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THE QUEST FOR MICROWAVE FOREGROUND X

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ABSTRACT

The *Wilkinson Microwave Anisotropy Probe* (*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's "synchrotron" template is in fact dominated not 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 cosmic microwave background 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 — methods: data analysis — radiation mechanisms: nonthermal — radiation mechanisms: thermal

On-line material: color figure

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 μm dust emission, but with a spectrum rising toward 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* Differential Microwave Radiometer (DMR) data by Kogut et al. (1996a, 1996b), who tentatively identified it as free-free emission.[5] It has since been detected in a variety of data sets such as Saskatoon (de Oliveira-Costa et al. 1997), the Owens Valley Radio Observatory (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 Advanced Cosmic Microwave Explorer/South Pole 1994 (ACME/SP94) data (Hamilton & Ganga 2001), Python V (Mukherjee et al. 2003), the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) data (Lagache 2003; Finkbeiner 2003), as well as in some other non-CMB data sets between 8 and 15 GHz (Finkbeiner et al. 2002; Finkbeiner et al. 2003, hereafter F03). Adding pieces to this puzzle, joint reanalysis of the *COBE* DMR and the 19 GHz survey (Banday et al. 2003) and the OVRO and 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.[6]

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 Galactic Plane Survey maps,[7] F03 have challenged these conclusions, arguing that the *WMAP* team's "synchrotron" template is in fact dominated not by synchrotron radiation but by some dust-related Galactic emission process, perhaps spinning dust grains. Given this dispute about whether or not the *WMAP* K-band "synchrotron map" produced by B03b is really a map of synchrotron radiation, let us hereafter refer to it as the *mystery map*, to avoid interpretative language.

The logic behind identifying the *WMAP* team's 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 μm dust emission and Hα emission, respectively. F03 argue that, in contrast, the *WMAP* team's 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 in the spectral index, whereas F03 argue that it is because the map (essentially defined as a component having a synchrotron-like spectrum across the *WMAP* frequencies 23–

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[5] Draine & 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 that 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 & Lazarian 1999).
[6] See http://lambda.gsfc.nasa.gov/product/map.
[7] The Green Bank Galactic Plane Survey maps the Galactic plane within $\pm 4°$, 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.

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 23GHz 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 toward 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 and 14 GHz) for the study of foreground X, their survey was highly confined to the Galactic plane ($|b| < 4°$). In this context, one could argue that F03's 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),[8] 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 $\boldsymbol{y}$ as a sum

$$\boldsymbol{y} = \boldsymbol{x}a + \boldsymbol{x}_{\rm CMB} + \boldsymbol{n}, \quad (1)$$

where $\boldsymbol{n}$ is a vector that contains the Tenerife detector noise, $\boldsymbol{x}$ is a vector that contains the foreground template convolved with the Tenerife triple beam (i.e., $\boldsymbol{x}_i$ would be the ith 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 $\chi^2 \equiv (\boldsymbol{y} - \boldsymbol{x}a)^T\boldsymbol{C}^{-1}(\boldsymbol{y} - \boldsymbol{x}a)$, where the covariance matrix $\boldsymbol{C}$ includes both the experimental noise $\boldsymbol{n}$ and CMB sample variance in the CMB signal $\boldsymbol{x}_{\rm CMB}$. 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

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

with variance[9]

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

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 $\boldsymbol{C} = \sigma^2\boldsymbol{I}$. Equations (2) and (3) then become simply

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

Note that when using equation (3), we evaluate $\boldsymbol{C}$ using the known noise properties of the Tenerife data (G00). However, when using equation (4), we simply measure σ directly from the data, since it corresponds to the scatter around the best-fit linear fit:

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

We use the latest version of the Tenerife data (Mukherjee et al. 2001), which has the estimated point-source 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), and 93 (W band) GHz (Bennett et al. 2003a), the *WMAP* K-band mystery map[10] (B03b), and a foreground-cleaned CMB map made from a combination of the five *WMAP* CMB maps (Tegmark, de Oliveira-Costa, & Hamilton 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 were 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 σ) correlations listed in this table are in boldface. Since the fluctuation levels depend strongly on Galactic latitude, we perform our analysis for two different latitude cuts: 20° and 30°. Since the bulk of the correlation analysis presented in the literature is done for a $|b| > 20°$ cut, we use this cut below unless explicitly stated.

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 $|b| > 20°$ Galactic cut, obtaining $\hat{\boldsymbol{a}} = 0.80 \pm 0.12$ at 15 GHz and $\hat{\boldsymbol{a}} = 0.59 \pm 0.19$ at 10 GHz. This provides a beautiful validation of the Tenerife observations, showing a detection of the CMB signal at about the 7 σ

[8] The Tenerife switched-beam experiment was a ground-based sky survey between $0° \leq$ R.A. $\leq 360°$ and $30° \leq \delta \leq 45°$. It was carried out at an angular resolution of 5°.1 FWHM with an instrument that uses a double-differencing technique. Data were taken at frequencies of 10 and 15 GHz (we omit the 33 GHz data here because of a lack of low-latitude sky coverage).

[9] Note that the detector noise in the *WMAP* data is extremely small compared with that in the Tenerife data. Once the *WMAP* data are smoothed to the Tenerife resolution, its noise becomes so small that its exact value is irrelevant for our particular application. We therefore take it to be zero and use only the Tenerife covariance matrix $\boldsymbol{C}$ when performing our calculations.

[10] We also removed point sources from the mystery map before calculating the correlations. Using the point-source catalog of B03b, we replaced the temperature for all pixels centered within a circle of 1° radius around each source by the mean temperature in an annulus between 1° and 2° 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%.

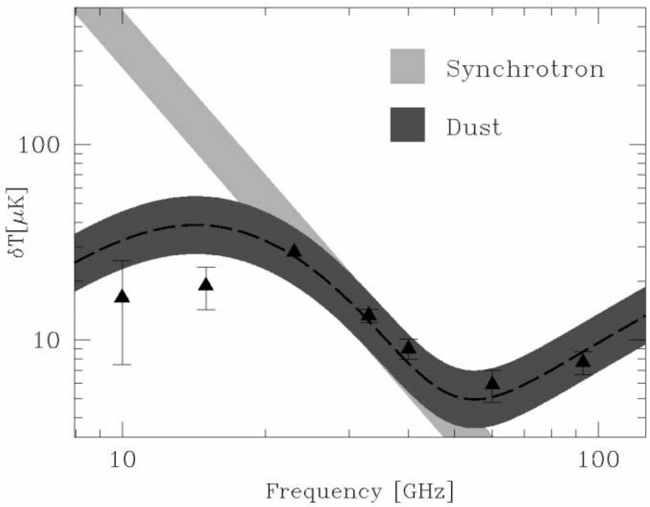

FIG. 1.—Contribution of the foreground traced by the mystery map (the *WMAP* K-band "synchrotron" template) at different frequencies for the $|b| > 20°$ Galactic cut (*triangles*). The shaded bands show models for synchrotron radiation (*cyan/light gray*) and foreground X emission (*red/gray*), assuming a synchrotron spectrum $\delta T \propto \nu^{-2.8}$ and a spinning dust spectrum from Draine & Lazarian (1998), normalized to the $|b| > 20°$ cut at 23 GHz added to a 20 K thermal dust component normalized at 90 GHz. [*See the electronic edition of the Journal for a color version of this figure.*]

level at 15 GHz and at the 3 σ 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 $|b| > 30°$ Galactic cut, we still detect the CMB signal at about the 6 σ 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 us to make an independent test of the calibration of the Tenerife measurements. For a $|b| > 20°$ 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 σ at 15 GHz and 2.2 σ 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 the 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.

3.2. *Foreground X Results*

We then cross-correlate the Tenerife data with the *WMAP*-K mystery map (see Fig. 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 δT plotted in Figure 1 are obtained by multiplying the measured coefficient $\hat{a}$ by $\sigma_{\rm Gal}$, the rms fluctuations in the *WMAP*-K mystery map convolved with the

TABLE 1
CORRELATIONS WITH THE MYSTERY MAP[a]

Map	$\hat{a} \pm \delta\hat{a}$	$\hat{a}/\delta\hat{a}$[b]	$\sigma_{\rm Gal}$ (μK)	δT[c] (μK)	$\delta T_{\rm syn}$ (μK)
$|b| > 20°$					
Tenerife 10 GHz	0.88 ± 0.48	1.8	18.7	16.5 ± 8.9	347.7
Tenerife 15 GHz	1.05 ± 0.26	**4.0**	…	19.6 ± 4.9	95.8
WMAP-K	1.55 ± 0.07	**22.1**	…	28.9 ± 1.3	36.4
WMAP-Ka	0.73 ± 0.06	**12.2**	…	13.7 ± 1.1	13.8
WMAP-Q	0.49 ± 0.06	**8.2**	…	9.2 ± 1.1	7.3
WMAP-V	0.31 ± 0.06	**5.2**	…	5.8 ± 1.1	2.0
WMAP-W	0.41 ± 0.05	**8.2**	…	7.7 ± 0.9	0.8
$|b| > 30°$					
Tenerife 10 GHz	−2.51 ± 1.56	−1.5	9.3	−23.3 ± 14.5	51.5
Tenerife 15 GHz	−0.49 ± 0.96	−0.5	…	−4.6 ± 8.9	14.2

[a] Upper limits are 2 σ.
[b] Statistically significant (>2 σ) correlations are in boldface.
[c] $\delta T \equiv (\hat{a} \pm \delta\hat{a})\sigma_{\rm Gal}$.

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 the $|b| > 20°$ cut. For comparison, we plot theoretical models for synchrotron (*cyan/light gray*) and foreground X (or spinning dust; *red/gray*) models, assuming a synchrotron spectrum $\delta T \propto \nu^{-2.8}$ and a spinning dust spectrum from Draine & Lazarian (1998), normalized to the $|b| > 20°$ cut at 23 GHz added to a 20 K 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 $|b| > 20°$ δT-measurement should have been about an order of magnitude larger at 15 GHz and about 2 order of magnitudes larger at 10 GHz. Even with a shallow spectral slope $\nu^{-2.3}$, the discrepancy is a factor of 5 at 15 GHz. For a straightforward comparison, we present the expected amplitude of the synchrotron model ($\delta T_{\rm syn}$) in the last column of Table 1. The fact that we observe a plateau instead, with a hint of a downturn, strongly disfavors this synchrotron hypothesis and agrees better with the F03 interpretation that the mystery map is dominated by foreground X, i.e., anomalous dust emission.[11]

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 α varies with an rms $\Delta\alpha$ across the sky, then correlations of the type that we have measured are suppressed by a factor

$$r \approx e^{-1/2[\Delta\alpha \ln(\nu_2/\nu_1)]^2}, \quad (6)$$

where ν_1 and ν_2 are the two frequencies involved. Comparing $\nu_1 = 15$ GHz and $\nu_2 = 23$ GHz for our $|b| > 20°$ 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 $\delta T(\nu_1)/\delta T(\nu_2) = 0.46 \pm$

[11] We also performed a joint fit of the *WMAP*-K mystery map with the DIRBE 100 μm (Boggess et al. 1992) dust template and the Haslam (Haslam et al. 1982) synchrotron template in the Tenerife observing region. For a $|b| > 20°$ Galactic cut, we found the DIRBE-correlated contribution to be highly significant (30.8 ± 1.2 μK), whereas the Haslam-correlated contribution was not statistically significant (with the 2 σ upper limit of ≈3 μK). This reenforces our conclusion that the *WMAP*-K mystery map is dominated by dust emission, not synchrotron radiation.

0.15, i.e., a factor of 7 discrepancy. The middle-of-the-road 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 7. 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 mystery map and, say, the 408 MHz Haslam map would be suppressed by a dramatic factor of 4 for $\Delta\alpha = 0.4$ since the frequency lever arm is much longer.

Also, assuming that all of the rms signal seen by *WMAP*-K mystery map at $|b| > 20°$ cut is due to synchrotron emission, we should expect to have a synchrotron signal of $18.7(10/23)^{-2.8} \approx 192.6\ \mu$K at 10 GHz and $18.7(15/23)^{-2.8} \approx 61.9\ \mu$K at 15 GHz. For comparison, the observed Tenerife rms CMB signal is $\delta T_\ell = 30^{+15}_{-11}\ \mu$K (G00).

4. DISCUSSION

The spectacular *WMAP* data have 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 toward 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 agree well with *WMAP*, detecting the *WMAP* CMB signal at about 7 σ. Cross-correlating Tenerife with the *WMAP*-K mystery map shows that the mystery map cannot be dominated by synchrotron emission at Galactic latitudes $|b| > 20°$ 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 downturn below 20 GHz, just as predicted in spinning dust models.

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