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A Template of Galactic Polarized Synchrotron Emission in the Frame of CMBP Experiments

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Abstract. We present a method to model the polarized Galactic synchrotron emission in the microwave range (20–100 GHz), where this radiation is expected to play the leading role in contaminating Cosmic Microwave Background (CMB) data. Our method is based on real surveys and aims at providing the real spatial distributions of both polarized intensity and polarization angles. Its main features are the modelling of a polarization horizon to determine the polarized intensity and the use of starlight optical data to model the polarization angle pattern. Our template is virtually free of Faraday rotation effects as required at cosmological window frequencies.

1 Introduction

Recent DASI (Kovac et al. 2002) and WMAP measurements (Kogut et al. 2003) of the Cosmic Microwave Background Polarization (CMBP) highlighted the importance of studying the polarized emission of foregrounds. In fact, a sound measurement of CMBP requires good knowledge of polarized foregrounds (both Galactic and extragalactic) which are potentially more dangerous than in total intensity.

Among the polarized foreground components, the Galactic synchrotron radiation is expected to be the most relevant up to 100 GHz. In spite of its importance, synchrotron emission is scarcely surveyed: existing data mainly cover the Galactic Plane area at frequencies up to 2.7 GHz (Duncan et al. 1997; Duncan et al. 1999; Uyaniker et al. 1999; Gaensler et al. 2001; Landecker et al. 2002), far away from the 30–150 GHz frequency band which is usually considered as the cosmological window. Only the Leiden data (Brouw & Spoelstra 1976) cover high Galactic latitudes, but are limited to < 1.4 GHz and are largely undersampled.

This lack of data both in the CMB frequency range and at high Galactic latitudes can be partially recovered by building templates of the synchrotron polarized emission. Template maps would allow reliable numerical simulations to set–up and test destriping techniques as well as foreground separation methods (Revenu et al. 2000; Sbarra et al. 2003; Tegmark et al. 2000 and references therein) and could substantially help to clean CMB maps from foreground contamination (e.g. see Bennett et al. 2003).

Here we summarize the approach to model the Galactic polarized synchrotron emission in the 20–100 GHz range fully described in Bernardi et al. (2003). The method is based on real surveys and fitted to the real spatial distribution of both polarized intensity and polarization angles. Low–frequency data are used to model the polarized intensity, and optical starlight is used to model polarization angles. This allows the construction of Q and U maps covering about half of the sky with the SPOrt experiment (Cortiglioni et al. 2003) angular resolution (FWHM = 7°).

The great advantage of this approach is to produce Q and U maps free from Faraday rotation, allowing a direct extrapolation to the cosmological window.

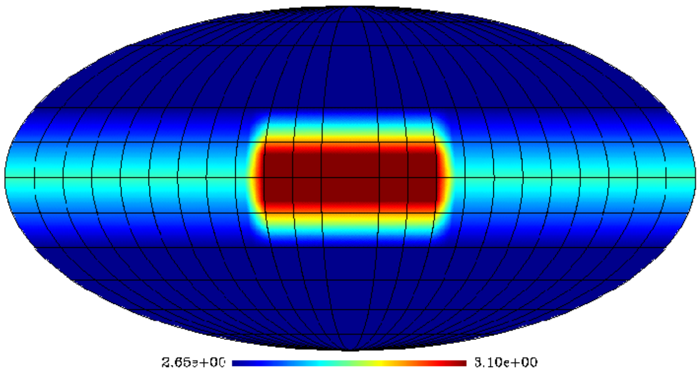


Fig. 1. Synchrotron spectral index map in the 0.408–1.4 GHz range. A steep $\beta = 3.1$ spectral index is observed towards the Galactic centre, a moderately steep spectrum ($\beta = 2.8$) relies on the Galactic Plane and a flatter one ($\beta = 2.65$) at high Galactic latitude.

2 The Model

To generate Q and U template maps of the Galactic synchrotron polarized radiation in the 20–100 GHz range, we need two ingredients:

1. a polarized intensity (I_p) map which can be obtained from existing total intensity (I) sky surveys assuming a model to link the polarized to the total intensity synchrotron emission after cleaning the free–free component;
2. a polarization angle map not affected by Faraday rotation.

The first requirement can be fulfilled by using the 0.408 GHz Haslam et al. map (Haslam et al. 1982) and the 1.4 GHz Reich map (Reich 1982; Reich & Reich 1986) to provide a pure total–intensity synchrotron map clean from free–free emission. Such emission is not negligible in low–frequency data, in particular in the Galactic Plane (see also Reich & Reich 1998) and must be subtracted off.

The second requirement can be fulfilled by using the Heiles starlight polarization catalogue (Heiles 2000), starlight data being virtually free of Faraday rotation. A complete polarization angle map can be obtained interpolating the sparse starlight data.

2.1 The Polarized Intensity Map

Free–free subtraction from the low–frequency radio surveys is performed by applying a modified Dodelson (1997) technique which takes into account the different spectral behaviours of synchrotron and free–free radiations.

In the Dodelson formalism a scalar product is defined for vectors, whose normalization is based on the CMB shape (see Dodelson (1997) for details). We modify it by using the free–free shape.

The subtraction procedure requires the knowledge of the synchrotron and free–free spectral indices. For the latter we adopt $\beta = 2.1$ (Reich & Reich 1988), whereas for the synchrotron radiation we derive a simple model for its spatial variation based on the Reich & Reich (1988) analysis (Figure 1).

The separation procedure results in a pure total intensity synchrotron map which can be converted into a polarized intensity map providing a relation between total and polarized intensities.

We assume the existence of a *polarization horizon* (Duncan et al. 1997; Duncan et al. 1999; Landecker et al. 2002; Gaensler et al. 2001), that is a sort of bubble centred in the observer position: the observed polarized signal comes from integration along the line of sight out to the horizon, whereas the signal beyond it is depolarized by variations of polarization angles (changes in the Galactic magnetic field). The size of the horizon is not yet known: it depends on several effects along the line of sight, like Galactic magnetic field turbulence and electron density variations. However, it has been suggested that it may range from 2 kpc (Gaensler et al. 2001) up to 7 kpc (Duncan et al. 1997; Landecker et al. 2002), so that a few kpc appear to be an acceptable estimate.

This polarization horizon allows us to model the relation between polarized and total intensity synchrotron emission. Given the mean total synchrotron emissivity $J^s(\nu, l, b)$ at Galactic coordinates (l, b) as well as the thickness $L(l, b)$ of the synchrotron emitting region in the same direction, the brightness temperature $T^s(\nu, l, b)$ at frequency ν is:

$$T^s(\nu, l, b) = \frac{c^2}{2K\nu^2} J^s(\nu, l, b)\, L(l, b)\ , \tag{1}$$

where K is the Boltzmann constant. The thickness $L(l, b)$ depends on the geometrical model describing the space distribution of the relativistic–electron gas responsible for synchrotron emission. We consider the simplest case where the gas is uniformly distributed in the Galactic halo represented by a sphere of radius $R = 15$ kpc centred into the Galactic Centre (GC). Thus the thickness $L(l, b)$ is the distance between the Sun and the edge of this sphere:

$$L(l, b) = d\,\cos(b)\,\cos(l)\left[1 + \sqrt{1 + \frac{(R^2/d^2 - 1)}{\cos^2(b)\,\cos^2(l)}}\right]\ , \tag{2}$$

where $d = 9$ kpc is the Sun's distance from the GC (see Bernardi et al. (2003) for details).

Similarly, the polarized brightness temperature T_p^s can be defined provided the emission is integrated out to the polarization horizon R_{ph} and a polarization degree p is introduced:

$$T_p^s(\nu, l, b) = \frac{c^2}{2K\nu^2}\, p\, J^s(\nu, l, b)\, R_{ph}\ . \tag{3}$$

Finally, equations (1) and (3) provide the relation between polarized and total intesity emissions:

$$T_p^s(\nu, l, b) = p\frac{R_{ph}}{L(l, b)} T^s(\nu, l, b)\ . \tag{4}$$

The quantity $p\, R_{ph}$ is unknown and represents a free parameter to be calibrated with real data.

2.2 Polarization Angle Map

Since at microwave frequencies Faraday rotation effects become negligible (Bernardi et al. 2003), the distribution of polarization angles cannot be derived directly from existing low–frequency radio surveys due to the presence of a relevant amount of Faraday rotation.

Brown & Taylor (2001) estimate a typical Rotation Measure (RM) of the Galactic Plane as RM $= -183 \pm 14\ \cos(l - 84° \pm 4°)$ rad m^{-2}, which means that the polarization angle can be rotated up to $|160°|$ at 2.7 GHz, which is the survey with the highest frequency available (Duncan et al. 1999).

To overcome this problem we use the Heiles catalogue of starlight polarization, the optical frequencies being unaffected by Faraday rotation. The polarization vector of starlight is parallel to the Galactic magnetic field $\mathbf{B}$ because of selective absorption by interstellar dust grains, whose minor axis is aligned with $\mathbf{B}$ (Fosalba et al. 2001). Since the synchrotron polarization vector is perpendicular to $\mathbf{B}$, starlight polarization angles can be used as a template for polarization angles provided a 90° rotation is performed. Also, starlight polarization has the great advantage of sampling the high Galactic latitude regions not present in low–frequency polarization surveys.

Most of the Heiles catalogue stars ($\simeq 87\%$) are within 2 kpc, tracking the local magnetic field. Their distance is of the order of the polarization horizon size, confirming that the Heiles catalogue can be safely used as a template for the polarization angles of synchrotron emission.

Since starlight polarization angles are irregularly distributed (Figure 2), we fill data holes by linear interpolation. We perform the interpolation by generating Q, U pairs corresponding to the Heiles polarization angles θ:

$$Q_\theta = \cos(2\theta) \qquad U_\theta = \sin(2\theta). \tag{5}$$

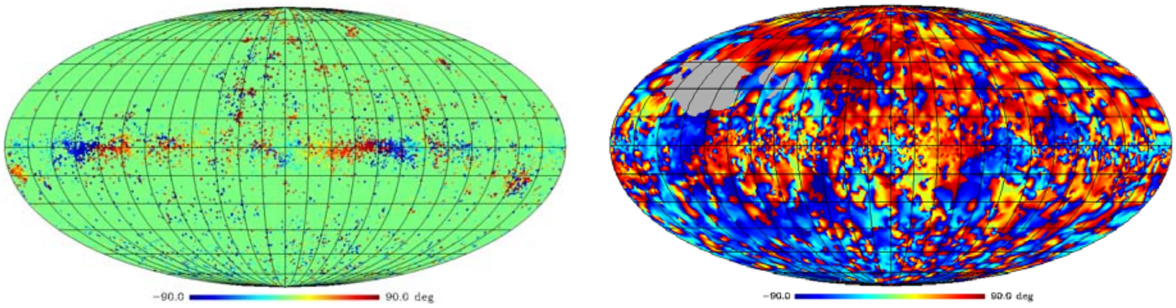


Fig. 2. Left: Map of starlight polarization angles. Right: Interpolated map of starlight polarization angles.

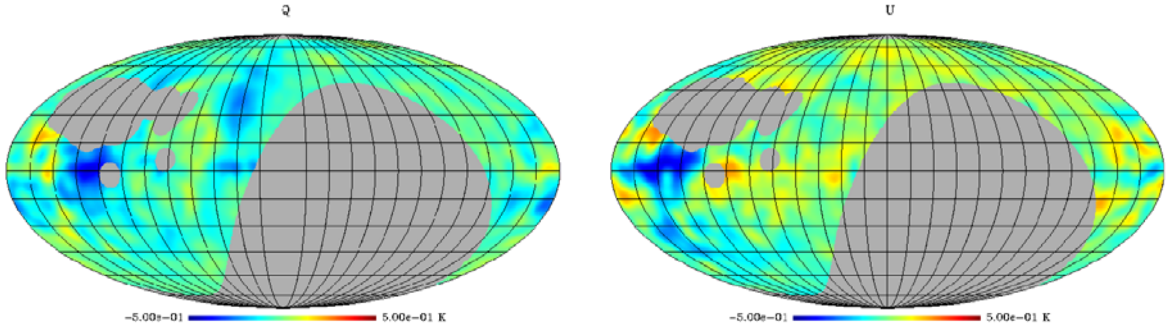


Fig. 3. Left: Template map of the Stokes parameter Q at 1.4 GHz with a 7° resolution. Right: The same but for the Stokes parameter U.

Then, for each pixel of the template map to be built we linearly interpolate the Q_θ and U_θ values of the three closest stars and compute the corresponding polarization angle; the interpolated map is shown in Figure 2. The interpolation method uses parallel transport as described in Bruscoli et al. (2002).

3 Results

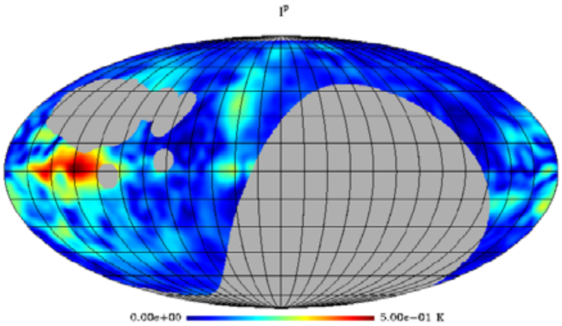
Our results are shown in Figure 3, where the Q and U templates at 1.4 GHz are presented. Figure 4 shows a comparison between the polarized intensity I_p of our model and the I_p map obtained from the Brouw & Spoelstra (1976) data. The comparison is done only for I_p because polarization angles are strongly affected by Faraday rotation at 1.4 GHz. Our template is able to reproduce the basic and brightest structures in the Brouw & Spoelstra (1976) data like the *Fan region* and the North Galactic Spur, though the latter is fainter than in real data.

The good agreement between the map obtained from the Brouw & Spoelstra (1976) data and our model allows us to calibrate the parameter $p\,R_{ph}$ by matching the I_p emission of the two maps in a well defined area. We use the Fan region, the most defined and morphologically similar area in both maps. The calibration uses the 820 MHz Brouw & Spoelstra (1976) data (see Figure 2 in Bruscoli et al. 2002) rather than those at 1.4 GHz, because of their better sampling, providing

$$p\,R_{ph} = 0.9 \pm 0.09 \text{ kpc} . \qquad (6)$$

Assuming the polarization degree p on 7° scales is in the range $\sim$ 0.15–0.3 (Tegmark et al. 2000) we obtain for the polarization horizon $3\,\text{kpc} < R_{ph} < 6\,\text{kpc}$, in good agreement with present estimates (Duncan et al. 1997; Gaensler et al. 2001; Landecker et al. 2002).

We extrapolate the Q and U templates at 1.4 GHz to the cosmological window, and in particular to the frequencies of 22, 32, 60 and 90 GHz which are of interest for the SPOrt experiment. We use a power law with the mean synchrotron spectral index $\beta = 3.0$ found by Platania et al. (1997) in the



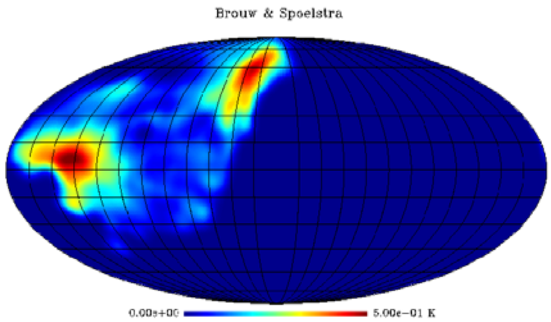


Fig. 4. Left: Template map of the polarized intensity I_p at 1.4 GHz with 7° resolution. Right: Map of the polarized intensity I_p at 1.4 GHz obtained from the Brouw & Spoelstra data and convolved with a FWHM = 7° Gaussian beam.

Table 1. Peak emission (*Fan region*) and $P_{\rm rms}$ of our template at the four SPOrt frequencies. The $P_{\rm rms}$ is computed on the low emission areas (the faintest 50% pixels).

ν (GHz)	$I_{p,\max}$ (μK)	$P_{\rm rms}$(μK)
1.4	5×10^5	6.6×10^4
22	130	17
32	43	5.6
60	6.5	0.84
90	1.9	0.25

1–19 GHz range. In Table 1 we report the emission of the most important structure (the Fan region) and the mean polarization level $P_{\rm rms} = \sqrt{\langle Q^2 \rangle + \langle U^2 \rangle}$ of the low–emission areas (the faintest 50% pixels) for all the SPOrt frequencies.

4 Conclusions

We have presented a method to build template maps of the polarized Galactic synchrotron emission free from Faraday rotation effects, which can be safely extrapolated to the cosmological–window frequency range. Differing from previous spatial models (Giardino et al. 2002; Kogut & Hinshaw 2000), our template is intended to provide the real spatial distribution of both polarized intensity and polarization angles. Most previous work adopted a complementary approach based on angular frequency rather than real space (Tucci et al. 2000, 2002; Baccigalupi et al. 2001; Giardino et al. 2002; Bruscoli et al. 2002) where the angular power spectra of the polarized synchrotron foreground were computed for low–frequency data and then extrapolated to high frequency. Such extrapolation is not trivial due to Faraday rotation, affecting low–frequency data and being negligible in the cosmological window.

The template developed here is intended to overcome such a problem: polarization angular spectra in the cosmological window should be computed on the spatial template rather than simply extrapolated from the direct analysis of low–frequency maps.

Template maps obtained with the present method still suffer from the uncertainties in the extrapolation due to our ignorance of the synchrotron spectrum. In order to minimize such uncertainties, template maps of the synchrotron polarized emission should be directly at microwave frequencies, as is now possible thanks to WMAP latest total intensity maps (Bennett et al. 2003). Such a work is the subject of a forthcoming paper (Bernardi et al. 2004).

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