Foregrounds and experiments below 33 GHz

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Abstract. In this paper I report on the recent results obtained from the Tenerife switched beam (10 GHz to 33 GHz) experiment and Jodrell Bank 5 GHz interferometer and their predictions for foreground levels. The full data analysis and results will be presented elsewhere. It is found that free-free emission dominates above 10 GHz, whereas synchrotron emission dominates below 5 GHz.

In the beginning there was only darkness, dust and water. The darkness was thicker in some places than in others. In one place it was so thick that it made man. The man walked through the darkness. After a while, he began to think.

Creation myth from the Pima tribe in Arizona

1. Introduction

One of the biggest problems in improving the results from current Cosmic Microwave Background (CMB) experiments is that of foreground contamination. Without prior knowledge of the spatial and frequency spectra of foregrounds it is impossible to say for certain which components present in the data can be attributed to the CMB or to Galactic or extra-Galactic foregrounds. The only way to overcome this problem is to use multi-frequency information to constrain the various foregrounds and derive their properties. This paper will try to put some extra constraints on the dominant foregrounds at the lower frequency range (5 GHz to 30 GHz) that is of interest to CMB astronomy.

2. The Tenerife experiments

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The Tenerife switched beam radiometers have been operating since 1984 at the Teide Observatory in Tenerife. There are three instruments operating at 10 GHz, 15 GHz and 33 GHz. The beams have a full width half maximum (FWHM) of about 5° and a triple beam pattern is obtained by switching two beams in right ascension (RA) by 8.1°. More details about the experiments can be found in Davies et al. (1996) and the most recent results are to be published in Gutierrez et al. (1999).
The data from the experiments are analysed in two different ways. Statistical techniques (for example, the likelihood function) are used to obtain constraints on cosmological parameters from the raw data (after calibration) and maximum entropy (Jones et al. 1998) is used to construct maps of the sky at 5° resolution. Figure 1 shows the 15 GHz Tenerife result produced by maximum entropy in the Mollwiede projection. The average sensitivities of the three frequencies are 48 µK, 19 µK and 30 µK per beam for the 10, 15 and 33 GHz instruments respectively. Additional information on the point sources (data taken by the Michigan monitoring program; Aller & Aller 1997) has been taken simultaneously over a 10 year period so accurate subtraction of this foreground is possible and has been carried out here prior to the Galactic foreground analysis.

2.1. Cross-correlation with existing templates

The first attempt at calculating the level of Galactic foreground in the Tenerife data is to calculate the cross-correlation with other data which is known to be dominated by the foregrounds. We have cross-correlated the raw data from the 10 GHz and 15 GHz (the 33 GHz does not have enough sky coverage) with templates from the DIRBE experiment (1-3 THz) to test for dust or correlated free-free emission and with the two low frequency surveys at 408 MHz (Haslam, Salter, Stoffel & Wilson 1982) and 1420 MHz (Reich & Reich 1988). Table I summarises the results from this analysis.

As can be seen from the table no significant correlation was found between the low, or high, frequency data and the 15 GHz Tenerife data. It is therefore possible to say that the templates for free-free and synchrotron do not contribute greatly to the 15 GHz data and that most of this signal is likely to be CMB in origin. However, at 10 GHz a ~ 3 sigma detection was found with both the 408 MHz and 1420 MHz surveys with a signal corresponding to about half of the total signal ($\Delta T_{10} = 29^{+10}_{-10}$ µK; Gutierrez et al. 1999) present in the 10 GHz data. Therefore, it is very likely that free-free or synchrotron emission is a
significant foreground in this channel. However, care must be taken as artefacts in both of the low frequency maps may also be contributing to the correlation and so further analysis must be carried out.

| Template | 10 GHz | 15 GHz |
|----------|--------|--------|
|          | Significance | Signal (µK) | Significance | Signal (µK) |
| DIRBE08  | 0.93   | 8.5     | 1.44       | 7.8       |
| DIRBE09  | 0.19   | 1.7     | 0.35       | 1.7       |
| DIRBE10  | 1.06   | 9.5     | 0.96       | 5.1       |
| HASLAM   | 3.74   | 32.7    | -0.07      | -0.4      |
| R&R      | 2.32   | 22.4    | 0.53       | 3.0       |

Table 1. Results from the cross-correlation of the 10 GHz and 15 GHz Tenerife data with the Dirbe 100 (DIRBE08), 140 (DIRBE09) and 240µm (DIRBE10), Haslam 408 MHz and Reich & Reich 1420 MHz surveys. The significance in standard deviations is shown and the corresponding signal contributing to the data is shown in µK.

2.2. Joint likelihood analysis

Previous likelihood analyses have been performed on the Tenerife data but always using the frequencies as separate channels (either assuming that all the signal present is either CMB or Galactic). However, if we perform a joint likelihood analysis on the overlap region between the 10 GHz and 15 GHz data assuming some spectral index for the Galactic signal then it will be possible to extract CMB and Galactic results simultaneously. We assume that each pixel has a temperature which can be represented by

\[ \Delta T_{10}^{10,15} = \Delta T_{CMB} + \Delta T_{Gal}^{10,15} \]

where

\[ \Delta T_{Gal}^{15} = \Delta T_{Gal}^{10} \times (15/10)^{-\beta} \]

Figure 2 shows the two dimensional likelihood function for the joint analysis of the 10 and 15 GHz data as a function of the temperature of the CMB and Galactic signal at 10 GHz. As can be seen there is no firm detection of the Galactic signal, only an upper limit (\(\Delta T_{Gal}^{10} < 28\mu K\) at 68% confidence limits) but the CMB is detected with a signal which corresponds to \(Q_{rms-ps} = 20^{+10}_{-7}\mu K\) (assuming a Harrison-Zeldovich spectrum). This is in agreement with the COBE result of \(Q_{rms-ps} = 18 \pm 1.6\mu K\) (Bennett et al. 1996).

2.3. Foreground map making

Another possible analysis technique is to use the frequency information on a pixel by pixel basis to perform a multi-frequency decomposition of the data. To put more constraints on the data we have incorporated the common region of sky that was observed using the COBE satellite. We allowed the spectral
Figure 2. The 2-D likelihood function for the Galactic and CMB contribution to the 10 and 15 GHz Tenerife experiments. The temperatures are shown in $\mu$K.
index of the Galactic channel to vary and found that the most likely value was consistent with free-free emission. Multi-frequency maximum entropy (Hobson, Jones, Lasenby & Bouchet 1998) was used (at these angular scales both the signal and noise are Gaussian so the maximum entropy method reduces to the simple Wiener filter) to analyse the data. See Jones et al. (1999a) for a detailed study of the results.

3. The Jodrell Bank interferometer

[Project collaborators: R.D. Davies, S. Melhuish, A.W. Jones, G. Giardino, A. Wilkinson, H. Asareh, A.N. Lasenby]

A 5 GHz interferometer has been operating at Jodrell Bank since 1991. It has a primary beam of 8° FWHM and data has been taken on two baselines corresponding to angular sensitivities of $\ell = 71 \pm 13$ (the narrow spacing) and $\ell = 184 \pm 20$ (the wide spacing). It is not a tracking interferometer so the angular resolution in Declination is different from that in RA and this has to be taken into account in the analysis. For more details on the instrument see Melhuish et al. (1997) and for more details on the data and subsequent analysis see Giardino et al. (1999), Asareh et al. (1999) and Jones et al. (1999b). Again, maximum entropy was used to produce the maps shown here. The sensitivity per beam for the two baselines is 20$\mu$K.

The data from the wide spacing configuration is shown in Figure 3. As can be seen the four main point sources in this region are easily identifiable. Comparing this map to that produced by the narrow spacing data (Figure 4) an excess signal is clearly seen. This is due to Galactic features and by performing a multi-frequency analysis with the 408 MHz and 1420 MHz surveys (see Jones et al. 1999b) it was found that the Galactic spectral index is $\beta = 2.9 \pm 0.3$, consistent with a synchrotron origin.

4. Discussion

It is found that there is significant Galactic contamination even in the relatively clean area away from the Galactic plane that has been observed by the Jodrell Bank interferometer and the Tenerife beam-switching experiments. Analysis using the new multi-frequency maximum entropy methods showed that synchrotron emission dominates below 5 GHz while free-free emission dominates above 10 GHz. Figure 3 summarises the expected levels of the low frequency foregrounds for a 5° FWHM experiment. It is therefore very difficult to use the low frequency templates to predict the position of Galactic foregrounds at higher frequencies. It is important to note that the predictions presented here are most likely lower limits for the Galactic emission in other regions of the sky.

Acknowledgments. We are grateful to all those involved in the Tenerife and Jodrell Bank experiments and their continued perseverance in correct art of data analysis. The author acknowledges King’s College, Cambridge, for support in the form of a Research Fellowship.
Figure 3. The data from the 5 GHz wide spacing interferometer showing the point source contribution at that frequency. The temperature is shown in mK.

Figure 4. The data from the 5 GHz narrow spacing interferometer which shows a clear excess of sources above the point sources (Figure 3). The temperature is shown in mK.
Figure 5. Estimate of the dominant foreground level from the results presented in this paper. The levels shown are for a 5° FWHM experiment.

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