in the tensor spherical harmonics $\pm Y_{lm}$ as

$$(Q \pm iU)(\hat{n}) = \sum_{lm} a_{\pm 2,lm} \pm 2Y_{lm}(\hat{n}).$$

The expansion coefficients for E and B modes can then be defined as:

$$a_{E,lm} = -(a_{+2,lm} + a_{-2,lm})/2, \quad a_{B,lm} = i(a_{+2,lm} - a_{-2,lm})/2.$$ (3)

The electric and magnetic analogy comes from the properties of E and B modes under parity transformation $\hat{n} \rightarrow -\hat{n}$: while the $a_{E,lm}$ remain unchanged, the $a_{B,lm}$ change sign [5]. The power spectra associated with E and B modes, as well as their relation with the power spectrum of $Q$ and $U$ can be easily evaluated as:

$$C_{l}^{E} = \frac{1}{2l+1} \sum_{m} |a_{E,lm}|^2, \quad C_{l}^{B} = \frac{1}{2l+1} \sum_{m} |a_{B,lm}|^2, \quad C_{l}^{E} + C_{l}^{B} = \frac{C_{l}^{Q} + C_{l}^{U}}{2}.$$ (4)

Due to the opposite parity properties, no correlation exists between E and B. It is also useful to recall that E modes are correlated with the total intensity fluctuations, giving rise to a $C_{l}^{TE}$ power spectrum. The latter can be stronger than that of E and B CMB spectra since it receives contributions from total intensity fluctuations that are expected to be 10 times or so larger than the polarization ones. The description of the polarization field in terms of E and B modes is more convenient than the classical one in terms of local Q and U Stokes parameter because while E receives...
contribution from all the types of cosmological perturbations, B is non-zero only if vector or tensor fields are present in the cosmological perturbations [5]. Of particular interest are tensor perturbations associated to gravitational waves because their amplitude is directly related to the vacuum energy density during inflation.

To give a worked example, consider the constraints on cosmological parameters set by the recent data from BOOMERanG [8]. According to these data, the present cosmological energy density is consistent with the critical one, being made by a 70% of vacuum energy ($\Omega_\Lambda = 70\%$), a 25% of dark matter and a 5% of baryons with an Hubble constant of 70 km/sec/Mpc ($\Omega_b h^2 = 0.022$). In Fig. 1 the TE, E and B power spectra are shown for this cosmological model, further assuming a contribution to the temperature quadrupole of tensor perturbations equal to 30% of the contribution of scalar perturbations. The main power resides in TE and E since these modes receive inputs from acoustic oscillations occurring inside the horizon at decoupling, corresponding to $l \geq 200$ in the figure. The B component is subdominant since it is excited by gravitational waves which decay rapidly inside the horizon.

This example gives an idea of the importance of measuring E and B modes of the CMB polarization fluctuations. It is therefore extremely important to study the power of the foregrounds as contaminants to this signal. In the next two Sections we give our present guess of the contamination coming from the low frequency Galactic and extragalactic emissions, taking as reference model the one presented in Fig. 1.
POLARIZED GALACTIC SYNCHROTRON EMISSION

We summarize here the main results of our recent paper [6] in which we analyzed data from low and medium Galactic latitudes at 1.4, 2.4, 2.7 GHz [9, 10], having resolution of several arcminutes, and from high Galactic latitudes on large angular scales [11]. We focus here on the results concerning the power spectrum on sub-degree angular scales, that we recast in terms of E and B modes.

By comparing total with polarized emissions we were able to observe the following facts. The polarized emission does not show any significant decrease with increasing Galactic latitude, up to the highest latitudes considered \((|b| \approx 20^\circ)\), while the total intensity decreases by a large factor. Correspondingly, the polarization degree increases from typical values of a few percent on the Galactic plane to about 30% at latitudes \(10^\circ \leq b \leq 20^\circ\).

We found that the low polarization degree on the Galactic plane can be largely explained by the contribution to the observed total intensity from known intrinsically unpolarized HII regions, cataloged by [12], which are concentrated on the plane. We verified that, after removal of the contributions from HII regions, the polarization degree drops to values consistent with those found at medium latitudes. Of course, HII regions themselves also contribute to Faraday depolarization of synchrotron emission coming from outer Galactic regions.

Regions were identified where rotation measures towards pulsars and extragalactic sources, the high polarization degree and, in some cases, data on the distribution of polarization vectors and on the Galactic magnetic field, consistently indicate low Faraday depolarization. The mean Galactic synchrotron power spectrum was estimated as the average power spectrum of several such regions. In terms of the E and B modes, and assuming a spectrum of the form \(S_\nu \propto \nu^{-0.9}\), i.e. antenna temperature \(T_A \propto \nu^{-2.9}\), we have, on degree and subdegree angular scales \((100 \leq l \leq 1000)\):

\[
C_l^E \simeq C_l^B = (1.2 \pm 0.8) \cdot 10^{-9} \cdot \left(\frac{l}{450}\right)^{-1.8 \pm 0.3} \cdot \left(\frac{\nu}{2.4 \text{ GHz}}\right)^{-5.8} \text{K}^2.
\]

The power is almost equally distributed among E and B modes, as is expected since the alignment is preferentially determined by magnetic fields, which do not have the characteristic parity properties of scalar density perturbations (see [13]).

In Fig. 2 we plot this results (solid line at \(100 \leq l \leq 1000\)), scaled to 100 GHz, against the different components of the CMB spectrum shown in Fig. 1. This, albeit preliminary, estimate, suggests that contamination from diffuse synchrotron is not a serious hindrance for measuring the the CMB E-mode polarization, but poses a serious challenge for measurements of the B-mode power spectrum.

EXTRAGALACTIC RADIO SOURCES

The confusion fluctuations due to a Poisson distribution of extragalactic sources in the case of a polarimetric survey have been discussed by [14] and [15]. Briefly, in the case of a population with uniform evolution properties and constant (time-independent) polarization degree \(\Pi\), the polarization fluctuations \(\sigma_p^2\) for cells of solid angle \(\omega\) are simply given by

\[
\sigma_p^2 = \sigma_t^2 \langle \Pi^2 \rangle,
\]

where \(\sigma_t^2\) is the amplitude of intensity fluctuations for the given cell size (see, e.g. [16]) and

\[
\langle \Pi^2 \rangle = \int_0^1 \Pi^2 \rho(\Pi) d\Pi,
\]

\(\rho(\Pi)\) being the distribution function of the polarization degree. Clearly, an uncorrelated source distribution give equal contributions to the E- and B-mode power spectra.

The estimates by [15] exploited the models by [16] to estimate \(\sigma_t^2\). To estimate the mean polarization degree, they defined a complete sub-sample of BL-Lacs for which polarization measurements at cm wavelengths are available. The mean polarization degree at \(\lambda = 2\text{ cm}\) was found to be 5%. The available data at shorter wavelengths suggest that the polarization degree remains constant down to \(\lambda \approx \text{ few mm}\). The E-mode (or B-mode) power spectrum of polarization fluctuations due to radio sources, assuming \(\Pi = 0.5\%\) for all populations contributing to the 100 GHz counts, is shown in Fig. 2.

A new analysis, currently underway by [17], exploits the NRAO VLA Sky Survey (NVSS) [7] which has provided I, Q, and U data at 1.4 GHz for almost \(2 \times 10^6\) discrete sources brighter than \(s \approx 2.5\text{ mJy}\) over about 10.3 sr of sky.
(about 82% of the celestial sphere). Whenever possible, spectral indices of sources have been determined combining the 1.4 GHz flux densities with those given by the GB6 [18] and PMN [19] catalogues at $\approx 5 \text{GHz}$. Extrapolations of polarized fluxes to higher frequencies have been made assuming that the polarization degree is frequency independent. A very preliminary estimate of the derived polarization power spectrum is shown in Fig. 2.

Advantages of this latter approach are that it automatically takes into account the real space distribution of point sources, including clustering effects, as well as the actual distribution of their polarization properties. The large extrapolations in frequency introduce, however, substantial uncertainties. On one side, the polarization degree may be higher at higher frequencies both because the Faraday depolarization becomes negligible and because additional polarized components become optically thin. A hint in this direction is provided by the fact that the mean polarization degree of NVSS sources turns out to be $\approx 1.4\%$, to be compared with the 5% mean polarization at 15 GHz found by [15]. On the other side, it is known that many sources with flat or inverted spectrum up to $\sim 5 \text{GHz}$ show spectral breaks at higher frequencies. Thus, the assumption of a constant spectral index up to 100 GHz leads to an overestimate of polarization fluctuations. The two effects go in opposite directions and therefore tend to counterbalance each other. To the extent that the hypothesis of constant spectral indices holds, the effective spectral index is found to be $\alpha_{\text{eff}} \approx 0.1$ ($S_{\nu} \propto \nu^{-\alpha}$, which becomes $T_{A} \propto \nu^{-2-\alpha}$ in antenna temperature). In order to estimate the polarization fluctuation power spectrum we need to specify the maximum flux of contributing sources (i.e. the minimum flux of sources that can be individually detected and subtracted out). Assuming that all sources with total flux larger than 5 times the global rms fluctuations (including contributions of noise, CMB and Galactic foregrounds), as estimated by [16], can be removed, the E- and B-mode power spectrum of polarization fluctuations due to extragalactic sources is described by:

$$C_{E}^l \propto C_{B}^l = 1.4^{+0.7}_{-0.4} \cdot 10^{-7} \mu K^2 \cdot \left(\frac{\nu}{100 \text{GHz}}\right)^{-4.2},$$

This result is represented by the solid line extending up to $l = 3000$ in Fig. 2. We must caution that the assumption about the flux limit for source subtraction may be somewhat optimistic, so that the amplitude of fluctuations may be somewhat underestimated. On the other hand it is reassuring that the two totally independent estimates mentioned above give quite similar results. It is also interesting to note that the power spectrum derived from NVSS data is fully consistent with a Poisson distribution of sources: clustering effects turn out to be essentially negligible, as argued by [16].

CONCLUSIONS

There is growing interest and excitement about CMB polarization studies. Measurements are extremely challenging because of the extreme weakness of the signal to be detected. So, advances in experimental techniques will be crucial, particularly to measure the B-mode power spectrum, induced by gravitational waves. On the other hand, it is not yet clear whether our ability to measure the CMB polarization power spectrum will be limited by detector sensitivity or by foregrounds. In fact, polarized foregrounds are currently very poorly understood.

On the other hand, new surveys are providing important pieces of information, on which we can found preliminary but quantitative estimates of the effect of foregrounds. We have focussed here on polarized synchrotron emission from our own Galaxy and on extragalactic radio sources. As for synchrotron emission, recent high resolution and high sensitivity polarization maps at frequencies in the range 1.4–2.7 GHz ([9, 10]), although covering rather limited regions of the sky, have allowed to estimate the power spectrum at sub-degree angular scales.

We have also presented and briefly discussed polarization fluctuations due to extragalactic radio sources, based on two approaches. On one side there are estimates based on counts as a function of total flux, complemented with estimates of the mean polarization degree. On the other side, the polarization measurements provided by the NVSS were used together with estimates of the spectral index of individual sources derived by combining NVSS data with higher frequency catalogues (GB6 and PMN). The two approaches yield results very close to each other.

Although the analysis is admittedly preliminary and does not consider yet other potential polarized foregrounds at cm/mm wavelengths (e.g. magnetic or spinning dust grains, see [21]), some indications are already emerging. Polarized foregrounds do not seem to be a serious hindrance for measurements of the CMB E-mode power spectrum on degree and sub-degree angular scales, particularly in the frequency range 60–100 GHz (see [20] for a discussion of polarized foregrounds at higher frequencies). However, foregrounds appear to be a potentially serious limiting factor for experiments aimed at detecting B-mode CMB polarization. More data and more detailed analyzes will therefore be essential for designing future experiments.
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