

# Limits on CMBP $B$ -Mode Measurements by Galactic Synchrotron Observations

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**Abstract.** The  $B$ -Mode of the Cosmic Microwave Background Polarization (CMBP) promises to detect the gravitational wave background left by Inflation and explore this very early period of the Universe. In spite of its importance, however, the cosmic signal is tiny and can be severely limited by astrophysical foregrounds. In this contribution we discuss about one of the main contaminant, the diffuse synchrotron emission of the Galaxy. We briefly report about recent deep observations at high Galactic latitudes, the most interesting for CMB purposes because of the low emission, and discuss the constraints in CMBP investigations. The contamination competes with CMB models with  $T/S = 10^{-2}$ – $10^{-3}$ , close to the intrinsic limit for a 15% portion of the sky (which is  $T/S \sim 10^{-3}$ ). If confirmed by future surveys with larger sky coverage, this gives interesting perspectives for experiments, that, targeting selected low emission regions, could reach this theoretical limit.

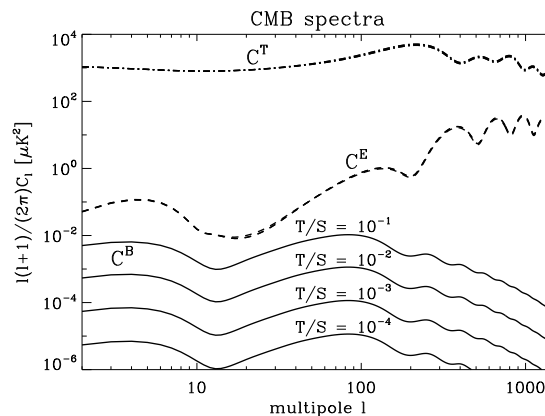
## 1. Introduction

The polarization of the Cosmic Microwave Background radiation (CMBP) is a powerful tool to investigate the early Universe. The tensor perturbations of the primordial Gravitational Wave (GW) background left by Inflation, and the reionization history of the Universe can be effectively studied by the two components the CMBP can be expanded in: the  $E$ - and  $B$ -mode (Zaldarriaga & Seljak 1997).

The  $B$ -mode component is faint, but can give us the first tool to investigate the physics of the Inflation. In fact, the  $B$ -mode level on degree scales is related to the amount of the primordial GW background emitted by Inflation, which is usually measured through the tensor-to-scalar perturbation power ratio  $T/S$  (Fig. 1 and, e.g.: Boyle et al. 2006; Kinney et al. 2006). The  $B$ -mode spectrum normalization has a linear dependence on it (see Fig. 1), while the other CMB components are almost insensitive to these tensor perturbations<sup>1</sup>. In combination with parameters measured by the CMB Temperature spectrum (the scalar perturbation spectral index  $n$  and its running  $dn/d\ln k$ ), it distinguishes among the several Inflation models.

However,  $T/S$  is unknown so far and only upper limits exist ( $T/S < 0.22$ , 95% C.L., Seljak et al. 2006). The many Inflation models predict it to range within orders of magnitude (approximately  $10^{-4} < T/S < 10^{-1}$ ), which corresponds to signals as low as 3–100 nK. The detection of the  $B$ -mode is thus fundamental to distinguish among different models and to measure their relevant parameters, like the energy density of the Universe when Inflation itself occurred. Still undetected, the measurement of this CMBP component is a hot topic in cosmology.

<sup>1</sup> The temperature spectrum  $C^T$  has some sensitivity for values  $T/S > 0.1$ .



**Fig. 1.** Angular power spectra of temperature anisotropy ( $C^T$ ),  $E$ -mode ( $C^E$ ) and  $B$ -mode ( $C^B$ ) of the CMB. Cosmological parameters of the so-called *concordance* model after the WMAP data are assumed (Spergel et al. 2006). In particular an optical depth of the reionized medium of  $\tau = 0.1$  is used. Spectra for some values of the unknown  $T/S$  parameter are plotted.

## 2. Contamination by foreground emissions

The weakness of the CMB  $B$ -mode makes it easily contaminated by foreground emission from both the Galaxy and extragalactic sources. Figure 1 allows the comparison of the  $B$ -mode spectrum  $C^B$  with the temperature one ( $C^T$ ). The  $B$ -mode looks  $3 \times 10^3 - 1 \times 10^4$  times fainter in signal (corresponding to  $10^5 - 10^8$  times in spectrum), depending on the value of  $T/S$ . This way, the higher polarization fraction expected for foreground emissions (Galactic emission can be highly polarized, with values of 10–30% expected for dust and synchrotron emission) makes the polarization case potentially more affected by foreground contamination than the Temperature one.

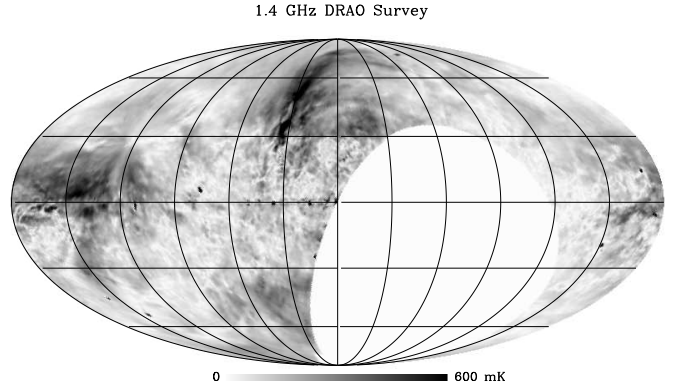
The study of astrophysical foregrounds is thus crucial to set the capability of CMBP experiments to in-

investigate the early Universe. To measure the emission level sets the detectability limit of the  $B$ -mode, and, in turn, the limit of  $T/S$ . The latter defines which part of the Inflationary model space is accessible through CMBP. Also, the weakness of the  $B$ -Mode signal will most likely require the application of cleaning procedures to minimize residual contaminations (e.g. Tegmark et al. 2000; Tucci et al. 2005; Page et al. 2006). The cleaning technique efficacy is greatly improved by the knowledge of the emission properties of the contaminant, like frequency and angular behaviour. This further calls for careful foreground characterizations, especially at high Galactic latitudes, where lowest contamination is expected and there are better chances to detect the elusive cosmic signal.

At frequencies lower than 100-GHz, the most relevant contaminant is expected to be the synchrotron emission, that is best studied at radio wavelengths. First estimates, based both on total intensity data and polarized emission on the Galactic plane, depicted a synchrotron emission that severely contaminates even models with  $T/S > 0.1$ , thus compromising  $B$ -mode investigations even for most optimistic Inflation scenarios (e.g. Tucci et al. 2005). Direct measurements at high Galactic latitude are thus mandatory to do more reliable estimates and set the actual limits on  $B$ -mode detection induced by this Galactic foreground component.

Because of the frequency behaviour, the Galactic synchrotron is best studied at radio frequencies, where dominates the other foreground and CMB emissions. Polarization measurements with large sky coverage are available at 1.4-GHz (Wolleben et al. 2006; Testori et al. 2004). At this frequency, though, angular power spectra are severely modified by Faraday Rotation (FR) effects. A power transfer from large to small angular scales can occur, which generates depolarization and modifies the shape of the power spectrum (Carretti et al. 2005a). This way, 1.4-GHz data are unlikely representative of the Galactic emission at the higher frequencies of the CMB window (30–150-GHz). The map of DRAO northern sky survey<sup>2</sup> by Wolleben et al. (2006), reported in Fig. 2, shows evident depolarization in the Galactic plane area up to a Galactic latitude of  $|b| \sim 30^\circ$ . After a transition region still modified by FR action, only latitudes  $|b| > 50^\circ$  looks free from such effects (see also Carretti et al. 2005a, whose comparison among maps at 5 frequencies in the range 408–1411 MHz highlights such a behaviour).

Deep observations either at higher frequencies or at latitudes above  $|b| > 50^\circ$ , and with sensitivity matching CMBP needs, are thus necessary to reliably estimate the contamination by Galactic synchrotron emission.



**Fig. 2.** Polarized emission map of the DRAO northern sky survey at 1.4-GHz (Wolleben et al. 2006).

### 3. Galactic synchrotron emission at high Galactic latitudes

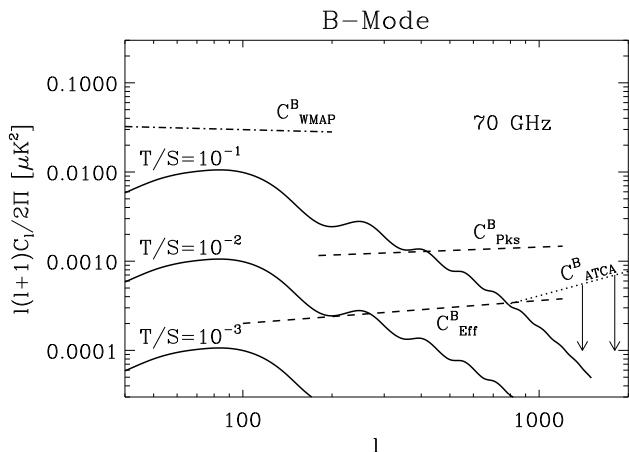
First deep observations at high Galactic latitudes have been carried out in low emission areas. The goal was to first detect the synchrotron signal at high latitudes, leading to survey small fields ( $\leq 10 \text{ deg}^2$ ) to reach proper pixel sensitivity. Areas in the target fields of BOOMERanG (Masi et al. 2005), BaR-SPOrt (Cortiglioni et al. 2003), and DASI experiment (Leitch et al. 2005) have been surveyed with the Parkes, Effelsberg, and ATCA telescope, respectively. Full details of such observations and description of the emission properties of these areas are reported in Carretti et al. (2005b), Carretti et al. (2006), and Bernardi et al. (2006), respectively, while the main features are reported in Table 1. These areas are located in low total emission regions, that cover about 15% of the sky and are expected to feature lowest contamination even in polarization.

DASI and BaR-SPOrt areas are at the Galactic latitude of  $b \sim -60^\circ$  and  $b \sim +63^\circ$ , respectively, above the limit of  $|b| \sim 50^\circ$  under which the FR effects significantly modify measurements at 1.4-GHz. The area in the BOOMERanG field, instead, is at lower latitude ( $b \sim -38^\circ$ ) and has required observations at 2.3-GHz. There are indications those observations are actually unaffected by FR effects, so that angular power spectra obtained from them provide first reliable estimates of the synchrotron contamination. Figure 3 reports the  $B$ -mode spectra of the synchrotron measured in the BOOMERanG and BaR-SPOrt areas extrapolated to 70-GHz, that is considered in the best frequency window for CMB (Carretti et al. 2005b; Page et al. 2006). The comparison with CMBP spectra for different  $T/S$  values suggests that the properties of Inflation models with a GW amount down to  $T/S = 10^{-2}$ – $10^{-3}$  would be accessible in these low emission regions, even without applying any foreground cleaning algorithm. Cleaning procedures could assure to reach even lower values ( $T/S < 10^{-3}$ ). The measurements in the DASI fields did not allow any signal detection, even though an upper limit have been set

<sup>2</sup> <http://www.drao-ofr.hia-ihh.nrc-cnrc.gc.ca/26msurvey>

**Table 1.** Main features of the radio frequency observations in the three low emission areas within the target fields of the BOOMERanG, BaR-SPOrt and DASI experiment, respectively. Both the two fields of DASI have been surveyed.

Area observed	BOOMERanG	BaR-SPOrt	DASI
Central frequency [GHz]	2.332	1.402	1.380
FWHM	8.8'	9.35'	3.4'
Galactic Coord.	$l \sim 255^\circ, b \sim -38^\circ$	$l \sim 172^\circ, b \sim +63^\circ$	Field 1: $l \sim 325^\circ, b \sim -58^\circ$ Field 2: $l \sim 309^\circ, b \sim -62^\circ$
Area size	$2.0^\circ \times 2.0^\circ$	$3.2^\circ \times 3.2^\circ$	$2.0^\circ \times 2.0^\circ$ (each)
$Q, U$ sensitivity in a beam pixel	0.27-mK	0.86-mK	3.2-mK
Telescope	Parkes	Effelsberg	ATCA
Ref.	Carretti et al. 2005b	Carretti et al. 2006	Bernardi et al. 2006



**Fig. 3.**  $B$ -mode power spectra of the Galactic synchrotron emission estimated at 70-GHz compared with the CMB ones. The cases of the two low emission areas in the target fields of the BOOMERanG ( $C_{\text{Pks}}^B$ ) and BaR-SPOrt experiments ( $C_{\text{Eff}}^B$ ) are plotted along with the upper limit in the DASI fields ( $C_{\text{ATCA}}^B$ ). CMB spectra are shown for three different  $T/S$  values (solid). The general contamination at high Galactic latitude, as estimated from WMAP data, is also reported: the spectrum of 74.3% of the sky at 22.8-GHz is considered (Page et al. 2006) and extrapolated to 70-GHz.

(Bernardi et al. 2006). This has been reported in Fig. 3 assuming a frequency slope  $\beta = -3.1$  (Bernardi et al. 2004). Although covering multipoles  $\ell > 800$  far from the angular scales of interest ( $\ell \sim 100$ ), this upper limit supports the low contamination level resulted in the other two fields.

The contribution of the ISM dust has to be considered as well to evaluate the limits induced by the whole Galactic emission. No reliable measurements exist at high Galactic latitude of its polarized component. Carretti et al. (2006) estimate it from the total intensity measurements at high Galactic latitudes (Masi et al. 2005) and assuming the 10 per cent polarization fraction deduced by Benoit et al. (2004). They find the dust contribution is similar to the synchrotron one around 70-GHz and does not significantly change the  $T/S$  limit discussed above.

The recently released 3-years WMAP data depict a different situation for the *normal* high Galactic latitudes conditions. In fact, WMAP has provided an all-

sky polarization map at 23-GHz that makes possible to derive the mean emission at high Galactic latitude (Page et al. 2006). Figure 3 reports the power spectrum they measured for the high Galactic latitudes (74.3% of the sky) scaled up to 70-GHz using a frequency slope  $\beta = -3.1$ . The CMB signal looks contaminated, with the Galactic signal competing with even optimistic models with  $T/S \sim 0.3$ , frustrating the possibility to detect the cosmic signal unless high  $T/S$  values (but disfavoured by last upper limits) or aggressive cleaning procedures.

Therefore, high Galactic latitudes are *normally* severely contaminated, making even more important to characterize the lowest emission regions. WMAP missed to detect the signal in such regions ( $S/N < 1$  on angular scale of  $4^\circ$ ), which, conversely, we successfully observed (our areas are located in the right side of the good regions identified by WMAP). Here, as discussed above,  $T/S$  limits are more optimistic and open new and interesting perspectives, showing the possibility to access a large part of the Inflation model space.

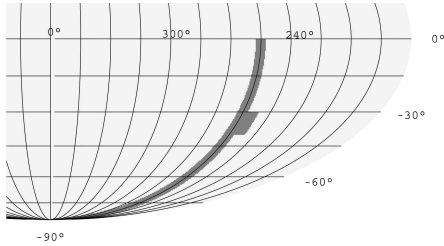
#### 4. Discussion

The results reported in Sect. 3 depict a situation with significant contamination even at high Galactic latitudes, but with better conditions in the low emission regions. Such *low lands* represent about 15% of the sky and could be the right place where to conduct deep CMBP observations to look for the  $B$ -mode.

To limit observations in small regions, however, imposes intrinsic limitation on the minimum detectable  $T/S$ , mainly because of the leakage from  $E$ - into the weaker  $B$ -mode. In fact, Amarie et al. (2005) find that an all-sky survey would allow a detection of  $T/S$  with a theoretical sensitivity limit<sup>3</sup> of  $\Delta T/S = 1.5 \times 10^{-5}$ , that becomes  $\Delta T/S = 3.2 \times 10^{-5}$  when 70% of the sky is available,  $\Delta T/S = 10^{-3}$  for 15%, and  $\Delta T/S = 10^{-2}$  in 1% (3- $\sigma$  C.L.). It is worth noting that the class of Inflation models with minimal fine-tuning have  $T/S$  values ranging within  $10^{-3}$  and  $10^{-1}$  (Boyle et al. 2006), for which a 15% sky portion would be large enough for the first detection of the tensor CMBP component.

Despite of these limitation, the minimum  $T/S$  value detectable in 15% of the sky almost matches the limit

<sup>3</sup> i.e. in the ideal case of negligible instrument noise.



**Fig. 4.** The PGMS survey coverage in Galactic coordinates.

**Table 2.** Main features of the PGMS survey.

Central frequency	2.332-GHz
Bandwidth	128-MHz
FWHM	8.8'
Galactic longitude	$l \sim 255^\circ$
Area size	$5.0^\circ \times 90.0^\circ$
$Q, U$ sensitivity in a beam pixel	0.5-mK
Telescope	Parkes

imposed by the foregrounds in low emission regions. The search for the  $B$ -mode in a sky portion of such a size could thus be a good trade-off between intrinsic and foregrounds limits. In addition, the weakness of the  $B$ -mode signal makes already a challenge to detect the signal for  $T/S = 0.1$  with the present technology (Cortiglioni & Carretti 2006). It is likely that significant technological improvements will be necessary before scientists can face an all-sky mapping mission with a sensitivity able to match the intrinsic limit of  $\Delta(T/S) \sim 10^{-5}$ . Therefore, an experiment aiming at detecting the  $B$ -mode in a smaller region (10-15% of the sky) can be an interesting intermediate step that would allow us to probe Inflation models down to  $T/S = 10^{-3}$ .

The observations conducted in the *low lands* cover small areas. Although taken in three independent samples, surveys of large portions of the sky are necessary to understand whether the areas observed so far are peculiar *lucky* lowest emission cases or are representative of the conditions of the *low lands*. New information are expected to come from the recently completed all-sky mapping at 1.4-GHz, even if, as mentioned in Sect. 2, these are likely modified by the FR action up to  $|b| \sim 50^\circ$ . First analyses using these data have been reported by La Porta & Burigana (2006). However, they regard half a sky and contain both large local high emission regions and the Galactic disc that is strongly modified by FR.

Deeper and higher frequency data will come soon from the Parkes Galactic Meridian Survey (PGMS, Carretti et al. 2005c) aimed at surveying a Galactic meridian at 2.3-GHz (Fig. 4). The survey is in progress at the Parkes radiotelescope and main features are reported in Table 2. It will explore the polarized Galactic diffuse emission along the meridian  $l = 255^\circ$  from Galactic plane to south Pole. The frequency is high enough to avoid significant FR effects and main goals are to reveal the intrinsic Galactic emission and study its behaviour with the

Galactic latitude. This meridian goes through one of the low emission regions visible in the WMAP data and more extended information about the Galactic emission level in the *low lands* are expected.

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