Observations in the BOOMERanG Field at 1.4 GHz

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Abstract. The synchrotron emission is expected to be the most important Galactic foreground noise for measurements of the polarization of the Cosmic Microwave Background (CMBP) and the identification of sky areas with low polarized emission by this contaminant is crucial. Observations at low radio frequencies allow both the definition of target regions for deep observations and the estimate of the residual contamination in the frequency range typical of CMBP experiments (30–150 GHz). We present the first observation of the diffuse polarized synchrotron radiation of a patch (about $3\times3^\circ$) in the BOOMERanG field, one of the areas with the lowest foreground emission in total intensity. The work has been carried out with the Australia Telescope Compact Array at 1.4 GHz with 3\'4 resolution. The mean polarized signal has been found to be $I_{\text{rms}} = \sqrt{(Q_{\text{rms}}^2 + U_{\text{rms}}^2)} = 11.6 \pm 0.6 \text{ mK}$, nearly one order of magnitude below that in the Galactic Plane. Extrapolations to frequencies of interest for cosmological investigations suggest that the detection of the CMBP E-mode should be accessible with no relevant foreground contamination at 90 GHz and even the B-mode detection for $T/S > 0.01$ is not ruled out.

1 CMBP and Foreground Contamination

Most of the information we have about the formation and the evolution of the Universe come from Cosmic Microwave Background (CMB) features like anisotropy and polarization. While the anisotropy has been extensively studied by both space (COBE-DMR, WMAP and the planned PLANCK) and ground experiments (BOOMERanG, MAXIMA and DASI among others), the investigation of the polarization is just at the beginning with the first detections of DASI (E-mode signal, Kovac et al. 2002) and WMAP (temperature–E-mode cross-spectrum $C_{\text{TE}}$, Kogut et al. 2003) and still far from a full characterization.

Fig. 1. Left: CMB anisotropy ($C_T$) and E-mode polarization ($C_E$) angular power spectra for a few values of the optical depth $\tau$ to the CMB of the re-ionized medium. The other cosmological parameters are those of the Concordance Model as from WMAP data (Spergel et al. 2003). Right: B-mode power spectrum of the same model for a tensor to scalar perturbation power ratio $T/S = 0.033$. $\tau$ is set to the WMAP best-fit value (Kogut et al. 2003)
The Polarization of the CMB (CMBP) brings us new information with respect to the anisotropy on both large and small angular scales. On large angular scales (multipoles $\ell < 10$), the multipole–angular-scale relation being $\theta = 180^\circ / \ell$, the Angular Power Spectrum (APS) of CMBP is highly sensitive to the presence of a re-ionized medium at the epoch of formation of the first stars and galaxies (Figure 1), and provides information on both the epoch of formation of the first structures and the re-ionization history of the Universe.

On sub-degree scales ($\ell = 200–1500$) the inflationary frame predicts a well-defined peak pattern of the $E$-mode APS, with minima corresponding to maxima of anisotropy and reverse, and a precise measurement of this pattern would be an important check of the Inflation paradigm (Kosowsky 1999).

In addition, the tensorial perturbations of the gravitational wave background generated by Inflation grows up the faint $B$-mode (Figure 1) giving us the exciting possibility to make a direct measurement of the energy density of the Universe when Inflation occurred (Kamionkowski & Kosowsky 1998).

In spite of its importance the CMBP signal is faint, especially the $B$-mode expected to be two–three (or more) orders of magnitude weaker than the $E$-mode, depending on the value of the tensor to scalar perturbation power ratio $T/S$. This calls for searching the CMPB emission in sky regions as free as possible from Galactic foreground contamination.

Among the several components of this foreground noise (synchrotron, free-free, thermal and spinning dust), the free-free emission is expected to be practically unpolarized and hence not relevant, while the spinning dust seems to be ruled out by WMAP results (Bennett et al. 2003). The synchrotron emission is thus expected to be the dominant foreground disturbance up to $\sim 100$ GHz (see Figure 2) and its study and characterization are mandatory to allow a reliable measurement of CMBP.

![Fig. 2. Polarized emission estimates for the main Galactic foregrounds. The synchrotron component has been normalized to the WMAP results at 23 GHz (Bennett et al. 2003) and assuming 20% polarization. The spectral index is $\beta = -3.2$ as provided by Bennett et. (2003) between 23 and 41 GHz. The thermal dust is modelled with the shape and normalization provided by WMAP data and assuming 1% polarization of the MID model of Tegmark et al. (2000). Finally, for the spinning dust we consider the upper limit provided by WMAP ($< 5\%$ of the total foreground emission at 33 GHz) and assuming the shape and the polarization degree (5%) of Tegmark et al. (2000). CMBP mean emission levels at two angular scales are also reported.](image-url)

### 2 Observations of a Low Synchrotron Emission Area

For several reasons balloon-borne and ground-based experiments limit the investigation of the CMBP signal on small patches of the sky (typically $10^\circ \times 10^\circ$) and are devoted to search for the sub-degree emission.

An important task is to identify patches with low foreground emission and characterize them to evaluate the degree of contamination on the CMB signal.

The southern target of the BaR-SPOrt experiment (Cortiglioni et al. 2003) has been identified using the Rhodes/HartRAO 2326 MHz radio continuum survey (Jonas et al. 1998) where the region already observed by the BOOMERanG experiment (de Bernardis et al. 2000) looks as the lowest...
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Fig. 3. Rhodes/HartRAO 2326 MHz radio continuum survey in total intensity (Jonas et al. 1999). The map is in celestial coordinates with RA=0° in the middle. The purple square identifies the region described in this work.

The polarization maps (intensity and angles) are shown in Figure 4. The polarized emission $I^p$ presents a patchy structure distributed over the whole field. However, a bright feature appears like a filament in the south-west corner of the area with an extension of $\sim 1°$ in declination. The Stokes $I$ image (Figure 5) does not show any particular diffuse structure at the same coordinates even though the strong point-source contamination makes the comparison difficult.

A Faraday screen is likely acting along the line of sight as a small-scale modulation of a relatively uniform background, transferring the power from larger to smaller scales (for a comprehensive discussion see Tucci et al. (2002), and Wieringa et al. (1993), Gaensler et al. (2001)). Our data show a uniformity scale for polarization angles of $10°$–$15°$ and we checked that this results in a power increase of $Q$ and $U$ on the $3°$–$30°$ scales to which the interferometer is sensitive. In the light of this the detected signal represents an upper limit of the polarized synchrotron emission in the range where the CMBP

Table 1. Main characteristics of the 1.4 GHz observations

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Frequency</td>
<td>1380 MHz</td>
</tr>
<tr>
<td>Effective Bandwidth</td>
<td>205 MHz</td>
</tr>
<tr>
<td>Array Configuration</td>
<td>EW214</td>
</tr>
<tr>
<td>Sensitivity Range</td>
<td>3.4 – 30′</td>
</tr>
<tr>
<td>Area Position</td>
<td>RA = 5°, DEC = –49°</td>
</tr>
<tr>
<td>Area Size</td>
<td>3° × 3°</td>
</tr>
<tr>
<td>Observation Period</td>
<td>June 2002</td>
</tr>
<tr>
<td>Effective Observing Time</td>
<td>(~ 70)h</td>
</tr>
<tr>
<td>Sensitivity per beam</td>
<td>0.18 mJy beam(^{-1})</td>
</tr>
<tr>
<td>Sensitivity per beam</td>
<td>3.2 mK</td>
</tr>
</tbody>
</table>
peaks ($\sim 5'-30'$). Faraday screens, therefore, do not influence the evaluation of the mean polarized emission, because they produce only a power transfer from large to small scales.

The typical Faraday rotation amount is around $|\text{RM}| \sim 50 \text{ rad/m}^2$, consistent with RM measurements from extragalactic radio sources (Simard-Normandin & Kronberg 1980) who find values between 30 and 60 rad/m$^2$ at about the same latitudes. This limits the bandwidth depolarization to $p \sim 0.92$, which is insignificantly different from 1 for our purposes of estimating the mean polarized synchrotron emission in the field.

To estimate the mean polarized synchrotron emission, we computed $rms$ values of the polarized intensity $I_p$ and of the Stokes parameters $Q$ and $U$. The results, corrected for the $rms$ noise contribution and restricted to the central highest sensitivity $2\degree \times 2\degree$ sub-field, are

$$Q_{rms} \sim 8.1 \pm 0.4 \text{ mK}$$
$$U_{rms} \sim 8.4 \pm 0.4 \text{ mK}$$
$$I_{rms} \sim 11.6 \pm 0.6 \text{ mK}$$

(1)

where the error budget is dominated by the calibrator accuracy. It is worth noting that this value is nearly one order of magnitude lower than the 100–200 mK background emission found near the Galactic Plane by Uyaniker et al. (1999) at the same frequency of 1.4 GHz.
3 Effects on CMBP Measurements

We extrapolate the polarized emission found in the field to estimate the mean polarized signal at the frequencies of both BaR-SPOrt and BOOMERanG experiments by using the typical spectral index $\beta = -3.1$ found by Bernardi et al. (2004) for the synchrotron emission in the 1.4–23 GHz range. Table 2 shows the signal expectation at 32, 90 and 150 GHz as estimated after the conversion to CMB thermodynamic temperature.\(^1\)

\begin{table}[h]
\centering
\begin{tabular}{lc}
\hline
$\nu$ (GHz) & Mean polarized signal ($\mu$K) \\
\hline
32 & 0.7 \\
90 & 0.04 \\
150 & 0.01 \\
\hline
\end{tabular}
\caption{Estimated synchrotron foreground noise values at frequencies of cosmological interest.}
\end{table}

Since the CMBP signal is expected to be a few $\mu$K on sub–degree angular scales, both from theoretical predictions (Zaldarriaga et al. 1997) and from the recent DASI result (Kovac et al. 2002), our $P_{\text{rms}}$ estimate suggests that in this patch the polarized synchrotron emission would not prevent the detection of the CMBP already at a frequency of 32 GHz.

The 90 GHz value is even more encouraging with the estimated synchrotron contamination two orders of magnitude lower than the predicted CMBP signal. Therefore, it is likely to measure CMBP without foreground contamination. Also, this conclusion should not be affected by the uncertainties in the synchrotron spectral index. In fact, assuming an uncertainty of $\sim 0.2$, we obtain a worst case foreground signal of $\sim 0.08$ $\mu$K, comfortably well below CMBP expectations. Considering that the new WMAP results show a steepening of $\sim 0.5$ in the synchrotron spectral index between K and Q bands (Bennett et al. 2003), our estimate appears to be conservative, especially at 90 and 150 GHz.

The contamination at 150 GHz is even lower, though at this frequency the limit to the CMBP detectability is driven by the dust emission.

These results are interesting also for the $B$-mode. Its very low level ($P_{\text{rms}} < 0.3$ $\mu$K for $T/S < 1$) makes the foreground contamination even more important than for the $E$-mode, and selected patches of the sky with low Galactic emission have to be identified to attempt the detection. Our results provide an upper limit of the Galactic synchrotron emission in the $3'-30'$ range and cannot be directly compared to the $B$-mode, which peaks on a $2^\circ$ scale. However, the emission level on a certain scale is related to the APS by

$$I_p \propto \ell^2 C_\ell.$$  \hspace{1cm} (2)

Since the Galactic synchrotron APS follows a power law $C_\ell \propto \ell^{-\alpha}$ with $\alpha < 2$ (see Figure 6), the emission we measure in the $3'-30'$ range represents an upper limit of the Galactic synchrotron contamination both on $2^\circ$ scales and, in turn, on the $B$-mode.

The polarized synchrotron emission estimated at 90 GHz in this area ($\sim 0.04$ $\mu$K) corresponds to the $B$-mode signal in models with $T/S \sim 0.01$, suggesting us the sensitivity for this cosmological parameter achievable in this low foreground emission area. It is worth noting that this result should be an upper limit of the contamination in this area which, therefore, appears to be a candidate for CMBP $B$-mode investigations.

This work is part of an activity aimed at investigating the Galactic synchrotron properties in low emission areas. Apart from a more complete analysis of this data set (e.g. APS computation), we already performed observations of the same region at 2.3 GHz. Furthermore, we have observed in June 2003 the patch target of the DASI experiment. Finally, we have successfully observed and analyzed a region in the northern sky: the northern target of BaR-SPOrt. Observations have been done with the Effelsberg telescope in collaboration with E. Furst, P. Reich and W. Reich (MPIfR

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\(^1\)We use the conversion factor $c = \left(\frac{2 \sinh \frac{x}{\nu}}{\nu} \right)^2$, where $x \equiv h \nu/kT_{\text{cmb}} \approx \nu/56.8$ GHz.
Fig. 6. Extrapolation to 30 and 90 GHz of the APS of Galactic synchrotron emission on the Galactic Plane computed by Bruscoli et al. (2002) from 2.4–2.7 GHz data (green solid line). As a reference, CMB APSs with cosmological parameters of the Concordance Model as from WMAP data are reported.

Bonn). Preliminary results are already available and will be subject of a forthcoming paper (Carretti et al. 2004).

Acknowledgments

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References