Mon. Not. R. Astron. Soc. **364,** L5–L7 (2005) doi:10.1111/j.1745-3933.2005.00092.x

The synchrotron foreground and the cosmic microwave background temperature–polarization cross-correlation power spectrum from the first-year *WMAP* data

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Accepted 2005 August 9. Received 2005 August 7; in original form 2005 July 20

ABSTRACT

We analyse the temperature–polarization cross-correlation in the Galactic synchrotron template that we have recently developed, and between the template and cosmic microwave background (CMB) temperature maps derived from *WMAP* data. Since the polarized synchrotron template itself uses *WMAP* data, we can estimate residual synchrotron contamination in the CMB C_ℓ^{TE} angular spectrum. While C_2^{TE} appears to be contaminated by synchrotron, no evidence for contamination is found in the multipole range which is most relevant for the fit of the cosmological optical depth.

Key words: polarization – methods: data analysis – cosmic microwave background – diffuse radiation.

1 INTRODUCTION

The *Wilkinson Microwave Anisotropy Probe* (*WMAP*) experiment measuring the temperature–polarization cross-correlation power spectrum of the cosmic microwave background (CMB) found an excess of power at large angular scales (the multipole range $\ell < 10$), which has been interpreted as evidence for an early reionization (Kogut et al. 2003). A clean measurement of the cosmological signal relies on a successful removal of the foregrounds, which on large angular scales are mainly generated by dust, free–free and synchrotron emissions from the Galaxy. In particular, the synchrotron radiation is the main polarized foreground at *WMAP* frequencies. According to Bennett et al. (2003), the CMB maps used to compute the angular power spectrum C_ℓ^T have negligible foreground contamination, thanks to the wide frequency coverage of the *WMAP* experiment and a safe foreground subtraction achieved with fits of foreground templates. Also Kogut et al. (2003) claimed that the contamination in the *Q*, *V* and *W* bands is low when the Galactic plane is cut out and the C_ℓ^{TE} power spectrum of the CMB is free of foreground contamination.

However, several groups have performed independent analyses of the *WMAP* data to address the foreground contamination on the CMB maps. Tegmark, de Oliveira-Costa & Hamilton (2003, hereafter TOH) claimed to have obtained a CMB map[1] cleaner than that of the *WMAP* team. Naselsky, Doroshkevich & Verkhodanov (2003) applied a phase analysis to the internal linear combination map obtained by the *WMAP* team, showing some residual foreground contamination. Also, Naselsky, Verkhodanov & Doroshkevich (2004) compared the internal linear combination map obtained by the *WMAP* team's analysis with TOH's, and found evidence for a residual contamination in the low-multipole power spectrum region. Dineen & Coles (2004, 2005) used the cross-correlation between the rotation measures of extragalactic radio sources and the CMB maps to identify a possible foreground residual; they found evidence for that in both the *WMAP* and TOH CMB maps. However, these works cannot tell us whether the foreground residual may affect the C_ℓ^{TE} power spectrum to a significant extent, and it looks harder to improve the cross-correlation analysis of Kogut et al. (2003) because polarization maps have not been provided yet by *WMAP*. The issue of possible foreground contamination on C_ℓ^{TE} is, however, very important in the light of the reported anomalies in the large-scale output of *WMAP*, including north–south asymmetries (Eriksen et al. 2004; Hansen, Bandai & Gòrski 2004a; Land & Magueijo 2005) and multipole alignments (TOH; Copi, Huterer & Starkman 2004; de Oliveira-Costa et al. 2004). As far as we are concerned about the robustness of the C_ℓ^{TE} power spectrum and the inferences on cosmological reionization, the most troublesome result is due to Hansen et al. (2004b), according to which the high optical depth ascribed to the cosmological medium by the *WMAP* team should originate from the Southern (Galactic or Ecliptic) hemisphere.

In the light of the above results, it is necessary to investigate further the possible impact of foregrounds on the C_ℓ^{TE} power spectrum. Owing to the absence of measured polarization maps at microwave frequencies, uncertainties on the foreground contamination in polarization are greater than in total intensity. In this Letter we want to tackle the problem of the foreground contamination on the CMB C_ℓ^{TE} power spectrum on large angular scales using the templates of synchrotron polarized emission developed by Bernardi et al. (2003) and Bernardi et al. (2004, hereafter B04). The B04 template in

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[1] http://space.mit.edu/home/tegmark/index.html

particular is expected to be much more accurate than the earlier one which relies on the extrapolation of surveys at ∼1 GHz. However, its superiority derives from the use of the *WMAP* total intensity maps.

2 SYNCHROTRON AND CMB C_ℓ^{TE} POWER SPECTRA

B04 provided Q and U template maps of the Galactic synchrotron emission at 23 GHz, which is obtained from the 23-GHz total intensity synchrotron map released by the *WMAP* team (by using the polarization direction field of starlight as well as a polarization horizon model). B04 also derived a Galactic map of the synchrotron spectral index, which is used to scale the polarization template to higher frequencies. In the present work, the same spectral index map is used to scale the *WMAP* 23-GHz total intensity synchrotron map released by the *WMAP* team. We choose a frequency of 60 GHz, which can be regarded as an approximate mean of the frequencies of the *WMAP QVW* data set. Synchrotron T, Q and U maps (with T the antenna temperature) are generated at an angular resolution of 7° owing to the limitation of the B04 template. We are then able to compute the 60-GHz synchrotron C_ℓ^{TE} power spectrum by integration of the two-point correlation function. This procedure (see, for the implementation, Sbarra et al. 2003) allows us to account properly for the incomplete sky coverage of the B04 template, and for the kp2 Galactic plane mask applied to the synchrotron maps (for details, see Bennett et al. 2003). A similar procedure allows us to investigate cross-correlations between the CMB and the synchrotron template.

Fig. 1 shows the synchrotron C_ℓ^{TE} power spectrum at 60 GHz and the CMB C_ℓ^{TE} power spectrum measured by *WMAP*. The error bars on the synchrotron spectrum only account for a variation $\Delta\alpha = \pm\, 0.2$ of the frequency spectral index of the synchrotron emission. Therefore they represent the uncertainty on the overall normalization of the fiducial synchrotron template at 60 GHz, and do not account for statistical errors. Clearly, the 60-GHz synchrotron C_ℓ^{TE} is much smaller than the corresponding CMB spectrum in the range $\ell = 3$–10 where most information about cosmological reionization is encoded. The situation of course would be still better at 90 GHz. We note that the synchrotron quadrupole C_2^{TE} has a large and negative value and this indicates a potential source of contamination for the CMB quadrupole; however, this very fact does not indicate any inadequacy in the *WMAP* team's technique of foreground removal. On the other hand, reasonably strong evidence for a residual contamination can be provided by a cross-correlation between the CMB temperature and the synchrotron polarization fields, both being derived from *WMAP* data.

In order to cross-correlate our Q and U templates with CMB anisotropy, we use two different CMB maps. The first one is obtained by averaging the Q, V and W maps released by the *WMAP* team after foreground subtraction (we refer to this as the *WMAP* CMB map); the other one is the CMB map produced by TOH. The $C_\ell^{T_{\rm CMB}E_{\rm SYNCH}}$ power spectra computed for both these maps are also shown in Fig. 1. Both power spectra show very similar behaviours for $\ell > 2$. We find no evidence of a CMB–synchrotron correlation in the range $\ell = 4$–10. The multipole $\ell = 3$ shows a cross-correlation which at 60 GHz is comparable to the CMB C_3^{TE}. This should not be so disturbing after all, since the large reionization optical depth is essentially generated by slightly larger ℓs. The most intriguing feature is still the behaviour of the quadrupole. When the synchrotron template is correlated with the *WMAP* CMB map we find a large (∼8 μK^2) negative value, whereas the use of the TOH CMB map leads to a relatively lower (∼5 μK^2) but positive value. For comparison, the CMB quadrupole is $C_2^{TE} \sim 3\,\mu\mathrm{K}^2$, a factor of 2–4 lower than the magnitude of $C_2^{T_{\rm CMB}E_{\rm SYNCH}}$.

The discrepancy between cross-correlation quadrupoles is not surprising, since TOH already noted that their temperature quadrupole C_2^T is significantly different from the one found by the *WMAP* team. This discrepancy, as well as the overall behaviour of the cross-correlation power spectra, is better understood by inspection of the CMB–synchrotron cross-correlation function. The latter is defined by

$$C^{TQ}(\theta) = \sum_{ij} I_i Q_j^r, \qquad (1)$$

where the Stokes parameter Q^r is computed in the frame of the great circle connecting pixels (i, j). Fig. 2 shows the cross-correlation functions derived from the *WMAP* and TOH maps and their difference. It is interesting to note that the cross-correlation functions have the same behaviour up to $\theta \sim 20°$ but they differ significantly for larger angular scales. There is clear evidence for strongly correlated signals between the *WMAP* CMB map and the polarized

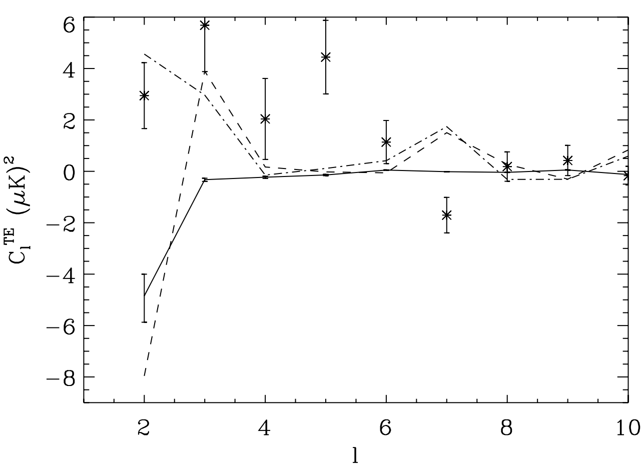

Figure 1. The synchrotron C_ℓ^{TE} power spectrum at 60 GHz (solid line) compared with the CMB C_ℓ^{TE} from Kogut et al. (2003) (asterisks). Also reported are the $C_\ell^{T_{\rm CMB}E_{\rm SYNCH}}$ power spectra for the *WMAP* CMB map (dashed line) and for the TOH CMB map (dash–dotted line).

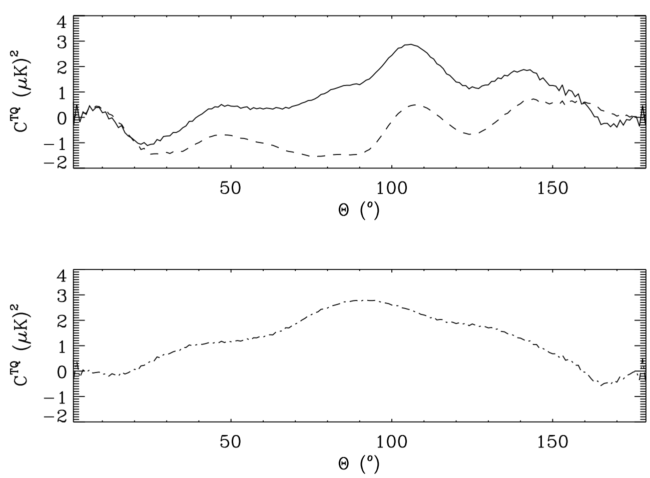

Figure 2. Top panel: the correlation function between the synchrotron Q^r and the CMB temperature maps provided by the *WMAP* team (solid line) and by TOH (dashed line). Bottom panel: the difference between the two correlation functions.

synchrotron at angular scales $\theta > 50^{\circ}$. The absolute maximum of $C^{TQ}(\theta)$ is $\sim 2\,\mu K^2$ for $\theta \sim 110^{\circ}$. The cross-correlation function derived from the TOH CMB map is somewhat weaker, and it has an opposite sign at several scales, especially the scales that are the most relevant in the determination of $C_2^{T_{\rm CMB}E_{\rm SYNCH}}$. However, the difference between the two correlation functions approximately has a very simple angular dependence $\Delta C^{TQ}(\theta) \propto \sin\theta$ and is as large as $\sim 2\,\mu K^2$ for $\theta \sim 90^{\circ}$. This fully accounts for the discrepancy found for $C_2^{T_{\rm CMB}E_{\rm SYNCH}}$. The rather moderate decrease of both $C^{TQ}(\theta)$ and $C_2^{T_{\rm CMB}E_{\rm SYNCH}}$ achieved by using the TOH temperature map seems to imply that a residual contamination by synchrotron emission survives on the largest angular scales even in the TOH treatment.

3 CONCLUSIONS

The main purpose of this Letter is the study of the possible synchrotron contamination of the CMB C_ℓ^{TE} power spectrum derived from the first-year *WMAP* release. The comparison between the CMB and the synchrotron template C_ℓ^{TE} power spectra shows that the contamination in the 60-GHz CMB C_ℓ^{TE} should be negligible for $3 \leqslant \ell \leqslant 10$. The inspection of the cross-correlation spectrum $C_\ell^{T_{\rm CMB}E_{\rm SYNCH}}$ (as well as the analysis of the cross-correlation function) reinforces this conclusion at least in the range $4 \leqslant \ell \leqslant 10$. On the other hand, the high values of the synchrotron quadrupole C_2^{TE} and of the CMB–synchrotron cross-correlated signal on large angular scales ($\theta > 50^{\circ}$) suggest a residual synchrotron contamination. We emphasize that the B04 template uses the *WMAP* total intensity synchrotron map at 23 GHz: the CMB contamination on that map is not likely to correlate so strongly with the best CMB maps available today, after rescaling to 60 GHz. Therefore the contamination should be in the CMB maps; this would also explain why the synchrotron template is more correlated with the *WMAP* CMB map than with the TOH one. The relatively high level of contamination might be, potentially, a serious problem for the CMB quadrupole C_2^T. Although this point is far from being proved by the present analysis, the foreground contamination might partly account for the low CMB quadrupole measured by *COBE* and *WMAP*.

In spite of the above open problem, we find that the multipole region where there is no evidence for contamination includes the range that dominates the standard *WMAP* fitting of the reionization optical depth. This result, obtained at 60 GHz, should be adequately representative for the *QVW* data set. Therefore, it seems really hard to explain in this way the north–south asymmetry in the optical depth fits declared by Hansen et al. (2004b). If such an asymmetry is confirmed, it should be of extragalactic (although not necessarily cosmological) origin. This possibility is supported by Schwartz et al. (2004) in connection with other *WMAP* anomalies.

ACKNOWLEDGMENTS

This work has been carried out in the framework of the SPOrt programme funded by the Italian Space Agency (ASI).

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