Galactic foregrounds and CMB Polarization

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Abstract. The CMB polarization promises to unveil the dawn of time measuring the gravitational wave background emitted by the Inflation. The CMB signal is faint, however, and easily contaminated by the Galactic foreground emission, accurate measurements of which are thus crucial to make CMB observations successful. We review the CMB polarization properties and the current knowledge on the Galactic synchrotron emission, which dominates the foregrounds budget at low frequency. We then focus on the S-Band Polarization All Sky Survey (S-PASS), a recently completed survey of the entire southern sky designed to investigate the Galactic CMB foreground.

1. CMB polarization

The Cosmic Microwave Background (CMB) is the radiation emitted at the decoupling of matter and radiation as the temperature of the Universe dropped below some 3000 K. Emitted in the early stages of the Universe about 400 thousand years after the Big Bang, the CMB bears the signature of the primeval Universe conditions. The study of its temperature angular power spectrum carried out by a plethora of experiments (WMAP and the others, see e.g. Hinshaw et al. 2009 and references therein) has been outstandingly successful measuring average properties of the Universe like geometry, matter-energy content and nature, and expansion rate. It is worth noticing that the existence of the Dark Energy and its leading the matter-energy budget has been discovered thanks to the CMB anisotropies in combination with high redshift Supernovae data.

The study of the linearly polarized component is the next stage of CMB investigations. Usually described in terms of the 2-spin tensor Stokes parameters $Q$ and $U$, the polarized radiation is best studied in terms of the $E$ and $B$-Modes in the case of the CMB (see Zaldarriaga 1998, for a review). These modes are defined by the pattern of the polarization angle field, which is axisymmetric for the $E$-Mode realising either radial or circular patterns, while is rotated by $45^\circ$ for the $B$-Mode realising whirlpool-like shapes (see Fig. 1). They have the undoubted benefit to be scalar quantities.

The $E$-mode retains the signature of the reionisation history of the Universe. The large angular scales peak (Figure 2) is generated by the interaction of the CMB photons with the medium reionised at the end of the Dark Ages when the first Galaxies formed and stars lit up. The amplitude of the peak measures the optical depth of the medium to the CMB, while its position tells about the redshift this event occurred at. That makes it a powerful tool to distinguish between several reionisation models.

But the most appealing feature of the CMB polarization is that the scalar (matter) perturbations can generates only the $E$-mode component, so that the $B$-Mode bears...
the tensor (gravitational waves) perturbations contribution uncontaminated by the much stronger scalar component. That way the CMB $B$-mode is a direct signature of the primordial gravitational wave background (GWB) emitted by the Inflation (e.g., Kamionkowski & Kosowsky 1998; Boyle et al. 2006). The amplitude of its angular power spectrum is proportional to the GWB power (Figure 3) and is usually measured in terms of fraction of the scalar perturbations by the tensor-to-scalar perturbation power ratio $r$. Still undetected, the current upper limit is set to $r < 0.20$ by the WMAP results (95% C.L., Komatsu et al. 2009). Besides the evidence of a primordial GWB a measure of $r$ would help distinguish among several inflation models and investigate the physics of the very early stages of the Universe.

However, this spectacular science goal is made difficult by the CMB $B$-Mode tiny signal, which ranges from about 100 nK of the current upper limit down to 1 nK of the smallest $r$ accessible by CMB ($r \sim 2 \times 10^{-5}$, Amarie et al. 2005). Apart from the challenge of the required sensitivity, at such low levels the cosmic signal is easily overcome by the foreground Galactic synchrotron and dust emissions, which can set the actual detection limit. The former leads the budget at low frequency and its study is essential to investigate this cutting-edge fields of the current astrophysics research.

2. Foregrounds: the Galactic Synchrotron emission

Until a few years ago the Galactic synchrotron emission at high Galactic latitude was mostly unknown with large uncertainties even about its emission level, making unclear the actual limit to detect the CMB polarized component. A number of observations have
Figure 2. CMB $E$-Mode power spectrum $C_E^\ell$ of three models differing for the optical depth $\tau$ of the CMB to the reionised medium. The spectrum is function of the multipole $\ell$, related to the angular scale by $\theta \sim 180^\circ/\ell$. The amplitude and the position of the peak at the large angular scales ($\ell < 10$) measure $\tau$ and the redshift $z_{\text{re}}$ the reionisation occurred at, respectively. The Temperature anisotropy spectra $C_T^\ell$ are also reported for comparison.

Figure 3. CMB $B$-Mode power spectra for three models differing for the gravitational wave power released by the Inflation. The amplitude is proportional to the gravitational wave power measured by the tensor-to-scalar perturbation power ratio $r$ (see text). Temperature ($C_T^\ell$) and $E$-Mode spectra ($C_E^\ell$) are also shown.
Figure 4. Polarized Galactic emission at high Galactic latitudes at 70 GHz: average of the entire high Galactic latitudes as estimated by WMAP 23 GHz data ($C_{\text{WMAP}}^B$, dotted) and in the best 15% of the sky as estimated in the halo section of the PGMS survey (solid). CMB $B$-Mode spectra for different $r$ values are also reported for comparison (dashed).

been conducted since early 2000s to fill this gap and now the overall picture seems to have been understood (Figure 4).

WMAP data have allowed for the first time to study the average emission at high Galactic latitude, the region useful for CMB observation because of the lower Galactic emission. Page et al. (2007) have analysed the 23 GHz WMAP polarized maps and find that the normal emission at high Galactic latitude is strong: scaled to 70 GHz it is equivalent to $r \sim 0.3$, which is even higher than the current upper limit (Figure 4). A similar result has been obtained by La Porta et al. (2006), who, using the 1.4 GHz all-sky map combination of the DRAO and Villa Elisa surveys (Wolleben et al. 2006; Testori et al. 2008), estimate an emission at 70 GHz equivalent to $r = 0.5$.

Better conditions have been found in the lowest emission regions of the sky. A first analysis to understand position and extension of the best regions has been carried out by Carretti et al. (2006) with WMAP data and shows that those regions cover a non-negligible part of the sky (about 15%). WMAP data have not been sufficient sensitivity to study the properties of the signal of these areas. A detailed analysis has been carried out only recently with the Parkes Galactic Meridian Survey (PGMS, Carretti et al. (2010a)), a survey of a 5-degree wide strip stretching from the Galactic plane to the south Galactic pole through the southern portion of these lowest emission areas.

Conducted at 2.3 GHz with the Parkes telescope, it was aimed at studying the polarized emission behaviour versus the Galactic latitude in a region uncontaminated by

\[1\] With "equivalent to $r$" we intend the value of $r$ for which the CMB $B$-Mode spectrum at the $\ell = 90$ peak matches that of the foreground.
Figure 5. Polarized angular power spectra of the 17 PGMS fields grouped by their Galactic latitude $b$ (Carretti et al. 2010a). The spectra are scaled to 70 GHz to estimate their level in the CMB frequency window. CMB $B$-Mode spectra for three values of $r$ are also reported for comparison (solid black).

large local structures like the big radio loops. The PGMS has identified three latitude sections distinguished: the disc, the halo, and a transition region connecting them (Figure 5). The halo section lies at latitudes $|b| > 40^\circ$ and has weak and smooth polarized emission mostly at large scale with steep angular power spectra, while the disc region covers the latitudes $|b| < 20^\circ$ and has a brighter, more complex emission dominated by the small scales with flatter spectra. The transition region has steep spectra as in the halo, but the emission increases toward the Galactic plane from halo to disc levels. The most interesting result is that the halo section does not show an obvious trend with respect to the Galactic latitude resulting in just one environment stretching over 50$^\circ$ with very low emission. This, once scaled to 70 GHz, is equivalent to the CMB $B$–Mode emission of models with $r_{\text{halo}} = (3.3 \pm 0.4) \times 10^{-3}$ (Figure 4). This are very good conditions for the detection of the $B$-mode both in terms of emission level and size of the area.

Therefore, the current picture shows a strong synchrotron contamination at high Galactic latitudes with a typical emission even higher than the current upper limit of the CMB $B$–Mode. This requires an aggressive foreground cleaning to search for the inflation signature with all-sky class surveys. Much better conditions exist in the best 15% of the sky, where the detection limit of $r$ drops to $\delta r = 2 \times 10^{-3}$ (3-$\sigma$ C.L.). This matches the needs of the forthcoming generation of ground-based and balloon-borne experiments ($r \sim 0.01$, e.g.: SPIDER, EBEX, and QUIET, Crill et al. (2008); Grainger et al. (2008); Samtleben & for the QUIET collaboration (2008)) and approaches the detection limits set for the next generation space missions currently under study such as B-POL and CMBPol (De Bernardis et al. 2009; Baumann et al. 2008).

Because of its implications for the experiment design another important point to account for is the frequency of minimum foreground emission where synchrotron and
Figure 6. WMAP polarized intensity map at 23 GHz. The data have been binned in 2° pixels and all the pixels with $S/N < 3$ have been blanked (white). The map is in Galactic coordinates centred at the Galactic Centre.

dust equate. WMAP results show that this is in the range 60–70 GHz on average at high Galactic latitudes [Page et al. (2007)]. The PGMS analysis shows that it should set in a similar range also in the weakest emission areas (60–80 GHz). If confirmed in other regions, this would imply that dust and synchrotron emission are mostly correlated across the sky and that the frequency of minimum foreground is nearly independent of the sky position. This is still an open point, however, because the polarized dust emission has not yet been detected in the PGMS area (or in other low emission areas) and the results are based on assumptions about the dust polarization fraction.

3. **Future Perspectives**

The high level of contamination at high Galactic latitude (even higher than the current CMB upper limit) requires aggressive cleaning and, in turn, sensitive and accurate foreground maps in case all-sky class CMB mission want to be carried out. The identification of the best regions of the sky and a full characterisation of their emission properties also call for sensitive all-sky class foreground surveys. The latter is essential for sub-orbital experiments (ground-based and balloon-borne), which target their observations to small areas with low foreground emission.

Even though the investigations conducted so far have clarified the picture of the contamination by synchrotron emission, the currently available data set is not sufficient for such jobs, however. As mentioned in Sect. 2, the 23 GHz map by WMAP has allowed a statistical detection at high Galactic latitude, but even smoothing the data on the 2 degree scale of the $B$-Mode peak the signal-to-noise ratio is $S/N < 3$ in about 55% of the sky. As shown by Figure 6 this is mostly the entire area useful for CMB observations and consists of all the high Galactic latitudes except the areas contaminated by large local structures like the big radio loops.
The 1.4 GHz all-sky map combination of the DRAO and Villa Elisa surveys (Figure 7) benefits of a better $S/N$, but modifications by Faraday Rotation (FR) affect the data. All the Galactic disc at latitude $|b| < 30^\circ$ is strongly depolarized and Faraday modulation is present up to $|b| = 50^\circ$ (Carretti et al. (2005)), making this data set not suitable to be extrapolated to the CMB frequency window and used as template for foreground separation.

The PGMS has the right sensitivity for cleaning purposes ($S/N > 7$ on 9 arcmin scale even in the lowest emission areas observed), but it has surveyed only a strip and is not sufficient to give a template map of the entire low emission regions.

More data are thus required. The observations conducted so far lead to the following main requirements for new surveys:

1. to be conducted at a low enough radio frequency for the synchrotron emission to dominate the other diffuse emission components;
2. at a frequency higher than 1.4 GHz to avoid significant Faraday Rotation effects;
3. at a frequency not too high not to compromise the $S/N$ ratio;
4. to be an all-sky class survey to be used as template for CMB space missions or to identify and characterise the areas with lowest Galactic emission;

There are two major surveys just completed or are currently on-going that satisfy such specifications: the S-band Polarization All Sky Survey (S-PASS) and the C-Band All-Sky Survey (C-BASS).

S-PASS is a survey of the entire southern sky at 2.3 GHz conducted with the Parkes telescope (see Sect. 4). It has an angular resolution of 9 arcmin which covers all the angular scale range required by CMB observations. It has has been recently completed and features a high $S/N$ ratio that can enable the cleaning procedures to extend the $B$-mode detection limit down to the lowest value of $r$ accessible by CMB.
C-BASS (Muchovej et al. 2010) covers the entire sky and it is complementary to S-PASS. It is conducted at higher frequency (5 GHz), but sports a lower S/N ratio (5 times lower by specifications) and a coarser resolution (about 1 degree), which enables it to cover the 2° CMB peak but does not stretch down to the 10 arcmin required by the gravitational lensing component. The observations are planned to start in 2010 and will last for a couple of years.

The combination of these two surveys promises to give a solid data base for the aggressive cleaning required to cope with the strong Galactic signal. S-PASS gives a sounding ground thanks to its high S/N, while the combination with C-BASS ensures the determination of the accurate frequency spectral index required for safe extrapolations to the CMB frequency window.

In the next Sections we will discuss about S-PASS, which has been recently completed and has already provided preliminary maps.

4. S-PASS

4.1. The survey

The S-band Polarization All Sky Survey (S-PASS) is a project mapping the diffuse polarized synchrotron emission of the entire southern sky with the Parkes radio telescope at 2.3 GHz (Carretti et al. 2007). Commenced in October 2007, the observations has been completed in January 2010 and the data reduction is in progress. Besides studying the CMB foregrounds the survey is aimed at investigating the Galactic magnetic field in the halo, in the disc, and at the disc-halo transition.

The resolution of 9 arcmin makes S-PASS ideal for CMB foregrounds investigations covering the entire angular scale range required. The sensitivity of 1 mK per beam-sized pixel gives $S/N > 3$ everywhere, and, for the sake of comparison with the existing data, corresponds to $S/N > 20$ on 1-deg scale. With such performances, S-PASS can clean CMB maps enabling $r$ detection limits of $\delta r = 4 \times 10^{-5}$ at 3-$\sigma$ C.L. (we use the estimators of Tucci et al. 2005). This is close to the lowest detection limit possible by the CMB B-Mode, so that S-PASS is a sort of ultimate synchrotron foreground survey in terms of sensitivity requirements.

A survey with such characteristics has posed several challenges to make it feasible with a large telescope like the 64-m dish of Parkes. For instance, for the scientific goals it is essential to detect the signal also in the lowest emission regions, where values of a few mK were expected. This makes the ground emission contamination a serious issue, especially for the need to preserve the signal up to the largest angular scales for absolute calibration purposes. Another example is the angular resolution, which with its 9 arcmin is a factor four better than that of the 1.4 GHz survey. This gives far more details, but, at the same time, requires four times more scans and observing time to fully sample the sky if conducted with a standard observing mode. Moreover, the Galactic physics goals set as key requirement for S-PASS the absolute calibration, a long standing issue of radioastronomical observations both because of instrumental offsets and ground emission contamination.
4.2. Scanning strategy and absolute calibration

To cope with these challenges a new non-standard observing strategy based on long and fast azimuth scans has been developed. A detailed description will be presented in a forthcoming paper (Carretti et al. 2010b), here we briefly report the key futures.

The azimuth scans have been chosen to minimise ground emission pick-up variations. In S-PASS data these are of the order of a few tens mK, against the typical variations of a few hundreds mK of previous surveys (e.g., cfr. Wolleben et al. 2006), which makes obvious the benefits of azimuth scans.

The scan length (about 115°) and elevation (Celestial south pole at Parkes) allow covering the entire DEC range in just one scan preserving the information on all the angular scales.

This type of scan has also required to set up a special observing mode based on an uninterrupted sequence of back and forth scans with both no loss of tracking at the turnoff and precise timing to enable a regular gridding of the sky. The Earth rotation lets the sky to drift in RA so that the entire 24-hour range can be covered in one sidereal day. As a result, a zig-zag in the sky is observed each night. The combination of observations taken in a number of nights appropriately offset in RA allows covering the entire southern sky.

The vast area to observe and the small size of the pixels (4.5') has required a high scan speed to conduct the survey in an acceptable time duration. The scan rate has been pushed up to 15°/min, which is a significant fraction of the slewing speed (24°/min), not a bad performance for a 1000-tons 64-m telescope. The use of long scans has allowed minimising the overhead to ramp up and down the telescope speed at the two scan ends, which is quite significant when using high scan rates. This, in combination with the high speed, has allowed to complete the survey in less than 2000-h of telescope time.

The data reduction of radioastronomical data usually requires baseline subtraction to remove both ground emission and instrumental offsets, which also removes the mean level of the signal over the scan. To recover the power on all angular scales a ”basket weaving” technique (scan crossing) is required. Basket weaving is a bit tricky with AZ scans. However, the same DEC range can be observed both when the sky rises and sets. We thus observed two sets of scans, one eastward and the other westward, whose combination realises an effective scan crossing (see Figure 8).

However, this is not yet sufficient to absolute calibrate the data since the basket-weaving can recover the power up to the scale of the map-size, but leaving the average signal still undetermined.

The new idea developed for S-PASS to solve this point has been to use the parallactic angle modulation of Stokes Q and U along a scan. Usually, a constant signal would be removed by the baseline subtraction, but the change of parallactic angle along a very long scan modulates both Q and U as sections of sinusoid in the instrument reference frame (Figure 9). That way, the baseline subtraction preserves most of the Q and U average signal. An appropriate inverse problem solving is able to recover the average signal and then absolutely calibrate the map (see Carretti et al. 2010b for full details and tests). Simulations conducted using the actual sensitivity, signal, and scanning strategy of S-PASS show that the absolute level can be reconstructed with a precision of about 50 µK, far better than the survey statistical noise, thus giving a negligible contribution to the overall error budget. It is worth noticing that conducting
Figure 8. Combination of two set of scans taken observing eastward and westward respectively. The crossing between scans of the two sets is obvious and enables effective basket-weaving.

Figure 9. The parallactic angle variation along a long AZ scan (arrows) modulates a signal constant in the sky reference frame into a section of sinusoid in the instrument reference frame (solid) so that the baseline subtraction (dashed) does not completely remove it. Very long scans are essential.
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uninterrupted very long scans is essential, otherwise the parallactic angle modulation would be marginal and the method ineffective.

4.3. Preliminary maps

Figure 10 shows a preliminary map of Stokes $Q$ at full resolution obtained using the entire data but without applying the full map-making procedure to recover the absolute calibration. (That way, stripes are still visible.) The map shows plenty of details and structures unseen at lower frequencies. The emission is smooth not only at high latitudes but also in the disc down to $|b|=5^\circ$–$10^\circ$ even in the inner Galaxy. This will enable first studies of the disc and the disc-halo transition with diffuse emission data.

The absolutely calibrated maps (not shown here) are featured by very large scale structures up to the size of the map which matches those of the WMAP 23 GHz map both in shape and position. That is both evidence of the quality of the overall data reduction procedure and that Faraday Rotation effects are marginal in the halo already at this frequency. The Faraday modulation would have either modified the structure shape or shifted their positions because of polarization angle shift. Therefore, the S-PASS data can be already used for CMB foreground cleaning purposes.

A number of features are visible on the Galactic plane too. At both sides of the Galactic Centre there are two large areas fully depolarized corresponding to two large local HII emission regions visible in the SHASSA map (Gaustad et al. [2001]). Their view at full resolution is dramatic: the signal is almost absent because fully depolarized, but it reappears at their edges as a narrow ring of strongly modulated emission, evidence that the FR is lower and cannot fully depolarize the signal but can still modulate it strongly. After that transition the signal is smooth, meaning that the FR effects are much lower. Always in the Galactic plane but in the outer Galaxy is visible a intriguing mottled region at $l=[230^\circ, 280^\circ]$ and $|b|<15^\circ$ in correspondence of the Gum Nebula.
Other objects like the Vela SNR, Centaurs A, Large Magellanic Cloud, and Fornax A are obvious.

In summary, S-PASS is revealing a new polarized sky. The disc emission looks unveiled at last, making possible investigations of this part of the Galaxy, while the high S/N at high latitude promises both a leap in the foreground cleaning efficiency and a better understanding of the large scale Galactic magnetic field in the halo.

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