THE QUEST FOR MICROWAVE FOREGROUND X

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ABSTRACT

The WMAP team has produced a foreground map that can account for most of the low-frequency Galactic microwave emission in the WMAP maps, tentatively interpreting it as synchrotron emission. Finkbeiner and collaborators have challenged these conclusions, arguing that the WMAP team “synchrotron” template is in fact not dominated by synchrotron radiation, but by some dust-related Galactic emission process, perhaps spinning dust grains, making dramatically different predictions for its behavior at lower frequencies. By cross-correlating this “synchrotron” template with 10 and 15 GHz CMB observations, we find that its spectrum turns over in a manner consistent with spinning dust emission, falling about an order of magnitude below what the synchrotron interpretation would predict.

Subject headings: cosmic microwave background – diffuse radiation – radiation mechanisms: thermal and non-thermal – methods: data analysis

1. INTRODUCTION

When doing precision cosmology with the Cosmic Microwave Background (CMB), a key challenge is accurately modeling and correcting for Galactic foreground contamination. There are currently three indisputably identified Galactic foregrounds: synchrotron radiation, free-free emission and thermal (vibrational) emission from dust grains. In the last few years, however, evidence for the existence of a fourth component began to mount. This component, nicknamed “Foreground X”, is spatially correlated with 100 $\mu$m dust emission but with a spectrum rising towards lower frequencies (in a manner that is incompatible with thermal dust emission), subsequently flattening and turning down somewhere around 15 GHz.

This fourth component was first discovered in the COBE DMR data by Kogut et al. (1996a, 1996b), who tentatively identified it as free-free emission. It has since been detected in a variety of data sets such as Saskatoon (de Oliveira-Costa et al. 1997), OVRO (Leitch et al. 1997), the 19 GHz survey (de Oliveira-Costa et al. 1998), Tenerife (de Oliveira-Costa et al. 1999, 2002; Mukherjee et al. 2001), QMAP (de Oliveira-Costa et al. 2000), the ACME/SP94 data (Hamilton and Ganga, 2001), Python V (Mukherjee et al. 2003), the WMAP data (Lagache 2003; Finkbeiner 2003), as well as in some other non-CMB data sets between 8-15 GHz (Finkbeiner et al. 2002; Finkbeiner et al. 2003, hereafter F03). Adding pieces to this puzzle, joint re-analysis of COBE DMR & the 19 GHz survey (Banday et al. 2003) and OVRO & SP94 data (Mukherjee et al. 2002) also show the presence of Foreground-X. Although a consensus about the existence of Foreground X had still not been reached, the case for spinning dust was beginning to look quite solid prior to the WMAP data release.

The WMAP team challenged this interpretation in their foreground analysis (Bennett et al. 2003b, hereafter B03b), arguing that there is still no solid evidence for an anomalous source of microwave emission at these wavelengths (i.e., no Foreground X). They argued that all foreground emission observed at the five WMAP frequencies could be accounted for with a model involving only three foreground emission components, which they produced maps of and interpreted as (thermally radiating) dust, free-free emission and synchrotron radiation, respectively.

Using the Green Bank Plane Survey maps, F03 have challenged these conclusions, arguing that the WMAP team “synchrotron” template is in fact not dominated by synchrotron radiation, but by some dust-related Galactic emission process, perhaps spinning dust grains. Given this dispute about whether the WMAP K-band “synchrotron map” produced by B03b is really a map of synchrotron, let us hereafter refer to it as the mystery map, to avoid interpretative language.

The logic behind identifying the WMAP team dust and free-free maps with these two physical emission sources is that they not only exhibit the right frequency dependence (by construction, from the way they were created) but spatially resemble external maps of 100 $\mu$m dust emission and H$\alpha$ emission, respectively. F03 argue that, in contrast, the WMAP team mystery map does not strongly resemble external synchrotron maps at lower frequencies such as the 408 MHz Haslam map (Haslam et al. 1982). B03b argue that this is due to strong spatial variations.

1Draine and Lazarian (1998) argued against the free-free hypothesis on energetic grounds, and suggested that Foreground X was caused by dust after all, but via rotational rather than vibrational emission. In the literature, Foreground X is sometimes called “anomalous” emission, and the most popular interpretation has been that it is emitted by spinning dust grains. There is also the possibility that Foreground X is due to magnetic dipole emission from ferromagnetic grain materials (Draine and Lazarian 1999).

2http://lambda.gsfc.nasa.gov/product/map/

3The Green Bank Galactic Plane Survey maps the Galactic plane within $\pm4^\circ$, with a resolution of FWHM=11.2’ at 8.35 GHz and FWHM=8’ at 14.35 GHz. See Langston et al. (2000) for more details.
in the spectral index, whereas F03 argue that it is because the map (essentially defined a component having a synchrotron-like spectrum across the WMAP frequencies 23-93 GHz) is dominated by dust-related emission, not by synchrotron emission.

The reason that such anomalous dust emission is so hard to pin down is that its intensity is predicted to peak around 10-15 GHz, making it difficult to detect in the available radio surveys below 10 GHz such as those used by B03b (where it becomes subdominant to synchrotron radiation) and in the WMAP data at 23 GHz and above (where its spectral index is similar to synchrotron and free-free emission). A smoking gun test for Foreground X therefore involves quantifying its behavior around 10-15 GHz, to see whether its spectrum continues to rise towards lower frequencies like synchrotron radiation or turns over.

It is important to point out, however, that although F03 used a data set in the desirable frequency range (8 & 14 GHz) for the study of Foreground X, their survey was highly confined to the Galactic plane ($|b| < 4^{\circ}$). In this context, one could argue that F03 results do not necessarily extend to higher Galactic latitudes. The purpose of this Letter is to investigate if such behavior can be extendible to higher Galactic latitudes and larger areas of the sky. In order to do so, we use the Tenerife 10 and 15 GHz maps, cross-correlating them with the WMAP K-band mystery map.

2. CROSS-CORRELATION METHOD

To clarify the Foreground X puzzle, our goal is to measure the frequency dependence of the emission traced by the WMAP mystery map down to 10 GHz. We do this by cross-correlating it with the Tenerife observations (Gutiérrez et al. 2000, hereafter G00), which remain the most accurate large-area sky maps at 10 and 15 GHz and have not previously been spatially compared with the WMAP maps. Details of the cross-correlation method can be found in de Oliveira-Costa et al. (1997). This method models the vector of the Tenerife data $y$ as a sum

$$y = xa + x_{CMB} + n,$$ (1)

where $n$ is a vector that contains the Tenerife detector noise, $x$ is a vector that contains the foreground template convolved with the Tenerife triple-beam (i.e., $x_i$ would be the $i$th observation if the sky had looked like the mystery map), and “$a$” is a number that gives the level at which this foreground template is present in the Tenerife data.

The estimate of “$a$” is computed by minimizing $\chi^2 \equiv (y - xa)^T C^{-1}(y - xa)$, where the covariance matrix $C$ includes both the experimental noise $n$ and CMB sample variance in the CMB signal $x_{CMB}$. Note that these quoted error bars include the effects of both noise and chance alignments between the Tenerife data and the template map. The minimum-variance estimate of “$a$” is

$$\hat{a} = \frac{x^T C^{-1} y}{x^T C^{-1} x},$$ (2)

with variance

$$\Sigma \equiv \langle \hat{a} \hat{a}^T \rangle - \langle \hat{a} \rangle \langle \hat{a}^T \rangle = [x^T C^{-1} x]^{-1}.$$ (3)

We also perform correlations between the mystery map and less noisy data sets such as the five WMAP CMB maps. In these cases, the noise variance is so small that its exact value is irrelevant for our particular applications, so we simply use a diagonal covariance matrix $C = \sigma^2 I$. Equations (2) and (3) then become simply

$$\hat{a} = \frac{x \cdot y}{x \cdot x}, \quad \Sigma = \frac{\sigma^2}{|x|^2}.$$ (4)

Note that when using equation (3), we evaluate $\Sigma$ directly from the data, since it corresponds to the scatter around the best fit linear fit:

$$\sigma = \frac{1}{N} \sum_{i=1}^{N} (y_i - \hat{a} x_i)^{1/2}.$$ (5)

We use the latest version of the Tenerife data (Mukherjee et al. 2001), which has the estimated point source

| $|b|$ | Map | $\hat{a} \pm \delta \hat{a}$ | $\sigma_{Gal}$ | $\delta T^{(a)}$ [\mu K] |
| --- | --- | --- | --- | --- |
| $> 20^{\circ}$ | Ten10GHz | $0.88 \pm 0.45$ | 12.6 | 16.5 \pm 8.9 |
| | Ten15GHz | $1.05 \pm 0.26$ | 8.2 | 19.6 \pm 4.9 |
| | WMAP-K | $1.55 \pm 0.07$ | 23.1 | 28.9 \pm 1.3 |
| | WMAP-Ka | $0.77 \pm 0.06$ | 12.2 | 13.7 \pm 1.1 |
| | WMAP-Q | $0.49 \pm 0.06$ | 8.2 | 9.2 \pm 1.1 |
| | WMAP-V | $0.31 \pm 0.06$ | 5.2 | 5.8 \pm 1.1 |
| | WMAP-W | $0.41 \pm 0.05$ | 8.2 | 7.7 \pm 0.94 |

(a) $\delta T \equiv (\hat{a} \pm \delta \hat{a}) \sigma_{Gal}$, $\sigma_{Gal} = 18.7$ \mu K
contribution (G00) removed before calculating the correlations. We also used the first-year WMAP CMB maps at 23 (K-band), 33 (Ka-band), 40 (Q-band), 60 (V-band) & 93 (W-band) GHz (Bennett et al. 2003a), the WMAP K-band mystery map\(^4\) (B03b), and a foreground-cleaned CMB map made from a combination of the five WMAP CMB maps (Tegmark et al. 2003, hereafter TOH03). Before performing the correlations, all maps were convolved with the Tenerife triple-beam function, and data not overlapping the Tenerife observing region was discarded.

3. CROSS-CORRELATION RESULTS

Cross-correlation results are presented in Figure 1 and Table 1. All fits were done for one template at a time, and statistically significant (\(> 2\sigma\)) correlations listed in this table are in boldface. We perform our basic analysis with a \(|b| > 20^\circ\) Galactic latitude cut to facilitate comparison with older results in the literature.

3.1. Validation of the Tenerife maps against WMAP

As a first reality check, we cross-correlate the Tenerife data with the TOH03 map for a \(|b| > 20^\circ\) Galactic cut, obtaining \(\hat{\alpha} = 0.80 \pm 0.12\) at 15 GHz and \(\hat{\alpha} = 0.59 \pm 0.19\) at 10 GHz. This provides a beautiful validation of the Tenerife observations, showing a detection of CMB signal at about the 1\(\sigma\) level at 15 GHz and at the 3\(\sigma\) level at 10 GHz. This also confirms and further strengthens the results of Lineweaver et al. (1995), who cross-correlated Tenerife and COBE DMR data (Smoot et al. 1992; Bennett et al. 1996) at high Galactic latitudes and concluded that the CMB signal was consistent between the two data sets. Using only the smaller sky area outside a \(|b| > 30^\circ\) Galactic cut, we still detect the CMB signal at about the 6\(\sigma\) level at 15 GHz but no longer obtain a significant detection at 10 GHz, where the Tenerife noise levels are higher.

This cross-correlation with WMAP allows an independent test of the calibration of the Tenerife measurements. For a \(|b| > 20^\circ\) Galactic cut, the above-mentioned numbers show that the relative calibration between WMAP and Tenerife is marginally consistent with being unity, with a slight preference for lower Tenerife values at the level of 1.7\(\sigma\) at 15 GHz and 2.2\(\sigma\) at 10 GHz. Down-calibrating Tenerife by say 10\% would be comfortably consistent with both the WMAP correlations reported here and previous estimates by the Tenerife team. The 10 GHz error bar should be taken with a grain of salt, since the 10 GHz Tenerife map appears dominated by foregrounds rather than CMB. This means that the above-mentioned 10 GHz error bars are likely to underestimate the true uncertainty by not including the effect of chance foreground alignments with the TOH03 map.

In what follows, we down-calibrate the Tenerife maps by 10\% to be pedantic. Note that this has no effect whatsoever on our conclusions, which hinge on a discrepancy of an order of magnitude rather than at this level of tens of percent.

\(^4\)We also removed point sources from the mystery map before calculating the correlations. Using the point sources catalogue of B03b, we replaced the temperature for all pixels centered within a circle of 1\(^\circ\) radius around each source by the mean temperature in an annulus between 1\(^\circ\) and 2\(^\circ\) around the source. This removal does not have a major effect on the results. Removing the point sources lowers the rms fluctuations in the mystery map by about 10\%.

3.2. Foreground X results

We then cross-correlate the Tenerife data with the WMAP-K mystery map – see Figure 1 and Table 1 for results. To extend Figure 1 to higher frequencies, we also perform the cross-correlation replacing the Tenerife data by the five WMAP CMB maps. All measurements \(\delta T\) plotted in Figure 1 are obtained by multiplying the measured coefficient \(\hat{\alpha}\) by \(\sigma_{\text{Gal}}\), the rms fluctuations in the WMAP-K mystery map convolved with the Tenerife triple-beam. This means that one can interpret these numbers as being the signal that is explained by (or traced by) the WMAP-K mystery map at different frequencies. The triangles correspond to the correlations at \(|b| > 20^\circ\) cut. For comparison, we plot theoretical models for synchrotron (cyan/light grey) and Foreground X (or spinning dust – red/grey) models, assuming a synchrotron spectrum \(\delta T \propto \nu^{-2.8}\) and a spinning dust spectrum from Draine & Lazarian (1998), normalized to the \(|b| > 20^\circ\) cut at 23 GHz added to a 20K thermal dust component normalized at 90 GHz.

Figure 1 shows that if the WMAP-K mystery map were strongly dominated by synchrotron emission, as assumed in B03b, then our \(|b| > 20^\circ\) \(\delta T\)-measurement should have been about an order of magnitude larger at 15 GHz and about two order of magnitudes larger at 10 GHz. Even with a shallow spectral slope \(\nu^{-2.3}\), the discrepancy is a factor of five at 15 GHz. The fact that we observe a plateau instead, with a hint of a down-turn, strongly disfavours this synchrotron hypothesis and agrees better with the F03 interpretation that the mystery map is dominated by Foreground X, i.e., anomalous dust emission.

For this conclusion to be valid, we need to close an important loophole. B03b point out that the poor correlation between the mystery map and low-frequency synchrotron maps could be due to variations in the synchrotron spectral index across the sky. Tegmark (1998) quantifies this effect, showing that if \(\delta T \propto \nu^{\alpha}\) and the spectral index \(\alpha\) varies with an rms \(\Delta \alpha\) across the sky, then correlations of the type that we have measured are suppressed by a factor

\[
r \approx e^{-\frac{1}{2}(\Delta \alpha \ln \frac{\nu_1}{\nu_2})^2},
\]

where \(\nu_1\) and \(\nu_2\) are the two frequencies involved. Comparing \(\nu_1 = 15\) GHz and \(\nu_2 = 23\) GHz for our \(|b| > 20^\circ\) case, an \(\alpha = -2.8\) synchrotron model would predict \(\delta T(\nu_1)/\delta T(\nu_2) = (15/23)^{-2.8} \approx 3.3\) whereas we measured \(\delta T(\nu_1)/\delta T(\nu_2) = 0.46 \pm 0.15\), i.e., a factor of seven discrepancy. The MID foreground model from Tegmark et al. (2000) has \(\Delta \alpha = 0.15\), which according to equation (6) gives a completely negligible suppression factor \(r \approx 0.998\) (since the two frequencies are so close together).

Even the extreme assumption \(\Delta \alpha = 1\) gives the negligible suppression \(r \approx 0.9\), i.e., a mere 10\% effect and nowhere near explaining the factor of seven. In summary, our analysis is rather immune to the effect of spectral index variations, since the Tenerife observing frequencies are so close to those of WMAP. In contrast, equation (6) shows that the correlation between the WMAP K-band and say the 408 MHz Haslam map would be suppressed by a dramatic factor of four for \(\Delta \alpha = 0.4\), since the frequency lever arm is much longer.

Also, assuming that all rms signal seen by WMAP-K mystery map at \(|b| > 20^\circ\) cut is due to synchrotron emission, we should expect to have a synchrotron signal of
4. DISCUSSION

The spectacular WMAP data has provided crucial new information about Foreground X. Although the WMAP analyses by Lagache (2003) and Finkbeiner (2003) suggest the presence of Foreground X across the WMAP frequencies (23-93 GHz), they cannot alone rule out the hypothesis of B03b that there is no Foreground X, merely a dust-correlated synchrotron component with strong spatial variations in the spectral index. The smoking gun test for Foreground X therefore involves quantifying its behavior around 10-15 GHz, to see whether its spectrum continues to rise towards lower frequencies like synchrotron radiation or turns over.

A joint analysis of the WMAP data with the Green Bank Galactic Plane Survey makes clear that the Foreground X provides a much better fit to the data between 8 and 93 GHz than the synchrotron hypothesis could (F03). It is important to bear in mind, however, that the Green Bank Galactic Plane Survey maps the sky only at very low Galactic latitudes, leaving open the question of whether the F03 results extend to the higher Galactic latitudes that are relevant for precision cosmology. The Tenerife–WMAP-K mystery map correlations that we have measured provide the missing information in this puzzle, quantifying the behavior of Foreground X at higher Galactic latitudes than studied by F03 and lower frequencies than observed by WMAP.

Cross-correlating Tenerife with a foreground cleaned WMAP CMB map shows that the Tenerife CMB data agrees well with WMAP, detecting the WMAP CMB signal at about 7σ. Cross-correlating Tenerife with the WMAP-K mystery map shows that the mystery map cannot be dominated by synchrotron emission at Galactic latitudes $|b| > 20^\circ$, since this would give 15 GHz measurements almost an order of magnitude larger than observed and even worse discrepancies at 10 GHz. Instead, we find that the Foreground X spectrum has a plateau and a hint of a down-turn below 20 GHz, just as predicted in spinning dust models.

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