HIGH-LATITUDE GALACTIC DUST EMISSION IN THE BOOMERANG MAPS

S. Masi,1 P. A. R. Ade,2 J. J. Bock,1,4 A. Borsacleri,1 B. P. Crill,1 P. de Bernardis,1 M. Giacometti,1 E. Hivon,3 V. V. Hristov,1 A. E. Lange,3 P. D. Mauskopf,6 T. Montroy,7 C. B. Netterfield,8 E. Pascale,5 F. Piacentini,1 S. Prunet,8 and J. Ruhl1

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ABSTRACT

We present millimeter-wave observations obtained by the BOOMERANG (Balloon Observations Of Millimetric Extragalactic Radiation ANd Geophysics) experiment of Galactic emission at intermediate and high (b < −20°) Galactic latitudes. We find that this emission is well correlated with extrapolated dust maps and is spectrally consistent with thermal emission from interstellar dust (ISD). The ISD brightness in the 410 GHz map has an angular power spectrum C_l ∝ l^{-3} with 2 ≤ β ≤ 3. At 150 GHz and at multipoles l ∼ 200, the angular power spectrum of the ISD-correlated dust signal is estimated to be (l + 1)c /2π = 3.7 ± 2.9 μK^2. This is negligible with respect to the cosmic microwave background (CMB) signal measured by the same experiment (l + 1)c /2π = 4700 ± 540 μK^2. For the uncorrelated dust signal, we set an upper limit to the contribution to the CMB power at 150 GHz and l ∼ 200 of (l + 1)c /2π < 3 μK^2 at 95% CL.

Subject headings: cosmic microwave background — dust, extinction — infrared: ISM: continuum — submillimeter

On-line material: color figures

1. INTRODUCTION

The patchy emission of our Galaxy is a major concern for measurements of the anisotropy of the cosmic microwave background (CMB). A “precision” phase, where temperature fluctuations are measured with a sensitivity of tens of microkelvins per pixel, has now begun (de Bernardis et al. 2000; Hanany et al. 2000). Forthcoming full-sky space missions (MAP and Planck) and a host of future suborbital experiments are expected to reach sensitivities of a few microkelvins per pixel. To fully exploit the potential of these new surveys, our knowledge of the diffuse emission of our Galaxy at high Galactic latitudes must improve as well.

At frequencies above ∼100 GHz, this emission is dominated by thermal radiation from large dust grains, heated by the interstellar radiation field to T ∼ 10–30 K. The interstellar dust (ISD) is distributed in filamentary “cirrus”-like clouds and covers the sky even at high Galactic latitudes (Low et al. 1984). The spectrum of this component in the 300–3000 GHz range has been mapped by the Far Infrared Absolute Spectrometer experiment (Wright et al. 1991) with 7° angular resolution and by the Diffuse Infrared Background Experiment (DIRBE) at frequencies greater than 1250 GHz (Hauser et al. 1998; Arendt et al. 1998) with resolution ∼0.7°. Arcminute resolution maps from the Infrared Astronomical Satellite (IRAS) are available only at ν > 3000 GHz. These have been recalibrated using the DIRBE maps at 3000 and 1250 GHz (Schlegel, Finkbeiner, & Davis 1998) and extrapolated to longer wavelengths using a variety of physical models (Lagache et al. 1998, 1999; Finkbeiner, Davis, & Schlegel 1999; tegmark et al. 2000). At those longer wavelengths, very few experimental data are available at subdegree resolution (see, e.g., Masi et al. 1995, 1996; Lim et al. 1996; Leitch et al. 1997; de Oliveira-Costa et al. 1997; Cheng et al. 1997; Hamilton & Ganga 2001 and references therein), “Anomalous” emission, morphologically correlated with the IRAS and/or DIRBE map but much larger than a naive extrapolation of thermal dust emission (Draine & Lazarian 1998; Kogut et al. 1996a), has been detected in microwaves (Kogut et al. 1996a, 1996b; Lim et al. 1996; Leitch et al. 1997; de Oliveira-Costa et al. 1997, 1998, 2000; Mukherjee et al. 2001).

Here we analyze 90, 150, 240, and 410 GHz maps of 3% of the sky at Galactic latitudes −60° ≤ b ≤ −10°. We compute the frequency and angular power spectrum of the fluctuations in these maps. We find that these maps are correlated with the emission mapped by IRAS extrapolated to our wavelengths using model 8 in Finkbeiner et al. (1999). We will refer to this as FDS8 in the following. We also set upper limits to the level of residual, non-CMB structures that are not correlated with FDS8.

2. OBSERVATIONS

We use the maps obtained from the 1998 long-duration flight of the BOOMERANG (Balloon Observations Of Millimetric Extragalactic Radiation ANd Geophysics) experiment (de Bernardis et al. 2000), all pixelized with 7° pixels and smoothed to a resolution of 22.5 FWHM. The instrument was calibrated against the CMB dipole at 90, 150, and 240 GHz (10% uncertainty) and against the rms CMB anisotropy at 410 GHz (20% uncertainty).
explained in next section. As representative of ISD fluctuations in the Galaxy in general, we use the FDS8 dust maps as maps to other maps of the sky. In addition to the four frequencies that have to be included if we want to consider the measured spectrum for a Gaussian field having the same power spectrum. The latter is computed to be negligible. The errors have been computed for the finite size of the cap, for filtering applied in the time domain, and for the contribution of instrumental noise (E. Hivon et al. 2001, in preparation). The results are shown in the bottom panel of Figure 1. The morphological and amplitude agreement of the two maps provides evidence that the 410 GHz data represent a good monitor for ISD emission in the BOOMERANG data. Bright compact structures apparent in the difference map correspond to the dense, cool cores of clouds that are not well modeled in FDS8. The remaining structures are mostly due to residual noise in the BOOMERANG data. In a similar way, we obtained extrapolated maps for the other BOOMERANG channels. We have computed the power spectrum of the 410 GHz map in three circular regions, each 18\degree in diameter, centered at (R.A., decl., b) = (10\degree, −47\degree, −17\degree), (92\degree, −48\degree, −27\degree), (74\degree, −46\degree, −38\degree), i.e., low, intermediate, and high Galactic latitudes, respectively. We used a spherical harmonics transform and corrected for the finite size of the cap, for filtering applied in the time domain, and for the contribution of instrumental noise (E. Hivon et al. 2001, in preparation). The results are shown in Figure 2. The contribution of CMB anisotropy to these spectra is computed to be negligible. The errors have been computed by adding an estimate of instrumental noise and an estimate of sampling variance (see, e.g., Scott, Srednicki, & White 1994) for a Gaussian field having the same power spectrum. The latter has to be included if we want to consider the measured spectrum as representative of ISD fluctuations in the Galaxy in general. The spectrum at the highest Galactic latitude is basically an upper limit for dust fluctuations, since the residual fluctuations are comparable to our estimate of detector noise plus CMB anisotropy. The spectra at low and intermediate latitudes are well fitted by a power law \( c_s \sim l^{-\delta} \) as in previous studies based on \textit{IRAS} and DIRBE maps (Gautier et al. 1992; Low & Cutri 1994; Guarini, Melchiorri, & Melchiorri 1995; Wright 1998; Schlegel et al. 1998). We find a power-law exponent \( 2 \leq \delta \leq 3 \) for a Galactic dust component in the maps obtained from the raw data using an iterative algorithm (Prunet et al. 2001). This reduces the large-scale artifacts due to 1/f noise and correctly estimates the noise in the data stream while producing a maximum likelihood map. Structures at scales larger than 10\degree are effectively removed in the process. This fact must be taken into account when comparing the BOOMERANG maps to other maps of the sky. In addition to the four frequencies mapped by BOOMERANG, we use the FDS8 dust maps as explained in next section.

3. DATA ANALYSIS

The highest frequency channel of the BOOMERANG photometer is centered at 410 GHz, with an FWHM of 26 GHz. At this frequency, the brightness of the CMB is smaller than at our lower frequencies, while thermal emission from Galactic dust is much larger. The 410 GHz map of the sky obtained by BOOMERANG is dominated by faint cirrus clouds at intermediate Galactic latitudes (−20\degree < b < −10\degree). In Figure 1 we compare our 410 GHz map (top panel) to the FDS8 extrapolation of the \textit{IRAS} map (middle panel) obtained as follows. FDS8 assumes two components of ISD with different temperature and spectral index of dust emissivity. The two temperatures depend on the observed direction. On the average \( T_{d,1} \sim 16.2 \text{ K}, \ T_{d,2} \sim 9.4 \text{ K}, \) and the average ratio between dust brightness at 3000 GHz and dust brightness at 410 GHz is \( \sim 13 \). The extrapolated map has been sampled along the scans of the 410 GHz channel of BOOMERANG and then high-pass and low-pass filtered using the 410 GHz detector transfer function, in order to create a synthesized time stream. This has been processed in the same way as the BOOMERANG data and smoothed to 22\arcmin to obtain the map shown in the middle panel of Figure 1. The morphological and amplitude agreement of the two maps provides evidence that the 410 GHz data represent a good monitor for ISD emission in the BOOMERANG data. Bright compact structures apparent in the difference map (Fig. 1, bottom panel) correspond to the dense, cool cores of clouds that are not well modeled in FDS8. The remaining structures are mostly due to residual noise in the BOOMERANG data. In a similar way, we obtained extrapolated maps for the other BOOMERANG channels.

We have computed the power spectrum of the 410 GHz map in three circular regions, each 18\degree in diameter, centered at (R.A., decl., b) = (10\degree, −47\degree, −17\degree), (92\degree, −48\degree, −27\degree), (74\degree, −46\degree, −38\degree), i.e., low, intermediate, and high Galactic latitudes, respectively. We used a spherical harmonics transform and corrected for the finite size of the cap, for filtering applied in the time domain, and for the contribution of instrumental noise (E. Hivon et al. 2001, in preparation). The results are shown in Figure 2. The contribution of CMB anisotropy to these spectra is computed to be negligible. The errors have been computed by adding an estimate of instrumental noise and an estimate of sampling variance (see, e.g., Scott, Srednicki, & White 1994) for a Gaussian field having the same power spectrum. The latter has to be included if we want to consider the measured spectrum as representative of ISD fluctuations in the Galaxy in general. The spectrum at the highest Galactic latitude is basically an upper limit for dust fluctuations, since the residual fluctuations are comparable to our estimate of detector noise plus CMB anisotropy. The spectra at low and intermediate latitudes are well fitted by a power law \( c_s \sim l^{-\delta} \) as in previous studies based on \textit{IRAS} and DIRBE maps (Gautier et al. 1992; Low & Cutri 1994; Guarini, Melchiorri, & Melchiorri 1995; Wright 1998; Schlegel et al. 1998). We find a power-law exponent \( 2 \leq \delta \leq 3 \).
spectra are shown as solid lines and labeled by their best-fit slope $\beta$. We consider the spectrum as an upper limit for dust brightness fluctuations. Best-fit power-law functions due to any dust component not correlated with the signal is small with respect to the detector noise, and we estimate upper limits for the fluctuations at $b < -20^\circ$. In fact, in this latitude range, the pixel-pixel scatter plot of our 410 GHz channel versus FDS8 at 410 GHz has a best-fit line with slope $0.644 \pm 0.038$, a highly significant correlation. This result has been obtained using a jackknife technique; we divide the latitude band $-20^\circ < b < -10^\circ$ into five $10^\circ \times 10^\circ$ regions, and we compute the best-fit slope for each of the regions. We then compute the average and standard error on the average as our best estimate of the general slope. In this way, we properly take into account the fact that deviations from an ideal correlation are dominated by fluctuations in dust properties, rather than by detector noise.

$\beta \approx 3$, consistent with the studies cited above, thus extending this result to wavelengths very close to those used for CMB studies. The power spectra of FDS8 at 410 GHz in the same sky regions are also shown in Figure 2 for comparison. The agreement is very good for the region centered at $b = -17^\circ$, where detector noise is negligible. The agreement is also good in the region centered at $b = -27^\circ$, but a systematic amplitude difference is evident. We estimate upper limits for the fluctuations due to any dust component not correlated with IRAS by computing the spectrum of the difference map obtained removing the F8 map from the measured 400 GHz map. The upper limits are of the same order of magnitude of the errors in the measured power spectrum of the 400 GHz map.

We made pixel-pixel correlations between our four maps and the corresponding FDS8 maps. The signal in each of our channels is a linear combination of Galactic emission, CMB anisotropies, and noise, with relative weights depending on the Galactic latitude and on the frequency of the channel. The advantage of correlating with the FDS8 maps is that the noises are uncorrelated, and at 3000 GHz the CMB is negligible. Any detected correlation is thus due to Galactic emission. In the BOOMERANG 410 GHz channel, we expect to have little CMB anisotropy and dominant Galactic dust emission, at least

![Diagram](image-url)

**Fig. 2.**—Angular power spectrum of the BOOMERANG 410 GHz map, for three disks with diameter 18°, centered at different Galactic latitudes (squares: $b = -17^\circ$; circles: $b = -27^\circ$; triangles: $b = -38^\circ$). At the highest latitude, the signal is small with respect to the detector noise, and we consider the spectrum as an upper limit for dust brightness fluctuations. Best-fit power-law spectra $\beta = 1.0$ are shown as solid lines and labeled by their best-fit slope $\beta$. The dashed lines are the power spectrum of the FDS8 map at 410 GHz in the same sky regions. The large thin error bars include cosmic/sampling variance, while the smaller thick ones are from instrumental noise only. [See the electronic edition of the Journal for a color version of this figure.]

![Table](table-url)

**Table 1**

| Band Center (GHz) | Slope $\beta$ (Pearson's $R$) |
|-------------------|--------------------------------|
|                   | $-20^\circ < b < -10^\circ$   | $b < -20^\circ$ |
|                   | (22,843 pixels)                | (68,987 pixels) |
| 410               | 3200 ± 190 (0.298)             | 4700 ± 1500 (0.138) |
| 240               | 254 ± 46 (0.156)               | 258 ± 52 (0.041) |
| 150               | 93 ± 23 (0.085)                | 46 ± 29 (0.003) |
| 90                | 58 ± 49 (0.032)                | -20 ± 110 (-0.028) |

![Diagram](image-url)

**Fig. 3.**—Angular power spectra of dust emission in a disk centered at R.A. = 92°, decl. = -48°, $b = -27^\circ$ that is correlated with the FDS8 IRAS extrapolation at 150 GHz (filled down triangles) and at 240 GHz (filled up triangles). The power spectrum of the microwave sky at 150 GHz (de Bernardis et al. 2000) is shown for comparison as filled circles. For the dust spectra, the error bars include the uncertainty due to the partial correlation between our data and the FDS8 extrapolated IRAS data. It is evident that in this region of the sky the Galactic dust signal is negligible with respect to the CMB signal at these frequencies. [See the electronic edition of the Journal for a color version of this figure.]
We have neglected correlations in the noise of different pixels since the pixel-pixel noise covariance matrix is approximately diagonal, but we have used the inverse of diagonal terms to properly weight each pixel in the fit. We have also neglected correlations in the CMB anisotropy (the other source of “noise” in the correlation). Using the method by Hamilton & Ganga (2001) on a subset of the data, we have verified that these approximations do not bias significantly the results. The slopes and Pearson’s linear correlation coefficients are listed in Table 1. As we move toward lower frequencies, the correlation at a given latitude range gets worse but is still significant. We have converted the measured slopes into brightness ratios $S_i = \Delta B_i/\Delta B_{IRAS}$ using the spectral response of the BOOMERANG bands. We compare the $S_i$ to an empirical model assuming a power law $B(\nu) \sim \nu^\alpha$. We find a best-fit $\alpha = 3.2 \pm 0.3$ at $b > -20^\circ$. In the FDS8 model, $\alpha = 3.15$ in the range 240–410 GHz, while $\alpha = 3.36$ in the range 240–150 GHz. At higher Galactic latitudes (four $10^\circ$ latitude range gets worse but is still significant. We have detected a component correlated with the CMB fluctuations. We have neglected correlations in the noise of different pixels, since the pixel-pixel noise covariance matrix is approximately negligible with respect to the CMB fluctuations. We computed the mean square fluctuation in the $i$-th band with the simple scaling formula $\sigma_i^2 = (S_i^2/S_{410}^2) \sigma_{410}^2$. The result is plotted in Figure 3 for the extrapolation of the 410 GHz spectrum centered at $b = -27^\circ$. Owing to the poor correlation, only upper limits are found for the 90 GHz band (at a level similar to the power spectrum estimates for the 150 GHz channel), which are not plotted. It is evident that at $l > 100$ the dust signals at 90 and 150 GHz are negligible with respect to the cosmological signal. These estimates of contamination are consistent with the dust foreground model of Tegmark et al. (2000; compare their Fig. 3 with our Fig. 3). If we scale to 150 GHz the upper limits for the uncorrelated component, assuming the same spectral ratios, we get 95% CL upper limits $l(l+1)c_i/2\pi \leq 5 \mu K^2$ for $50 \leq l \leq 600$.

4. CONCLUSIONS

BOOMERANG has detected thermal emission from ISD cirrus at intermediate and high Galactic latitudes. The 410 GHz map is morphologically very similar to extrapolation of the IRAS (3000 GHz) and DIRBE (1250 GHz) maps. The angular power spectrum of the dust-dominated 410 GHz map is a power law $c_i \sim l^{-\beta}$ with $2 < \beta < 3$. We have detected a component correlated with the IRAS/DIRBE map in all the BOOMERANG bands at $-10^\circ > b > -20^\circ$ and in the 150, 240, and 410 GHz bands at higher Galactic latitudes. This dust contamination is negligible with respect to the CMB anisotropy at high Galactic latitudes, accounting for less than 1% of the total angular power spectrum for multipoles $l > 100$ at $\nu < 180$ GHz. This Letter is focused on ISD as a CMB foreground; the analysis of ISD properties will be the subject of future publications.

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