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The large-scale polarization of the microwave foreground

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Abstract

Most of the useful information about inflationary gravitational waves and reionization is on large angular scales where Galactic foreground contamination is the worst, so a key challenge is to model, quantify and remove polarized foregrounds. We use the Leiden radio surveys to quantify the polarized synchrotron radiation at large angular scales, which is likely to be the most challenging polarized contaminant for the WMAP satellite. We find that the synchrotron *E*- and *B*-contributions are equal to within 10% from 408–820 MHz with a hint of *E*-domination at higher frequencies. We quantify Faraday rotation and depolarization effects and show that they cause the synchrotron polarization percentage to drop both towards lower frequencies and towards lower multipoles.

1. Introduction

CMB polarization and its decomposition into *E* and *B* modes is a topic of growing importance and interest in cosmology (Zaldarriaga, 2003). In the era of WMAP (Bennett et al., 2003a), a key issue is to estimate the contribution of Galactic foregrounds (more specifically, polarized synchrotron emission) at the large angular scales. Unfortunately, these large scales are also the ones where polarized foreground contamination is likely to be most severe, both because of the red power spectra of diffuse Galactic synchrotron and dust emission and because they require using a large fraction of the sky, including less clean patches. The key challenge in the CMB polarization endeavor will therefore be modeling, quantifying and removing large-scale polarized Galactic foregrounds.

Unfortunately, we still know basically nothing about the polarized contribution of the Galactic synchrotron component at CMB frequencies (Tegmark et al., 2000; Tucci et al., 2000; Baccigalupi et al., 2000; Burigana and La Porta, 2002; Bruscoli et al., 2002; Tucci et al., 2002; Giardino et al., 2002), since it has only been measured at lower frequencies and extrapolation is complicated by Faraday rotation. This is in stark contrast to

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the CMB itself, where the expected polarized power spectra and their dependence on cosmological parameters has been computed from first principles to high accuracy (Kamionkowski et al., 1997; Zaldarriaga and Seljak, 1997; Zaldarriaga, 1998; Hu and White, 1997).

This is the topic of the present proceeding. We will employ polarization sensitive radio surveys to further quantify the polarized synchrotron radiation, which is likely to be the most challenging contaminant in the polarization maps expected from the WMAP satellite (Bennett et al., 2003b; Kogut et al., 2003). This proceeding is organized as follows: in Section 2, we review the basics of the synchrotron emission, as well the problems involved with extrapolations from lower to higher frequencies. We present our results as well as discuss our conclusions in Section 3. For more details about this analysis consulte (de Oliveira-Costa et al., 2002a).

2. Our knowledge of synchrotron emission

The Galactic InterStellar Medium (ISM) is a highly complex medium with many different constituents interacting through a multitude of physical processes. Free electrons spiraling around the Galactic magnetic field lines emit synchrotron radiation (Rybicki and Lightman, 1979), which can be up to 70% linearly polarized (see Davies and Wilkinson, 1998; Smoot, 1999 for a review).

The power spectrum C_ℓ of synchrotron radiation is normally modeled as a power law in both multipole ℓ and frequency ν, which we will parametrize as

$$\delta T_\ell^2(\nu) = A\left(\frac{\ell}{50}\right)^{\beta+2} \quad \text{with } A \propto \nu^{2\alpha}, \qquad (1)$$

where $\delta T_\ell \equiv [\ell(\ell+1)C_\ell/2\pi]^{1/2}$. This definition implies that $C_\ell \propto \ell^\beta$ for $\ell \gg 1$ and that the fluctuation amplitude $\propto \nu^\alpha$. The standard assumption is that the unpolarized intensity has $\alpha \approx -2.8$ with variations of order 0.15 across the sky (Platania et al., 1998) – see also (Banday and Wolfendale, 1991; Jonas, 1999; Roger et al., 1999).

As to the power spectrum slope β, the 408 MHz Haslam map (Haslam et al., 1981, 1982) suggests β of order -2.5 to -3.0 down to its resolution limit of $\sim 1^\circ$ (Tegmark and Efstathiou, 1996; Bouchet et al., 1996; Bouchet and Gispert, 1999; de Oliveira-Costa et al., 2002b). A similar analysis done on the 2.3 GHz Rhodes map of resolution $20'$ (Jonas, 1999) gives $\beta = -2.92 \pm 0.07$ (Giardino et al., 2001) (flattening to $\beta \approx -2.4$ at low Galactic latitudes – Giardino et al., 2002).

For the polarized synchrotron component, our observational knowledge is, unfortunately, not as complete. To date, there are measurements of the polarized synchrotron power spectrum obtained basically from three different surveys (Reich et al., 2001): the Leiden surveys (Brouw and Spoelstra, 1976; Spoelstra, 1984), the Parkes 2.4 GHz Survey of the Southern Galactic Plane (Duncan et al., 1995, 1997), and the Medium Galactic Latitude Survey (Uyaniker et al., 1999a,b; Duncan et al., 1999). These measurements exhibit a much bluer power spectrum in polarization than in intensity, with β in the range from 1.4 to 1.8 (Tegmark et al., 2000; Tucci et al., 2000; Baccigalupi et al., 2000; Burigana and La Porta, 2002; Bruscoli et al., 2002; Tucci et al., 2002; Giardino et al., 2002). These results are usually taken with a grain of salt when it comes to their implications for CMB foreground contamination, for three reasons:

1. Extrapolations are done from low to high latitudes.
2. Extrapolations are done from low to high frequencies.
3. Much of the available data is undersampled.

The Leiden surveys extend to high Galactic latitudes and up to 1.4 GHz but are unfortunately undersampled, while the Parkes and the Medium Galactic Latitude Surveys only probe regions around the Galactic plane – see (de Oliveira-Costa et al., 2002a) for more details. In the following three subsections, we will discuss these three problems in turn.

2.1. The latitude extrapolation problem

There is a well-known empirical result that shows that whereas the unpolarized synchrotron emission (at MHz range) depends strongly on the Galactic latitude, the polarized component is approximately independent of Galactic latitude (see, e.g., Duncan et al., 1997). The usual interpretation for this very weak latitude dependence of polarized synchrotron radiation is that the signal is dominated by sources that are nearby compared to the scale height of the Galactic disk, with more distant sources being washed out by depolarization (to which we return in the next subsection). As a result, having well-sampled polarized maps off the galactic plane at the same frequencies would not be expected to affect our results much, since they would be similar to those in the plane. This issue, however, deserves more work as far as extrapolation to CMB frequencies is concerned: the latitude dependence may well return at higher frequencies as depolarization becomes less important, thereby revealing structure from more distant parts of the Galactic plane. In this case, extrapolating from an observing region around the Galactic plane to higher latitudes may well result in less small-scale power in the angular distribution.

2.2. Frequency extrapolation problem

It is important to point out, that Faraday rotation (see, e.g., Sokoloff et al., 1998) can only change the polarization angle and not the polarized intensity P ($P = \sqrt{Q^2 + U^2}$). The fact that we do see structure in P that is not correlated with a counterpart in intensity T implies that part of the radiation has been depolarized (Wieringa et al., 1993). Depending on the frequency and beamwidth used, depolarization can play an important role in polarization studies of the Galactic radio emission (Spoelstra, 1984) – for more details, see Cortiglioni and Spoelstra (1995). Because of the complicated interplay of these mechanisms, we should expect both the amplitude and the shape of the polarized synchrotron power spectrum to change with frequency.

2.3. Incomplete sky coverage and the undersampling problem

For the case of undersampling in the Leiden surveys, some authors have overcome this problem by doing their Fourier analysis over selected patches in the sky where they believe the average grid space in the patch is close to the map's beam size, so that they can apply a Gaussian smoothing on it – this is well explained and illustrated in (Bruscoli et al., 2002). Fortunately, we can eliminate this problem by measuring the power spectra with the matrix-based quadratic estimator technique that has recently been developed for analyzing CMB maps (Bond et al., 2000; Tegmark and de Oliveira-Costa, 2001; de Oliveira-Costa et al., 2002c). Although the undersampling and partial sky coverage results in unavoidable mixing between different angular scales ℓ and polarization types (E and B), this mixing (a.k.a. *leakage*) is fully quantified by the window functions that our method computes (Tegmark and de Oliveira-Costa, 2001) and can therefore be included in the statistical analysis without approximations. Specifically, we compute the six power spectra ($C_\ell^T \equiv T, C_\ell^E \equiv E, C_\ell^B \equiv B, C_\ell^{TE} \equiv X, C_\ell^{TB} \equiv Y, C_\ell^{EB} \equiv Z$) so that the much discussed (Tegmark and de Oliveira-Costa, 2001; Zaldarriaga, 1998; Jaffe et al., 2000; Zaldarriaga, 2001; Lewis et al., 2002; Bunn, 2001; Bunn et al., 2002) $E - B$ leakage is minimal (de Oliveira-Costa et al., 2002c).

3. Results and conclusions

We employed only the Leiden surveys (Brouw and Spoelstra, 1976; Spoelstra, 1984) for our analysis. The observations done by Brouw and Spoelstra covered almost 40% of the sky extending to high Galactic latitudes. Using the same instrument, they observed the polarized Galaxy in Q and U in five frequencies from 408 MHz up to 1.4 GHz and with angular resolutions from 2.3° at 408 MHz up to 0.6° at 1.4 GHz. Unfortunately this data were also undersampled, making it difficult to draw inferences about its polarized power spectrum.

Using matrix-based quadratic estimator methods (Tegmark and de Oliveira-Costa, 2001; de Oliveira-Costa et al., 2002c), we measure the power spectra from the Leiden surveys, obtaining the following key results:

1. Our analysis was performed using 10 multipole bands of width $\Delta\ell = 10$ for each of the six polarization types (T, E, B, X, Y, Z), thereby going

out to $\ell = 100$. We used the Haslam map for the unpolarized component T, scaled and smoothed to match Leiden's five different frequencies, and assuming a $|b| = 25°$ Galactic cut. The best fit normalizations A and slopes β for E and B are shown in Table 1. The values of β are consistent with previous analyses (Tegmark et al., 2000; Tucci et al., 2000; Baccigalupi et al., 2000; Burigana and La Porta, 2002; Bruscoli et al., 2002; Tucci et al., 2002; Giardino et al., 2002), showing that the slopes get redder as frequency increases. For all Leiden surveys, the X and Y power spectra are found to be consistent with zero – the 2.4 GHz Parkes survey had a similar finding for X (Giardino et al., 2002). These are not surprising results: if Faraday rotation makes the polarized and unpolarized components to be uncorrelated, it is natural to expect that $X, Y = 0$. However, at the CMB frequencies (where the effects of Faraday rotation and depolarization are unimportant) this should not be the case.

2. To study the frequency dependence, we average the 10 multipole bands of the Leiden power spectrum measurements together into a single band for each polarization type to reduce noise. From these results, we fit the average frequency dependence (for the 25° cut data) as a power law as in Eq. (1) with slope $\alpha_E = -1.3$ and $\alpha_B = -1.5$ for E- and B-polarization, respectively.
3. An interesting question about polarized foregrounds is how their fluctuations separate into E and B. Although many authors initially assumed that foregrounds would naturally produce equal amounts of E and B, Zaldarriaga (Zaldarriaga, 2001) showed that this need not be the case. Early studies (Baccigalupi et al., 2000; Giardino et al., 2002) have indicated that $E \approx B$ at 2.4 GHz in the Galactic plane. However, these analyses used Fourier transforms and spin-2 angular harmonic expansions, respectively, without explicitly computing the window functions quantifying the leakage between E and B. We therefore perform a likelihood analysis of the Leiden surveys specifically focusing on this question, and including an exact treatment of the leakage. Thelikelihood analysis of the data is done with two free parameters corresponding to the overall normalization of the E and B power spectra, and assuming that they both have the same power law shape given by the slopes β_E from Table 1. We obtain that the synchrotron E- and B-contributions are equal to within 10% from 408 to 820 MHz, with a hint of E-domination at higher frequencies. One interpretation is that $E > B$ at CMB frequencies but that Faraday Rotation mixes the two at low frequencies.
4. Faraday rotation and depolarization effects depend not only on frequency but also on angular scale – they are important at low frequencies ($\nu \lesssim 10$ GHz) and on large angular scales. Therefore, we must take into account Faraday rotation and depolarization effects when extrapolating radio survey results from low to high galactic latitudes and from low to high frequencies.
5. We detect no significant synchrotron X cross correlation, but Faraday Rotation could have hidden a substantial correlation detectable at CMB frequencies.
6. Combining the POLAR (Keating et al., 2002; O'Dell et al., 2002; de Oliveira-Costa et al., 2002a) and radio frequency results, and the fact that the E-polarization of the abundant Haslam signal in the POLAR region is not detected at 30 GHz, suggests that the synchrotron polarization percentage p at CMB frequencies is rather low ($p < 20\%$).

Experiments such as polarized WMAP and Planck will shed significant new light on synchrotron polarization and allow better quantification of its impact both on these experiments and on ground-based CMB observations.

Table 1
Normalization and spectral index[a]

ν (GHz)	A_E (mK^2)	β_E	A_B (mK^2)	β_B
0.408	5.5	−0.5	5.7	−0.4
0.465	5.4	−1.0	5.4	−0.5
0.610	5.1	−1.0	5.1	−0.8
0.820	4.5	−1.5	4.6	−1.8
1.411	3.9	−1.9	3.6	−2.6

[a] All fits are normalized at $\ell = 50$, i.e., $\delta T_\ell^2 = A(\ell/50)^{\beta+2}$.

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