An angular power spectrum analysis of the DRAO 1.4 GHz polarization survey: implications for CMB observations

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ABSTRACT

Aims. The aim of the present analysis is to improve the knowledge of the statistical properties of the Galactic diffuse synchrotron emission, which constrains sensitive CMB anisotropy measurements.

Methods. We have analysed the new DRAO 1.4 GHz polarization survey together with the Stockert 1.4 GHz total intensity survey and derived the angular power spectra (APS) of the total intensity, the polarized emission, and their cross-correlation for the entire surveys and for three low-intensity regions.

Results. The APSs of the diffuse synchrotron emission are modelled by power laws. For the E and B modes, a slope of \( \alpha \sim [-3.0, -2.5] \) for the multipole range \( \ell \sim [30, 300] \) is found. By the extrapolation of these results to 70 GHz, we can estimate the Galactic synchrotron contamination of CMB anisotropies, and we find results that are compatible with the ones coming from WMAP 3-yr data. In the low-intensity regions, the cosmological primordial B mode peak at \( \ell \sim 100 \) should be clearly observable for a tensor-to-scalar ratio \( T/S \gtrsim 0.5 \) and a synchrotron temperature spectral index \( \beta \sim -3 \). Its detection is also possible for \( T/S \gtrsim 0.005 \) and \( \beta \sim -3 \), in case a separation of the foreground from the CMB signal could be achieved with an accuracy of \( \sim 5 - 10\% \). For the TE mode, a mask excluding \( |b_{\text{gal}}| \lesssim 5^\circ \) (for \( \beta \sim -3.0 \)) or \( |b_{\text{gal}}| \lesssim 20^\circ \) (for \( \beta \sim -2.8 \)) from the surveys is sufficient to render the foreground contamination negligible, thus confirming the ability of WMAP to have a clear view of the temperature-polarization correlation peak and antipeak series.

Key words. Polarization – Galaxy: general – Cosmology: cosmic microwave background – Methods: data analysis.

1. Introduction

The polarized Galactic diffuse synchrotron radiation is expected to be the major foreground at \( \nu \lesssim 70 \) GHz on intermediate and large angular scales (\( \theta \gtrsim 30^\circ \)) at medium and high Galactic latitudes. At about 1 GHz, the synchrotron emission is the most important radiative mechanism out of the Galactic plane. Consequently, radio frequencies are the natural range for studying it, though it might be affected by Faraday rotation and depolarization. Before the DRAO survey became available, the Leiden polarization surveys (Brouw & Spoelstra 1976) provided a sky coverage, allowing to estimate the Galactic synchrotron APS on intermediate and large scales (La Porta & Burigana 2006). However, these surveys have sparse sampling, low sensitivity, and a good signal-to-noise ratio only for the brightest regions in the sky. A new linear polarization survey of the northern celestial hemisphere at 1.42 GHz with an angular resolution \( \theta_{\text{HPBW}} \approx 36^\prime \) has recently been completed using the DRAO 26 m telescope (Wolleben et al. 2006). The survey has a spacing, \( \theta_s \), of \( 15^\prime \) in right ascension and from 0:25 to 2:5 in declination, which requires interpolation to construct equidistant cylindrical (ECP) maps with \( \theta_{\text{pixel}} = 15^\prime \) (Wolleben 2005). The final map has an rms-noise of about 12 mK, which is unique so far in terms of sensitivity. The polarized intensity map appears cold and patchy at high Galactic latitudes, except for the “North Polar Spur” (NPS), extending far out of the plane at about \( \ell_{\text{gal}} \sim 30^\circ \). We used the polarization data in combination with the Stockert total intensity map at 1.42 GHz (Reich 1982; Reich & Reich 1986), having the same angular resolution, similar sensitivity, and \( \theta_s \approx 15^\prime \), to investigate

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1 The NPS has been extensively studied (see Egger & Aschenbach (1995) and references therein) and is interpreted as the shock front of an evolved local supernova remnant.
the statistical properties of the Galactic diffuse synchrotron emission. The major purpose of the analysis is the comparison of the foreground fluctuation properties with those of the CMB anisotropy field, as drawn in standard cosmologies. Therefore, we described the anisotropy field statistical properties in terms of its angular power spectrum (APS)\(^2\) (see Peebles 1993; Kamionkowski et al. 1997; Zaldarriaga 2001) and adopted HEALPix\(^3\) (Górski et al. 2005) as the tessellation scheme for the sphere. A detailed description of the algorithm to convert the original ECP maps into HEALPix maps was given by La Porta et al. (2005).

2. Selected areas and data analysis

We selected three areas with low polarized intensities (see Fig. 1), which are identified by the following Galactic coordinates: Patch A - 180° ≤ ℓ\(_{\text{gal}}\) ≤ 276°, b\(_{\text{gal}}\) ≥ 45°; Patch B - 193° ≤ ℓ\(_{\text{gal}}\) ≤ 228°, b\(_{\text{gal}}\) ≤ -45°; Patch C - 65° ≤ ℓ\(_{\text{gal}}\) ≤ 180°, b\(_{\text{gal}}\) ≥ 45°. Being interested in the diffuse Galactic synchrotron emission at 1.4 GHz, we subtracted discrete sources (DSs) from the data. We then introduced the quantity |

\[ \ell \]

which will be used in the following best-fit analysis. On

In the case of \( C^T_I \), \( C^E_I \) and \( C^B_I \), the polarization APSs are rather similar. We then introduced the quantity \( C^{E,B}_I \) which is used in the following best-fit analysis. On

Faraday rotation should not be relevant in such sky regions at the investigated angular scales. In fact, rotation measure (RM) maps (Johnston-Hollitt et al. 2004; Dineen & Coles 2005) obtained interpolating RM data of extragalactic sources show very low values in correspondence to such areas. However, the degree of polarization is on average a few percent, well below the maximum theoretical value of ~ 75% (Ginzburg & Syrovatskii 1965). The reason for the low fractional polarization is not clear. One possibility is that due to the contrary, the E and B modes of the primordial CMB anisotropies differ largely as they are induced by different mechanisms (e.g., Seljak & Zaldarriaga 1997; Kosowsky 1999).

2 The angular scale \( \theta \) and the angular power spectrum multipole \( \ell \) are related by \( \ell \sim 180\theta/\theta \). 3 \( \text{http://healpix.jpl.nasa.gov/} \) 4 In particular, \( C^T_I \simeq C^B_I \). We then introduce the quantity \( C^{E,B}_I = 0.5(C^T_I + C^B_I) \), which will be used in the following best-fit analysis.
polarization other than differential depolarization is present (e.g., Sokoloff et al. 1998).

The maps show the Galactic synchrotron emission and non-subtracted DSs convolved with the telescope beam and contaminated by noise. We then fitted the APSs of both total intensity and polarization (namely $C_T^{pl}$, $C_E^{pl}$, and $C_T^{ol}$) by modelling them as $C_\ell = (C_\ell^{\text{synch}} + C_\ell^{\text{err}}) \cdot W_\ell + C_\ell^{\text{WN}} \cdot \sigma_b^2$. We exploited the power law approximation $C_\ell^{\text{synch}} = \kappa \cdot \ell^\alpha$ and assumed a symmetric Gaussian beam, i.e., a window function $W_\ell = e^{-\sigma_b^2/\ell^2}$, where $\sigma_b = \theta_{21} \nu B_{21}$ (rad)/$\sqrt{8} \ln 2$. The contribution of non-subtracted DSs has been simply modelled with a constant term according to the formalism of Poisson fluctuations from extragalactic DSs (Carretti et al. 2006).

Higher resolution data on smaller sky areas (Baccigalupi et al. 2001; Tucci et al. 2004) may imply a presence (or combination) of spurious instrumental polarization at small scales, contaminated by noise. We then fitted the APSs of both total intensity maps and assumed a symmetric HEALPix map and a symmetric HEALPix pixel at a given latitude (for the total intensity maps $\sigma_{\text{pix}} \cdot \sigma_{\text{pix}} \cdot \text{ECP} \cdot N$ being the number of the ECP pixels corresponding to each HEALPix pixel at a given latitude (for the total intensity maps $\sigma_{\text{pix}} \cdot \sigma_{\text{pix}} \cdot \text{ECP} \cdot N$ being the number of the ECP pixels corresponding to each HEALPix pixel at a given latitude (for the total intensity maps $\sigma_{\text{pix}} \cdot \sigma_{\text{pix}} \cdot \text{ECP}$).

The parameter range for the Galactic synchrotron emission APS is $\alpha \sim [-2.71, -2.60]$ for the slope and $\log_{10} \sigma \sim [4.067, 4.339]$ (in mK$^2$) for the amplitude. The DS contribution is in the range $c_{\text{DS}} \sim [0.023, 0.047]$ mK$^2$, which is consistent with the above source counts estimate, within the errors. For polarization, the derived slopes are generally steeper, varying in the interval $\alpha \sim [-3.02, -2.62]$ for $C_E^{pl}$ and $\alpha \sim [-3.05, -2.55]$ for $C_T^{pl}$. The DS contribution is on average much lower than in temperature, since it is compatible with zero.

3. Discussion: implications for CMB observations

We have extrapolated the recovered APS of the $E$ and $B$ modes to 70 GHz and compared it with the APS of the CMB polarization anisotropy for a $\Lambda$CDM model including scalar and tensor perturbations compatible with the recent WMAP 3-yr results (Spergel et al. 2006). The frequency range between 60 GHz and 80 GHz seems the less contaminated by Galactic synchrotron and dust foregrounds in both temperature (Bennett et al. 2003) and polarization (Page et al. 2006) at angular scales $\lesssim 1^\circ$. The accurate measure of the $E$ mode is of particular relevance for breaking the existing degeneracy in cosmological parameter estimation, when only temperature anisotropy data are available (e.g., Bond et al. 1995, Efstathiou & Bond 1999). The detection of the primordial $B$ mode is of fundamental importance for testing the existence of a stochastic cosmological background of gravitational waves (e.g., Knox & Turner 1994). The results of our comparison have been displayed in Fig. 4 for two choices of the temperature spectral index ($\beta \sim 2.8, -3$). The $E$ mode extrapolated from the entire DRAO survey is also shown. It exceeds the CMB $E$ mode even at the peak at $\ell \sim 100$ for $\beta = -2.8$. For $\beta = -3$, the two APSs are almost comparable. Figure 4 also shows the APS extrapolated from the DRAO survey excluding the region $|b_{\text{gal}}| \leq 20^\circ$ and adopting $\beta = -3^\circ$. Such a sky mask reduces the Galactic APS below the CMB $E$ mode for $\ell \gtrsim 50$.

In this case, the CMB $B$ mode peak at $\ell \sim 100$ is comparable to (or exceeds) the synchrotron signal for tensor-to-scalar ratios $T/S \sim 0.5$. For the three patches and $T/S \gtrsim 0.5$, the cosmological $B$ mode peak at $\ell \sim 100$ is comparable to (or exceeds) the Galactic synchrotron signal extrapolated with $\beta \sim 2.8$, while it is larger by a factor $\sim 2$ in terms of $\sqrt{\ell}$ for $\beta \sim -3$. Furthermore, a separation of the Galactic synchrotron polarized signal from the CMB one with a $5 - 10\%$ accuracy (in terms of $\sqrt{\ell}$) would allow to detect the CMB $B$ mode peak at $\ell \sim 100$ even for $T/S \sim 0.005$ if $\beta \sim -3$. Similar results for the detection of the $B$ mode peak at $\ell \sim 100$ have been inferred from 1.4 GHz polarization observations of a small region with exceptionally low Galactic foreground contamination (Carretti et al. 2006), though at $\ell \sim$ few$\times$100 the CMB $B$ mode is expected to be dominated by the $B$ mode generated by lensing (Zaldarriaga & Seljak 1998). Finally, we note that for a sky coverage comparable with those of the considered patches ($\sim 3\%$), the cosmic and sampling variance does not significantly limit the accuracy of the CMB mode recovery at $\ell$ larger than some tens.

The CMB $T/E$ correlation constrains the reionization history from the power at low multipoles and the nature of primordial fluctuations from the series of peaks and antipeaks (e.g., Kogut 2003; Page et al. 2006). In Fig. 5 we compare the $T/E$ mode APS of the Galactic emission extrapolated to 70 GHz with the CMB one. The APS of the whole DRAO survey indicates a significant Galactic contamination at $\ell \lesssim 50$ GHz, $\beta \sim -3$ or $|b_{\text{gal}}| \leq 20^\circ$ for $\beta \sim -2.8$.

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5 The bulk of the factor $\sim 2$ of discrepancy between the value of $\sigma_{\text{pix}}$ recovered by our fit and that predicted from best-fit number counts can in fact be produced by the survey sky sampling ($\theta_{21}$) of 15'. For example, considering a lower limit corresponding to $\sim 15' / \sqrt{2}$ (instead of 0) in the integral over $\psi$ in Eq. (2) of Toffolatti et al. (1998), $c_{\text{pix}}$ decreases by a factor $\sim 1.53$.

6 The best-fit results may suggest a polarization degree (obtained considering the contribution of the subtracted DSs, $\sim 0.05 - 0.2$ mK$^2$, to the temperature APS) considerably higher than $\sim 2\%$, the value found for NVSS extragalactic (mainly steep spectrum) sources (Mesa et al. 2002; Tucci et al. 2004). It may imply a presence (or a combination) of spurious instrumental polarization at small scales, of a significant contribution from highly polarized Galactic sources (Manchester et al. 1999) non-subtracted in the maps, or of a flattening of the diffuse synchrotron polarized emission APS at $\ell \gtrsim 200 - 250$ in higher resolution data on smaller sky areas (Baccigalupi et al. 2001; Carretti et al. 2006).

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7 We used the CMBFAST code (version 4.5.1) for the computation of the CMB APS (http://www.cmbfast.org/).

8 http://lambda.gsfc.nasa.gov/

9 This APS is consistent with the WMAP foreground polarization APS at 63 GHz (see Fig. 17 in Page et al. 2006), thus supporting an effective 1.4 – 70 GHz polarization spectral index $\beta \sim -3$ far out of the Galactic plane.
greatly reduces the Galactic foreground contamination even at low multipoles. For the three cold patches, the Galactic $TE$ mode is negligible compared to the CMB one, independently of the adopted $\beta$. The $TE$ mode antipeak at $\ell \approx 150$ turns out to be very weakly affected by Galactic synchrotron contamination in all cases.

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Fig. 4. Comparison between the $E$ and $B$ modes of the CMB anisotropy at 70 GHz and of the Galactic polarized synchrotron foreground. Dotted and solid lines: CMB $E$ and $B$ mode for two different tensor-to-scalar ratios (thin line $T/S = 0.005$, thick line $T/S = 0.5$). Dashed lines: uncertainty associated with the cosmic and sampling variance for a sky coverage of $\sim 3\%$ and a binning of $10\%$ in $\ell$. Three dots-dashes: average of the $E$ and $B$ modes extrapolated from the whole DRAO survey for spectral indices $\beta = -2.8$ and $-3$, respectively. The anafast results have been divided by the window function to correct for beam smoothing. Thick long dashed line: the same as above, but with a mask at $|b| < 20$ for $\beta = -3$. Dashed (dot-dashed) power law: best-fit result corresponding to Patch B (resp. C), rescaled in frequency as above. The results are here in terms of thermodynamic temperature.

Fig. 5. Comparison between the $TE$ modes of the CMB anisotropy and the Galactic diffuse emission. Solid lines: CMB $TE$ mode with $T/S = 0.005$ (thick solid line) and corresponding cosmic variance (region between the thin solid lines), assuming all sky coverage and without binning in $\ell$. Dots: extrapolated DRAO $TE$ mode for a spectral index $\beta = -3$. Dashes (dot-dashes): as above, but masking the region at $|b| > 5^\circ$ and adopting $\beta = -2.8$ ($\beta = -3$). Three dots-dashes: as above, but excluding the region at $|b| > 20^\circ$ ($\beta = -2.8$). Top and bottom panels are identical, but with a different choice of the multipole and power range, for a better view of the results.

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