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Impact of polarized foregrounds on LSPE-SWIPE observations

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Abstract. A first measurement of Cosmic Microwave Background B-mode polarization on large scales could provide a convincing confirmation of the existence of a primordial background of gravitational waves as predicted in the inflation scenario. A major obstacle to observe B-modes is represented by polarized foreground contamination from our Galaxy. In particular, thermal dust and synchrotron emission dominate over the primordial signal at high and low frequencies, respectively. Several experiments have been designed to observe B-mode polarization. Here, we focus on the forthcoming LSPE-SWIPE balloon experiment, devoted to the accurate observation of large scale CMB polarization, and present preliminary forecasts on the impact of foreground contamination on LSPE-SWIPE observations. Using the last release of Planck foreground maps as templates, we estimate the amplitude of dust and synchrotron emission in the sky region and at the frequency channels of interest for LSPE-SWIPE. Furthermore, we investigate the generation of polarization-optimized Galactic masks and we give preliminary indications on the requirements of component separation methods.

1. Introduction

The analysis of the Cosmic Microwave Background (CMB) temperature anisotropy pattern has provided tight limits on the early stage, evolution and content of the Universe [1]. The Planck experiment has given an ultimate dataset for intensity maps but just opened the observation of the CMB (linear) polarization pattern. The polarization component, usually described in terms of the so-called E and B-modes, can further constrain some crucial aspects of the cosmological model. E-mode polarization has been widely detected, while there has been no detection of primordial B-modes so far. B-mode polarization is uniquely sensitive to the tensor mode of primordial perturbations, i.e. the gravitational wave stochastic background whose existence is predicted by the inflationary paradigm. Moreover, B-modes could also help in constraining critical aspects of the reionization history of the Universe. Therefore, the detection of B-modes represents the new frontier of cosmological observations. The B-mode amplitude is usually expressed in terms of the tensor-to-scalar ratio, r, which gives the relative amplitude of tensor and scalar primordial perturbations. Planck, BICEP2 and Keck Array [2] constrained r down to 0.07 at 95% C.L., but we do not have accurate indications on its lower limit. However, theory suggests $r > 10^{-3}$ [3]. A major obstacle to observe B-mode polarization is represented by the presence of foreground contamination: in particular, thermal dust and synchrotron emission from the Galaxy dominate over the primordial B-modes at high and low frequencies, respectively (see, e.g., [4]). Several experiments have been planned to detect B-mode polarization, either from ground, balloons or space. In this work, we focus on the forthcoming LSPE mission, that will be devoted to the accurate measurement of CMB polarization at large angular scales in order to constrain r down to 0.03 [5]. LSPE consists of two instruments: SWIPE, a balloon-borne array of bolometric polarimeters that will map the sky at 140, 220 and 240 GHz, and STRIP, a ground-based array of coherent detectors that will survey the same sky region at 43 and 90 GHz. This work focuses on the SWIPE experiment [6]. SWIPE will be likely launched during the winter 2018-2019 from the Svalbard islands and will operate for around 15 days during the Arctic night. A large fraction of the northern sky (around 30%) will be observed with angular resolution of about 1.5 deg Full Width at Half Maximum (FWHM). The 140 GHz band will be the main CMB science channel, while measurements at 220 and 240 GHz will be devoted to monitoring thermal dust contamination. The goal of this work is to provide a preliminary, but realistic, estimate of the foreground impact on LSPE-SWIPE observations.

2. Methodology and results

2.1. From Planck to LSPE-SWIPE

In order to infer the level of foreground contamination in the sky patch and at the frequency channels of interest for LSPE-SWIPE, we use the public foreground maps from the Planck satellite as templates [7]. In particular, we take the thermal dust and synchrotron maps estimated by the component separation method Commander [8] at reference frequencies of 353 and 30 GHz, respectively (see Fig. 1).

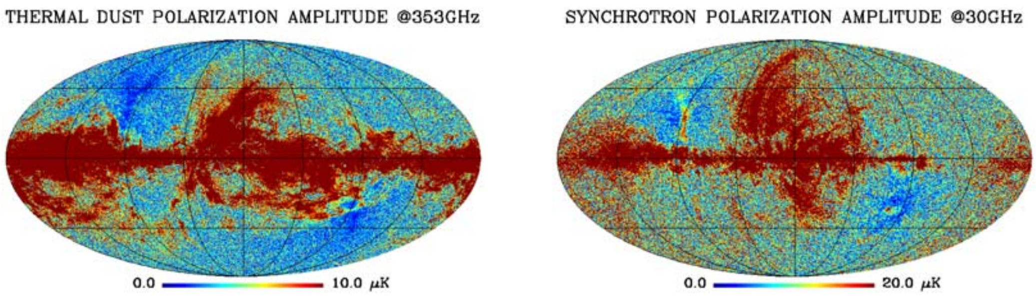

Figure 1. Thermal dust (left) and synchrotron (right) polarization amplitude maps ($P = \sqrt{Q^2 + U^2}$, where Q and U are the Stokes parameters for the linear polarization) from Planck. Maps are estimated by the component separation method Commander at reference frequencies of 353 and 30 GHz, respectively. Maps are in Galactic coordinates, antenna temperature units (μK_{RJ}) and a resolution of 10 arcmin for dust and 40 arcmin for synchrotron.

To first order, the dust spectrum is a modified Black Body (Gray Body) of the shape $\nu^{\beta_d} B_\nu$, where ν is the frequency, β_d is the dust spectral index and B_ν is the Planck function. Synchrotron emission is instead characterized by a power law spectrum with spectral index β_s. Hence, we rescale the dust and synchrotron maps to the LSPE-SWIPE frequency channels ($\nu = 140, 220, 240$ GHz) multiplying them by the following factors, respectively:

$$\alpha^d_\nu = \left(\frac{\nu}{\nu_{353\text{GHz}}}\right)^{\beta_d - 2} \frac{B_\nu(T_d)}{B_{\nu_{353\text{GHz}}}(T_d)}, \qquad \alpha^s_\nu = \left(\frac{\nu}{\nu_{30\text{GHz}}}\right)^{\beta_s} \tag{1}$$

where the dust and synchrotron spectral indices are $\beta_d = 1.58$ and $\beta_s = -3.04$ and the dust temperature is $T_d = 19.6$ K [4]. We convert the maps from the original antenna temperature to the more common thermodynamic temperature multiplying by the factor $g = \frac{(\exp(x)-1)^2}{x^2\exp(x)}$ where $x = \frac{h\nu}{kT_{CMB}}$, with h, k and T_{CMB} being the Boltzmann and Planck constants and the CMB average temperature, respectively. Finally, using the HEALPix package [9], we smooth and degrade the maps to 1.5 deg FWHM and to a map resolution parameter of $N_{side} = 128$, where N_{side} defines the total number of pixels N_{pix} in the map according to $N_{pix} = 12N_{side}^2$. In Fig. 2, we show realistic simulated maps of the CMB polarization amplitude, instrumental noise and foreground in the sky patch which will be observed by LSPE-SWIPE at 140 GHz. The CMB map has been produced with the HEALPix Synfast facility from theoretical power spectra calculated with the CAMB software [10] according to the Planck latest release of cosmological parameters [1] and assuming a tensor-to-scalar ratio $r = 0.03$. The noise map has been produced from a noise spectrum with a high frequency constant plateau of amplitude 15 μKs$^{1/2}$, and a low-frequency correlated $1/f^2$ part. Moreover, we include a low-frequency $1/f^2$ cross-correlated noise component equally shared by all the detectors. The knee frequency is set to $f_k = 0.1$ Hz. The noise map has been estimated with the ROMA map-making code [11] according to the nominal instrumental baseline and scanning strategy. The foreground (dust+synchrotron) map is produced according to the procedure described above.

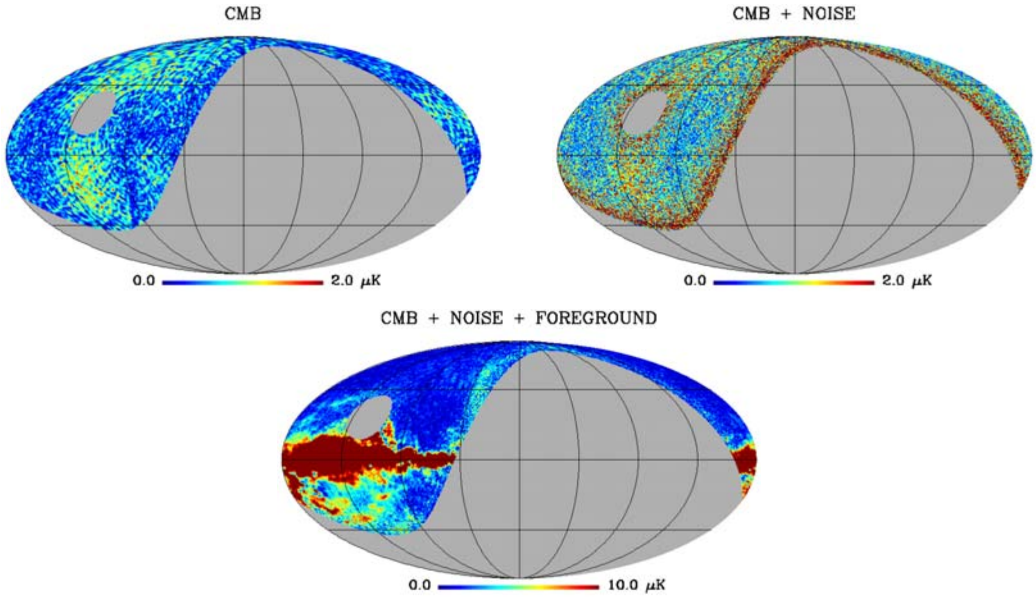

Figure 2. Simulated CMB (top left), CMB+noise (top right) and CMB+noise+foreground (bottom) polarization amplitude maps evaluated in the LSPE-SWIPE sky region at 140 GHz. Maps are in Galactic coordinates, thermodynamic temperature units (μK) and a resolution of 1.5 deg.

2.2. Forecasts on foreground contamination

In order to provide a quantitative assessment of the impact of foregrounds on LSPE-SWIPE observations, we estimate power spectra of the foreground maps generated as described in the previous section, but keeping the maps at native resolutions. In this process, masking the Galactic plane is a crucial step, as the foreground emission in that region is several orders of magnitude higher than the CMB signal we are interested in (as evident in Fig. 2). Galactic and extra-galactic polarized point sources need also to be masked out, as despite their low number they can alter the evaluation of the diffuse foreground power spectra. We use point source masks constructed from the polarized sources at 30 and 353 GHz in the Planck PCCS2 catalogue [12], for the synchrotron and dust templates, respectively. It is worth mentioning that the Planck maps we use as templates do actually contain noise. Therefore, to avoid any bias in our analysis, we compute the spectra by cross-correlating maps generated from the Half-Mission (HM) data splits, which have independent noise. In particular, we found that the effect of point sources and noise is subdominant for the dust maps in the multipole range considered here ($2 \leq \ell \leq 100$), while synchrotron maps are significantly affected by both. Spectra in this paper have been estimated using the MASTER approach [13, 14]. In order to validate the methodology for our analysis setup, we simulated a set of foreground maps as random Gaussian realisations of an input power spectrum of the form $C_\ell = A^{BB}(\ell/\ell_0)^{-2.4}$ with $A^{BB} = 0.5A^{EE}$ [15]. We estimated the power spectra of these maps on the masks used in the paper and verified that the mean recovered power spectra are actually unbiased. In Fig. 3, we show the dust and synchrotron BB spectra estimated in the LSPE-SWIPE sky region at 140, 220 and 240 GHz, produced either without or including a temperature Galactic mask (the Planck GAL70 mask), which reduces the effective sky fraction from 36% to 24%. As expected, the use of optimized Galactic masks and component separation methods will be unavoidable to face foreground contamination.

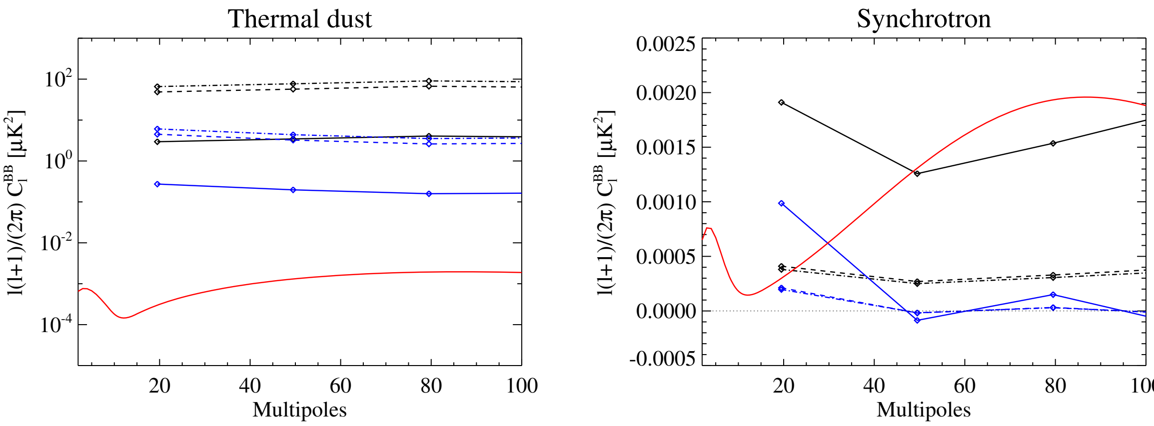

Figure 3. Thermal dust (left) and synchrotron (right) BB angular power spectra estimated in the LSPE-SWIPE sky region at 140 (solid line), 220 (dashed line) and 240 (dashed-dotted line) GHz, including (in blue) or not (in black) a temperature Galactic mask (the Planck GAL70 mask). We compute the spectra in three multipole bins for the ranges 5-34, 35-64 and 65-94. The theoretical CMB spectrum corresponding to $r = 0.03$ is shown in red for comparison.

To refine this analysis, we generate a set of polarization specific Galactic masks by thresholding a map obtained summing in quadrature the polarization intensity of the two foreground components at 140 GHz, built as $\sqrt{P^2_{dust} + P^2_{synch}} = \sqrt{Q^2_{dust} + U^2_{dust} + Q^2_{synch} + U^2_{synch}}$, after smoothing the original maps of the Stokes parameters to an effective resolution of 1.5 deg. We mask all the pixels in the map that are above certain thresholds, which we choose to be 0.75, 1, 1.5, 2, 2.5 and 3 σ_{CMB}, where $\sigma_{CMB} = \sqrt{\sigma^2(Q) + \sigma^2(U)} \simeq 0.38$ μK has been estimated from a simulation with $r = 0.03$ and the same resolution of the data maps. Finally, we smooth the masks with a Gaussian beam of 10 deg FWHM, put a threshold at 0.5 to have masks with only [0,1] values and combine these masks with the LSPE-SWIPE targeted sky patch. In Fig. 4, we show the six sky regions selected by these masks, which have effective sky coverages ranging from 1.3 to 15.1%. The choice of a proper Galactic mask must be done according to the specific requirements on the sky fraction and the residual foreground level, which will depend on the component separation method. Clearly, the effective sky fraction should be maximised to reduce cosmic variance, while the foreground amplitude should be mitigated as far as possible.

We then estimate the dust and synchrotron BB power spectra at 140 GHz for the different masks and we assess the uncertainties due to noise in Planck data from Full Focal Plane simulations [16]. We consider a set of 100 HM simulated noise maps both at 30 and 353 GHz and extrapolate them in frequency as it has been done for the data (see Eq. 1). We notice that these simulations underestimate the variance of the data by a (scale-dependent) factor of 5-20% [16]. The spectra have been computed in three multipole bins for the ranges 5-34, 35-64 and 65-94 and are shown in Fig. 5.

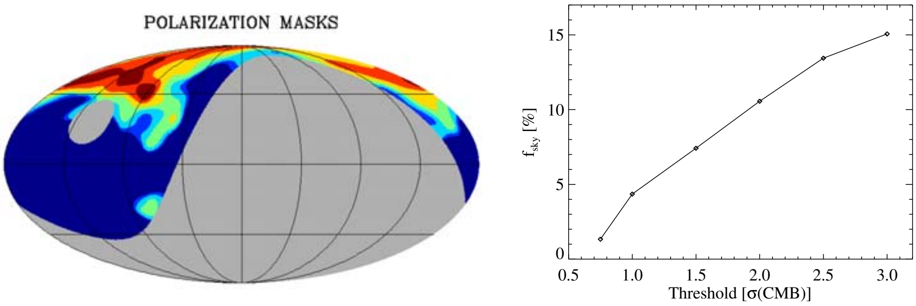

Figure 4. On the left: Masks obtained combining different masks of the Galactic plane with the LSPE-SWIPE scanning strategy. The Galactic masks are optimized in polarization assuming a frequency of 140 GHz and correspond to different thresholds: 0.75, 1, 1.5, 2, 2.5 and 3 σ_{CMB}. On the right: Plot of the sky fraction as a function of the threshold. See text for details.

Finally we calculate an equivalent tensor-to-scalar ratio for the foreground emission by dividing these spectra by the theoretical CMB BB spectrum with $r = 1$. In particular, we average through inverse-variance weighting the values of the equivalent tensor-to-scalar ratios from the two multipole bins ranging from $35 < \ell < 64$ and $65 < \ell < 94$ around the "recombination" bump, while we discard the lowest multipole bin as the Planck polarization data of the 2015 release still contain some low level residual systematics on those angular scales. Actually, it will be interesting to extend the analysis once the final Planck data, optimized for polarization on large scales, will be released at the end of 2017. Results are shown in Fig. 6 for the different sky fractions.

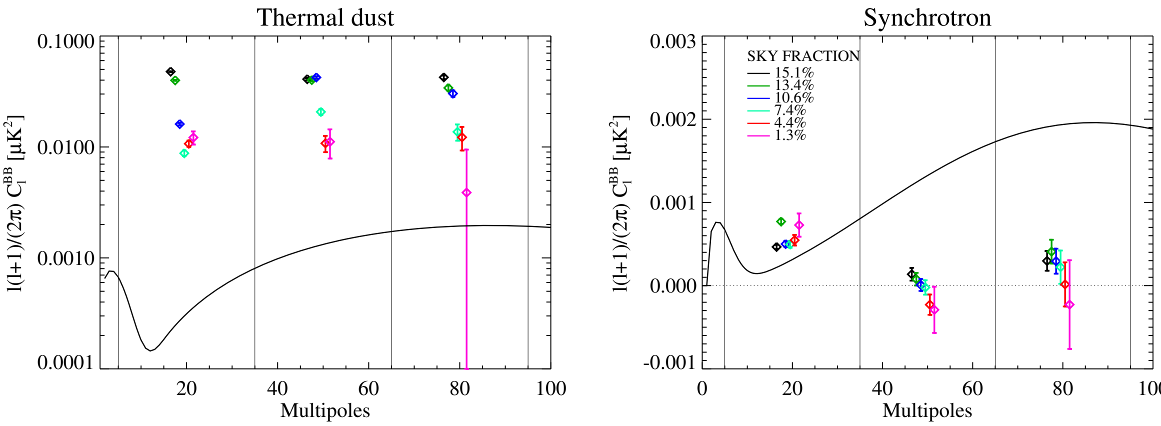

Figure 5. Thermal dust (left) and synchrotron (right) BB angular power spectra estimated in the LSPE-SWIPE sky region at 140 GHz, applying the Galactic masks given in Fig. 4. We compute the spectra in three multipole bins for the ranges 5-34, 35-64 and 65-94. The theoretical CMB spectrum corresponding to $r = 0.03$ is shown for comparison with a solid black line.

3. Conclusions

A CMB B-mode polarization detection would be a "smoking gun" evidence for inflation theory, as primordial B-modes are unambiguosly sensitive to the tensor mode of inflationary perturbations.

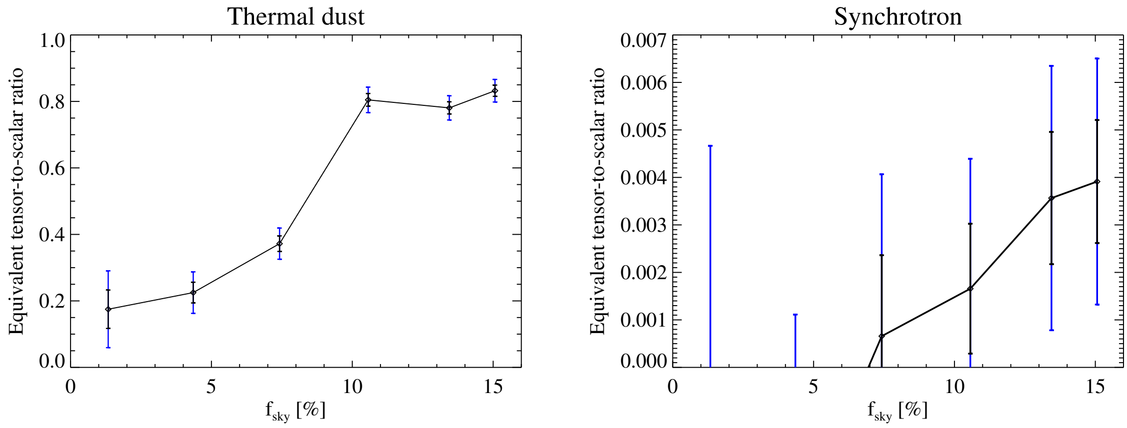

Figure 6. Equivalent tensor-to-scalar ratios vs sky fraction at 140 GHz for dust (left) and synchrotron emission (right). Error bars correspond to 1σ (in black) and 2σ (in blue) noise uncertainties.

A major obstacle to observe B-modes is represented by Galactic contamination of polarized thermal dust and synchrotron emission. In this work, using the latest Planck polarization data, we present preliminary forecasts on the impact of foregrounds on the observations of the upcoming LSPE-SWIPE balloon mission. Focusing on the main CMB channel (140 GHz) we find that, in the LSPE-SWIPE sky patch, the dust emission has a power spectrum larger than the target B-mode spectrum ($r = 0.03$) by around ~ 3 orders of magnitude across the entire multipole range we consider. Synchrotron emission is instead above the target B-modes only at the lowest multipoles, while it becomes sub-dominant on smaller scales. We generate polarization specific Galactic masks and verify that when preserving large sky fractions, at least 15%, the level of dust contamination is about a factor of 30 larger than the target primordial CMB B-mode signal. Therefore, our analysis shows that a foreground cleaning method able to reduce the foregrounds at the level of few percent will be required in order to disantangle the primordial signal from the Galactic contamination, and hence maximise the scientific return of the LSPE-SWIPE mission.

Acknowledgments

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