GALACTIC CONTAMINATION IN THE QMAP EXPERIMENT

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ABSTRACT

We quantify the level of foreground contamination in the QMAP cosmic microwave background data with two objectives: (1) to measure the level to which the QMAP power spectrum measurements need to be corrected for foregrounds and (2) to use this data set to further refine current foreground models. We cross-correlate the QMAP data with a variety of foreground templates. The 30 GHz Ka-band data are found to be significantly correlated with the Haslam 408 MHz and Reich & Reich 1420 MHz synchrotron maps but not with the Diffuse Infrared Background Experiment 240, 140, and 100 μm maps or the Wisconsin H-Alpha Mapper survey. The 40 GHz Q band has no significant template correlations. We discuss the constraints that this places on synchrotron, free-free, and dust emission. We also reanalyze the foreground-cleaned Ka-band data and find that the two band power measurements are lowered by 2.3% and 1.3%, respectively.

Subject headings: cosmic microwave background — diffuse radiation — methods: data analysis — radiation mechanisms: nonthermal — radiation mechanisms: thermal

1. INTRODUCTION

Quantifying Galactic emission in a cosmic microwave background (CMB) map is interesting for two different reasons. On one hand, the CMB is known to be a gold mine of information about cosmological parameters. Taking full advantage of this requires accurate modeling and subtraction of Galactic foreground contamination. On the other hand, the high-fidelity maps being produced as part of the current CMB gold rush offer a unique opportunity for secondary non-CMB science. This includes a greatly improved understanding of Galactic emission processes between 10 and 10^4 GHz.

This Letter is motivated by both of these reasons. The QMAP experiment (Devlin et al. 1998; Herbig et al. 1998; de Oliveira-Costa et al. 1998a, hereafter dOC98a) is one of the CMB experiments that has produced a sky map with accurately modeled noise properties, lending itself to a cross-correlation analysis with a variety of foreground templates. We present such an analysis in § 2, then compute the corresponding correction to the published QMAP power spectrum measurements in § 3, and finish by discussing the implications for Galactic foreground modeling in § 4.

2. METHOD AND BASIC RESULTS

The multicomponent fitting method that we use was presented in detail in de Oliveira-Costa et al. 1999 (hereafter dOC99), so we review it only briefly here. The joint QMAP map from both flights consists of N = 3164 (Ka-band, 26–36 GHz) and 4875 (Q-band, 36–46 GHz) measured sky temperatures (pixels). We model this map as a sum of CMB fluctuations, detector noise ni, and M Galactic components whose spatial distributions are traced in part by external foreground templates. Writing these contributions as N-dimensional vectors, we obtain

\[ y = Xa + x + n, \]

where \( X \) is an \( N \times M \) matrix whose rows contain the various foreground templates convolved with the QMAP beam (i.e., \( X_j \) would be the \( j \)th observation if the sky had looked like the \( j \)th foreground template) and \( a \) is a vector of size \( M \) that gives the levels at which these foreground templates are present in the QMAP data.

We treat \( n \) and \( x \) as uncorrelated random vectors with zero mean and the \( X \) matrix as constant, so the data covariance matrix is given by

\[ C = \langle yy^T \rangle - \langle y \rangle \langle y^T \rangle = \langle xx^T \rangle + \langle nn^T \rangle, \]

where

\[ \langle xx^T \rangle_{ij} = \sum_{l=2}^{\infty} \frac{2l + 1}{4\pi} \delta(\hat{\mathbf{r}}, \hat{\mathbf{r}}) W_l^2 C_l \]

is the CMB covariance matrix and \( \langle nn^T \rangle \) is the QMAP noise covariance matrix. We use a flat power spectrum \( C_l \propto l(l+1) \) normalized to a \( Q_{\text{obs}} = (5C_2/4\pi)^{1/2} = 30 \) μK (dOC98a). We model the QMAP beam as a Fisher function with an FWHM = (8 ln 2)^{1/2} \( \sigma = 0.9 \) for the Ka band and 0.6 for the Q band, which gives \( W_l \approx e^{-\sigma^2(l+1)/2} \).

Since our goal is to measure \( a \), both \( x \) and \( n \) act as unwanted noise in equation (1). Minimizing \( \chi^2 \equiv \langle (y - Xa)C^{-1}(y - Xa) \rangle \) yields the minimum-variance estimate of \( a \),

\[ \hat{a} = [X^T C^{-1} X]^{-1} X^T C^{-1} y. \]

with covariance matrix

\[ \Sigma = \langle \hat{a} \hat{a}^T \rangle - \langle \hat{a} \rangle \langle \hat{a}^T \rangle = [X^T C^{-1} X]^{-1}. \]

The residual effects of time-domain noise correlations and scan-synchro-nous offsets are included in \( \langle nn^T \rangle \). A detailed description of the calculation of the QMAP noise covariance matrix is presented in dOC98a.
The error bars on individual correlations are therefore \( \Delta \hat{a} = \sigma_{\hat{a}} / \sqrt{n} \). This includes the effect of chance alignments between the CMB and the various template maps, since the CMB anisotropy term is incorporated in \( \langle xx' \rangle \).

We cross-correlate the QMAP data with two different synchrotron templates: the 408 MHz survey (Haslam et al. 1982) and the 1420 MHz survey (Reich 1982; Reich & Reich 1986), hereafter Has and R&R, respectively. To study dust and/or free-free emission, we cross-correlate the QMAP data with three Diffuse Infrared Background Experiment (DIRBE) sky maps at wavelengths of 100, 140, and 240 \( \mu m \) (Boggess et al. 1992) and with the Wisconsin H-Alpha Mapper (WHAM)\(^7\) survey (Haffner, Reynolds, & Tufte 1999). For definiteness, we use the DIRBE 100 \( \mu m \) channel when placing limits below since it is the least noisy of the three DIRBE channels. Figure 1, three of our templates are shown together with the QMAP Ka band. Most of our interesting results come from the QMAP Ka band since the Q band was substantially noisier (the opposite was true for the Saskatoon experiment; see de Oliveira-Costa et al. 1997, hereafter dOC97).

Before calculating the correlations, we convolve the template maps with the QMAP beam function. We also remove the monopole and dipole from both the templates and the QMAP maps. As a consequence, our results depend predominantly on the small-scale intensity variations in the templates and are insensitive to the zero levels of the QMAP data and the templates.

Table 1 shows the coefficients \( \hat{a} \) and the corresponding fluctuations in antenna temperature in the QMAP data \( \Delta T = \hat{a} \sigma_{\hat{a}} \), where \( \sigma_{\hat{a}} \) is the standard deviation of the template map. Statistically significant \((>2 \sigma)\) correlations are listed in boldface.

Note that the fits are done jointly for \( M = 3 \) templates.\(^8\) The DIRBE, Haslam, and H\( \alpha \) correlations listed in Table 1 correspond to joint 100 \( \mu m \)–Has–H\( \alpha \) fits, whereas the R\&R numbers correspond to a joint 100 \( \mu m \)–R\&R–H\( \alpha \) fit. Only the two synchrotron templates are found to be correlated with the Ka band, while no correlations are found for the Q band. Repeating the analysis done for two different Galactic cuts (20° and 30°) indicates that the bulk of this contamination is at latitudes lower than 30°.

As in dOC97, de Oliveira-Costa et al. 1998b (hereafter dOC98b), and dOC99, the cross-correlation software was tested by analyzing constrained realizations of CMB and QMAP instrument noise. From 1000 realizations, we recovered unbiased estimates of \( \hat{a} \) with a variance in excellent agreement with equation (5). As an additional test, we computed \( \chi^2 \equiv (y - X \hat{a})C_{X}^{-1}(y - X \hat{a}) \) and obtained \( \chi^2/N \approx 1 \) in all cases. Including a synchrotron template lowered \( \chi^2 \) by a significant amount (18 for R\&R and 9 for Has), whereas adding the other templates resulted in insignificant reductions \( \Delta \chi^2 \sim 1 \).

\(^7\) Details also available at http://www.astro.wisc.edu/wham.

\(^8\) We obtain similar coefficients \( \hat{a} \) when the templates are fitted singly.
highest correlations for the original pointing. We reanalyzed the QMAP data set with the foregrounds allowed an independent confirmation of the QMAP result. Galactic foregrounds are expected to have a redder power spectrum than the CMB. The Ka-band correction is slightly smaller on small angular scales: 1.3% instead of 2.3%. This is expected since diffuse emission per unit foreground. Such measurements were used to normalize recent foreground models such as those of Bouchet & Gispert (1999) and Tegmark et al. (2000).

Below we discuss how our QMAP results affect such models.

### 4.2. Spinning Dust and Free-Free Emission

An important question is whether the DIRBE-correlated signal seen by so many experiments (Fig. 4, top) is due to dust-correlated free-free emission (Kogut et al. 1996) or spinning dust grains (Draine & Lazarian 1998). The turnaround at low frequencies suggests a spinning dust interpretation (dOC99), but an analysis using improved Tenerife data (Mukherjee et al.

\[ \sigma_{\text{Gal}} \]

We therefore plot \( \Delta T \) instead, i.e., the factor giving the frequency dependence of emission per unit foreground. Such measurements were used to normalize recent foreground models such as those of Bouchet & Gispert (1999) and Tegmark et al. (2000). Below we discuss how our QMAP results affect such models.

#### 4.1. Synchrotron

Writing the frequency dependence as \( a \propto \nu^{b} \) and recalling that the correlation coefficients are, by definition, \( a = 1 \) K \( \mu K^{-1} = 10^{b} \) for Has at 408 MHz and \( a = 1 \) mK \( \mu K^{-1} = 10^{b} \) for R&R at 1420 MHz, we obtain the spectral index limits \(-2.7 \leq b \leq -3.3 \) for the Ka–Has correlation and \(-2.6 \leq b \leq -2.8 \) for the Ka–R&R correlation. These values are slightly steeper than the canonical subgigahertz slope of \(-2.7 \leq b \leq -2.9 \) (Davies, Watson, & Gutierrez 1996; Platania et al. 1998) but consistent with a steepening of the spectrum of cosmic-ray electrons at higher energies (Rybicki & Lightman 1979, p. 174).

The relatively high QMAP synchrotron signal seen in Figure 4 could be interpreted as a slight spatial variability of the frequency dependence (Tegmark et al. 2000) but may also have other explanations. For instance, the worst striping problems in the Haslam map are right around the north celestial pole, which may have caused Saskatoon to underestimate the true synchrotron level there (dOC97).

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\[ \Delta T = \left(\frac{10 + 1.2\left(\nu^{2}\right)}{10^{2}}\right) \text{ mK} \]

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substantial H\alpha emission would be expected as well. Figure 4 (bottom) shows the expected correlation $a$ for the case of 8000 K gas (Bennett et al. 1992). It is seen that the H\alpha correlation, although marginal at best, is consistent with the theoretical curve. However, this possible $\sim 15 \mu K$ free-free contribution cannot explain the full $\sim 40 \mu K$ DIRBE-correlated signal from the other measurements in Figure 4.

To clarify this issue, we computed the correlation between the dust and H\alpha maps. As described in dOC99, equation (5) shows that we can interpret $\Sigma$ as the covariance between the various templates with dimensionless correlation coefficients $r_i = \Sigma_i (\Sigma_i^{-1})^{-0.5}$. Like in dOC99, the DIRBE maps were found to be almost perfectly correlated, and they were essentially uncorrelated ($r^2 \leq 3\%$) with the radio maps. The Has and R&R maps are correlated with $r \approx 83\%$ for $b > 20^\circ$. As a new result, we obtain a marginal correlation of $r \approx 0.2$ between the DIRBE maps and the H\alpha template. Since the statistical properties of these maps are not accurately known, we computed error bars by repeating the analysis with one of the templates replaced by $2 \times 2 \times 72 = 288$ transformed maps, rotated around the Galactic axis by multiples of $5^\circ$ and/or flipped vertically and/or horizontally. The actual correlation was found to be larger than 85\% of these, showing that the correlation is not significant at the 2 $\sigma$ level: $a = (0.25 \pm 0.19) R MJy^{-1} sr^{-1}$ (1 $\sigma$). This result is significantly smaller than that recently found by Lagache et al. (2000) for their DIRBE–WHAM correlation, which was done in a different region of the sky, but compatible with other marginal dust–H\alpha correlations (McCullough 1997; Kogut 1997).

This poor correlation is a challenge for the pure free-free hypothesis, which maintains that microwave emission traces dust because dust traces free-free emission. A cross-correlation analysis with large frequency and sky coverage will hopefully be able to determine unambiguously the relative levels of free-free and dust emission in the near future.

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