PROPERTIES OF GALACTIC CIRRUS CLOUDS OBSERVED BY BOOMERANG


ABSTRACT

The physical properties of Galactic cirrus emission are not well characterized. BOOMERANG is a balloon-borne experiment designed to study the Cosmic Microwave Background at high angular resolution in the millimetre range. The BOOMERANG 245 and 345 GHz channels are sensitive to interstellar signals, in a spectral range intermediate between FIR and microwave frequencies. We look for physical characteristics of cirrus structures in a region at high Galactic latitudes where BOOMERANG performed its deepest integration, combining the BOOMERANG data with other available datasets at different wavelengths. We have detected 7 emission patches in the 345 GHz map, consistent with cirrus dust in the IRAS maps. The analysis technique we have developed allows to identify the location and the shape of cirrus clouds, and to extract the flux from observations with different instruments at different wavelengths and angular resolutions. We study the integrated flux emitted from these cirrus clouds using data from IRAS, DIRBE, BOOMERANG and WMAP in the frequency range 23–5000 GHz (13 mm to 60 μm wavelength). We fit the measured spectra with a combination of thermal and non-thermal spectra considering two models for the thermal emission. The first model assumes the emission to be isothermal with a variable spectral index. The second model considers two temperatures in the cloud, both the components spectral indices being set to 2. The two models are statistically equivalent and the estimated temperatures are consistent. A 10 K component has been detected at high latitudes. In our sample, assuming the isothermal model, the temperature of the thermal component varies in the 20 – 25 K range and its emissivity spectral index is in the 0.5 – 1.5 range. The spectral index of the non-thermal emission at lower frequencies covers the -1.6 – -2 range in antenna temperature. We could not identify a clear physical relation between temperature and spectral index as had been proposed in previous works. This technique can be profitably used for the forthcoming Planck and Herschel missions data.

Subject headings: cosmology: observations — cosmology: foregrounds — galactic dust

1. INTRODUCTION

Characterising the properties of dust in our Galaxy is an important topic of millimeter (mm) and submillimeter astrophysical observations. At frequencies above 100 GHz this emission is dominated by thermal radiation from large grains in equilibrium with the interstellar radiation field. Interstellar dust is distributed in filamentary cirrus-like clouds and covers the sky at both low and high galactic latitudes (Low et al. 1984). This emission is usually described by a thermal spectrum, parametrized by the physical temperature of the grains $T_d$ and by their emissivity vs frequency, which is assumed to be a power law with spectral index $\beta$. While dust properties have been deeply studied in the Galactic plane (Desert et al. 2008; Dupac et al. 2003; Lagache et al. 1998), there is a lack of information at high Galactic latitudes. Dust emission at high Galactic latitudes is interesting for two reasons. First, at these latitudes the detection of each structure is not affected by the overlap of other structures along the line of sight; this allows an unequivocal estimation of the physical properties of the observed cloud. Second, a good knowledge of dust emission at high galactic latitudes is crucial to determine its potential contamination of the Cosmic Microwave Background (CMB) measurements, and to improve component separation techniques (Leach et al. 2008).

In the mm range there is a lack of observational data, and different models have been proposed by (Finkbeiner et al. 1999; FDS hereafter) to extrapolate the data measured by the Infra-Red Astronomical Satellite (IRAS) (Neugebauer et al. 1984) to the microwave frequency range.

Previous results on interstellar dust detected by BOOMERANG -98 at high Galactic latitudes are reported in Masi et al. 2001. BOOMERANG -03 offers an unprecedented combination of coverage and sensitivity, providing $10^8 \times 10^9$ maps of a high latitude region, at 145, 245 and 345 GHz, with an angular resolution $\lesssim 10$ arcminutes.

In this paper we present an analysis of the char-
acteristics of diffuse dust emission from Far Infra-Red (FIR) to microwave frequencies in the nearby interstellar medium, at Galactic latitudes $-50^\circ < b < -15^\circ$, using the BOOMERANG 03 (Masi et al. 2006), Wilkinson Microwave Anisotropy Probe (WMAP) (Hinshaw et al. 2007), IRAS (Neugebauer et al. 1984) and Diffuse Infra-Red Background Experiment (DIRBE) (Boggess et al. 1992) data. In particular we focus on the observation of seven high-latitude cirrus clouds located in the BOOMERANG deep integration field. We derive physical parameters of the dust in the clouds, and we studied the relation between these parameters which can provide insight into the nature of the dust grains as suggested by Meny et al. (2007).

The paper is structured as follows: Section 2 describes the datasets and the calibration; Section 3 describes the pipeline adopted; Section 4 reports the results on the dust properties. Conclusions are discussed in Section 5.

2. DATA PROCESSING

BOOMERANG 03 (hereafter B03) is a balloon-borne experiment which in January 2003 performed a 14 day flight over Antartica (Masi et al. 2006). It can be considered a pathfinder for the High Frequency Instrument (HFI) of the Planck satellite since it validated the detectors, the scanning strategy, and initiated the relevant data analysis techniques. B03 has observed the microwave sky in three frequency bands centered at 145, 245 and 345 GHz with high angular resolution ($\sim 10$ arcminutes at 145 GHz, $\sim 7$ arcminutes at 245 and 345 GHz). While the 145 GHz channel is devoted to CMB studies, the two high frequency channels mainly monitor foreground emission. The observed region covers approximately 4% of the sky in the southern hemisphere and has been divided in three areas: a “deep” (long integration) survey of $\sim 90$ square degrees, a “shallow” (long integration) survey of $\sim 750$ square degrees and a region of $\sim 300$ square degrees across the Galactic Plane. A detailed description of the B03 instrument and scanning strategy is published in Masi et al. (2006).

In this work we study the dust properties by analyzing the 245 and 345 GHz channel observations in the deep region ($70^\circ < RA < 95^\circ$ and $-52^\circ < DEC < -39^\circ$), which provides high signal-to-noise ratio observations of interstellar dust emission at high Galactic latitudes. B03 bands are in a particularly key position for the study of interstellar dust because they cover the Rayleigh-Jeans part of its spectrum, which is currently poorly constrained by observations, and they allow us to test the extrapolation of the models to long wavelengths (Finkbeiner et al. 1999).

In the 245 and 345 GHz detectors, radiation is concentrated on spider web bolometers by cold horns assemblies. A metal wire grid is placed in front of each detector, so that it is sensitive only to one of the two orthogonal polarizations. Intensity and polarization measurements can be derived combining signals from different detectors. In this paper we focus on the temperature signal only. B03 results on TT, TE and EE angular power spectra on the CMB and on the derived cosmological parameters are described in Jones et al. (2006); Picentini et al. (2006); Montrov et al. (2006); MacTavish et al. (2006) respectively.

In order to study the physical properties of diffuse dust over a wide range of frequencies, we include in our analysis the IRAS datasets at 100 $\mu$m and 60 $\mu$m (1100 and 160 in the following), the DIRBE dataset at 240 $\mu$m (D240 in the following), and the five WMAP bands. For the IRAS data, we used the Improved Reprocessing of the IRAS Survey (IRIS) described in Miville-Deschênes & Lagache (2005). Since the CMB signal in the region being studied is dominant at 94, 61 and 41 GHz (three of the frequencies of WMAP), we remove it using the foreground reduced maps (Hinshaw et al. 2007).

2.1. Timeline processing and CMB removal

The 245 and 345 GHz channels of B03 (hereafter B245 and B345, respectively) have 4 bolometers each, named W, X, Y and Z. In this analysis we consider only bolometers W, X, Y and Z at 245 GHz and W, X and Y at 345 GHz – the other detectors were affected by anomalous instrumental noise (Masi et al. 2006).

As in the standard pipeline, the raw time-ordered data (TOD) from each detector is deconvolved from its transfer function to remove the filtering effects of the readout electronics and of the time response of the detectors. The point-spread function is recovered from on-board attitude sensors, and bad data are flagged and not used for the analysis. The deconvolved time lines are then reduced with the ROMA map-making code (de Gasperis et al 2005) to produce brightness maps using the Healpix scheme (Gorski et al. 2005). Since we are looking for large scale structures, we use nside = 256 (which corresponds to a pixel size of 13.7 arcminutes) in this analysis.

At the frequency range and the observed region of the BOOMERANG experiment, the dust signal can sometimes be comparable/subdominant to the measured CMB anisotropy. Therefore, to study the physical properties of the diffuse dust at the BOOM data, we need first to remove the CMB signal from the 245 and the 345 GHz maps before performing any foreground studies on these data. In order to remove the CMB signal, we operated as follows:

1. Assuming that at 145 GHz dust emission is subdominant with respect to CMB anisotropy, we calibrate the BOOMERANG 245 and 345 GHz data using the WMAP and the BOOMERANG -98 data. In harmonic space, we compute the slope of the linear correlation between the BOOMERANG 245 (345) GHz map and the BOOMERANG -98 150 GHz map, and the slope of the linear correlation between the WMAP-94 GHz map and the BOOMERANG -98 150 GHz map. The ratio of the two slopes is a measurement of the calibration factor (in Volt/K$_{\text{CMB}}$) of the 245 (345) GHz data of BOOMERANG.

\[
K_{245X} = \frac{\langle a_{245X} \rangle}{\langle a_{98X} \rangle} \times \frac{\langle a_{245X} \rangle}{\langle a_{98X} \rangle} \quad (1)
\]

In other words we calibrate our detectors with respect to WMAP, using the B98 map as a transfer to select only the CMB part of the map. To account for different beams and scanning strategy, each $a_{98X}$ has been previously divided by its window function as discussed in Masi et al. (2006). The calibration factors on CMB against the reference channels B245W and B345W are reported in second column of Tab.1.

\[http://lambda.gsfc.nasa.gov\]

\[http://www.astronomical.utoronto.ca/~mamd/IRIS/\]

\[http://healpix.jpl.nasa.gov\]
TABLE 1
RELATIVE GAINS OF BOOMERANG DETECTORS

<table>
<thead>
<tr>
<th>Channel</th>
<th>R_245X/245Z</th>
<th>R_245Y/245Z</th>
<th>R_245Z/245W</th>
</tr>
</thead>
<tbody>
<tr>
<td>245X</td>
<td>1.00 ± 0.08</td>
<td>1.09 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>245Y</td>
<td>1.03 ± 0.07</td>
<td>1.15 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>245Z</td>
<td>1.16 ± 0.06</td>
<td>1.17 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>345X</td>
<td>0.85 ± 0.15</td>
<td>0.92 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>345Y</td>
<td>1.47 ± 0.16</td>
<td>1.26 ± 0.02</td>
<td></td>
</tr>
<tr>
<td>345Z</td>
<td>1.23 ± 0.18</td>
<td>0.94 ± 0.02</td>
<td></td>
</tr>
</tbody>
</table>

BOOMERANG detectors relative gains for CMB (second column) and dust (third column) against the reference channels B245W and B345W, respectively. The comparison is done with the cross-spectra method (see text). 1 − σ errors are reported.

We remove the CMB dipole signal from the time lines using a template derived from the parameters given in Mather et al. (1994). Then we subtract the 145 GHz map from the 245 and 345 GHz CMB calibrated time lines.

3. The CMB subtracted time lines are then filtered in the same way and assembled in a multi-detector map replicating the flight pointing and flagging of detectors. We then associate to each cloud the flux and the error corresponding to that mask size. Flux values and errors are reported in Tab. 2. An example of this technique is shown in Fig. 3 and the increasing mask method is shown in Fig. 4. From Fig. 3 we can see that the flux does not depend strongly on the mask size. Flux values and errors are reported in Tab. 2. An example of this technique is shown in Fig. 3 and the increasing mask method is shown in Fig. 4. From Fig. 3 we can see that the flux does not depend strongly on the mask size.

5. The relative calibration corrections have been applied to the CMB subtracted time lines to obtain multi-detector maps, one at 245 GHz and another at 345 GHz.

4. The relative calibration of the resulting CMB subtracted map is corrected for the effect of different spectral band-passes by using the IRAS 100 μm map as transfer:

\[
R_{245X/245W} = \frac{(a_{245X} \times a_{IRAS})}{(a_{245W} \times a_{IRAS})}
\]

where \( p \) identifies a pixel in the Healpix scheme, \( I \) is the intensity map, and \( \sigma \) is the rms of the intensity in the observed region.

\[
M(p) = \frac{I_{345}(p) \times I_{100}(p)}{\sqrt{\frac{1}{N_p} \sum_p I_{345}(p) \sum_p I_{100}(p)}}
\]

TABLE 2
CLOUDS LOCATIONS AND MEASURED FLUX

<table>
<thead>
<tr>
<th>Region #</th>
<th>Ra (deg)</th>
<th>Dec (deg)</th>
<th>S_{245} (Jy)</th>
<th>S_{345} (Jy)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>84.7</td>
<td>-48.3</td>
<td>&lt; 1</td>
<td>5 ± 1</td>
</tr>
<tr>
<td>2</td>
<td>88.4</td>
<td>-48.1</td>
<td>14 ± 6</td>
<td>83 ± 33</td>
</tr>
<tr>
<td>3</td>
<td>80.5</td>
<td>-45.5</td>
<td>8 ± 6</td>
<td>90 ± 33</td>
</tr>
<tr>
<td>4</td>
<td>83.3</td>
<td>-43.0</td>
<td>3 ± 2</td>
<td>7 ± 2</td>
</tr>
<tr>
<td>5</td>
<td>87.0</td>
<td>-40.5</td>
<td>&lt; 13</td>
<td>74 ± 20</td>
</tr>
<tr>
<td>6</td>
<td>80.0</td>
<td>-49.0</td>
<td>26 ± 12</td>
<td>90 ± 32</td>
</tr>
<tr>
<td>7</td>
<td>78.5</td>
<td>-42.0</td>
<td>6 ± 2</td>
<td>22 ± 3</td>
</tr>
</tbody>
</table>

Coordinates of the centers of circled areas in Figs. 1 and 2 (second and third column, respectively). Fourth and fifth columns reports flux values registered by BOOMERANG channels corrected from the bias with the procedure described in section 4.

\[
\hat{I}(p) = \frac{I_{345}(p) \times I_{100}(p)}{\sigma_{345} \times \sigma_{100}}
\]

where \( p \) identifies a pixel in the Healpix scheme, \( I \) is the intensity map, and \( \sigma \) is the rms of the intensity in the observed region. The equality in Eq. 3 holds since the average of the intensity maps is vanishing because of the high-pass filtering procedure. The normalization has been chosen in such a way that the correlation between two identical maps, summed over all pixels, is 1. Since we are interested in positive emission regions only, we masked the negative emission ones when computing the correlation map.

With this procedure we could identify seven large clouds which are marked by black circles in Figure 1. As a starting point for the pixel selection, in each of these areas we select the brightest pixels by imposing a threshold \( S(p) > 3 \). In order to preserve the irregular shape of the clouds, later on we increased the initial area in steps, extending it by 0.1° around each pixel. We choose this step size since pixels have 0.22° side (Nside = 256), so 0.1° starting from the center of the pixel is the minimum distance to collect another pixel. We patch a maximum distance of 1° from the starting mask, to avoid contributions from other structures. In this way, we preserve the shape of the significantly correlated region in the correlation map, and include the other pixels interested in dust emission, without missing any. The integrated flux increases and reaches a maximum; then it decreases if we further widen the selected area. In fact, the detectors are AC coupled, and produce negative bounces after detecting a positive signal from a localised source. The error bars on the flux are given by adding in quadrature the errors of each pixel belonging to the mask. We use this effect to detect the area to be included in the flux measurement deriving the dimension of the mask corresponding to the maximum flux through a Gaussian fit. We then associate to each cloud the flux and the error corresponding to that mask size. Flux values and errors are reported in Tab. 2. An example of this technique is shown in Fig. 3 and the increasing mask method is shown in Fig. 4. From Fig. 3 we can see that the flux does not depend strongly on the mask radius. In WMAP Q, Ka and K bands the beam size is comparable to the size of the smaller cirrus clouds. In these cases we measure the flux as the integral of the brightness over a circle centered in the source coordinates, with a 3σBEAM radius. We also check that this flux is consistent with the flux measured with the method described above.

We apply this procedure for each cirrus cloud at each frequency taking into account the noise and beam characteristics of each experiment. BOOMERANG and WMAP noise maps are available so that we can estimate the pixel standard devi-
Correlation map B345 x I100

Fig. 1.— Correlation map (Eq. 3) between B345 and I100. All positive structures shown in the map above were included in the final mask, with the exception of the regions centered at (RA,DEC) = (78°, -40°), and (88°, -50°) and the region 85° < RA < 90° and -46° < DEC < -42°. They are small parts of very complex shaped structures which have their largest part in the BOOMERANG shallow field.

In Fig. 2 we show the maps we used in the frequency range most sensitive to dust emission (245 – 3000 GHz). The areas that we have identified as cirrus clouds are circled and the approximate coordinates of the centers are reported in Tab. 2.

We compared the BOOMERANG fluxes to those predicted by the model 8 of FDS ([Finkbeiner et al. 1999]) at the nominal BOOMERANG frequencies, measuring the fluxes from extrapolated simulations of dust maps in the clouds regions we identified. A flux-to-flux comparison, made by plotting the real data fluxes versus the predicted ones, has a best fit line with slopes 2.2 ± 0.3 and 0.9 ± 0.4 at 345 and 245 GHz respectively. A good agreement between theory and observations would result in a slope 1: this indicates that, in the high Galactic latitude region observed by BOOMERANG, the FDS model under-predicts the dust signal approximately of a factor 2 at 345 GHz, as already found in ([Veneziani et al. 2009]).

3.1. Estimation of cirrus physical parameters

It is generally accepted that the sub-millimeter spectrum of thermal dust can be expressed as a blackbody times a frequency dependent (power-law) emissivity factor. Simple emission models predict the emissivity factor to be approximately 2. Significant variations to the 2 emissivity law occur when taking into account the disordered structure of amorphous dust grains ([Meny et al. 2007]). At tens of arcminutes angular scales is also possible to detect different temperatures in the clouds due to star formation processes in the cores. The temperature gradient could then reach up to 10 K in one single cirrus from the centre to the surface (see [Netterfield et al. 2009] and references therein). In these cases, an isothermal model could lead to spectral index values smaller than 2 while a two temperatures model with a cold dust component at approximately 10K and \( \beta = \frac{2}{3} \) could better approximate the physics of the emission. Both these models are tested on our flux data.

In order to analyze cirrus characteristics (e.g. temperature and emissivity) we fit the flux data taking into account two contributions: a thermal emission component, peaking in the far infra-red region, and a non-thermal emission component at lower frequencies parameterized as a power spectrum with a spectral index able to reproduce synchrotron or free-free emission. When assuming the thermal emission to be isothermal, the Spectral Energy Distribution (SED) results in

\[
S(\nu) = A_1 \left( \frac{\nu}{\nu_0} \right)^\alpha + A_2 \left( \frac{\nu}{\nu_1} \right)^\beta \frac{1}{\nu} \frac{BB(\nu, T_d)}{\nu}
\]

where \( BB(\nu, T_d) \) is the standard blackbody function. \( \nu_0 \) and \( \nu_1 \) are 33 GHz and 5000 GHz, respectively. \( T_d \) is the temperature of the considered dust cloud, \( \beta \) is the corresponding spectral index, and \( \alpha \) is the spectral index of the non-thermal contribution. \( A_1 \) and \( A_2 \) represent the amplitude of the two components, which at these Galactic latitudes is proportional to the optical depth. When modelling the thermal emission of the dust with a warm and a cold component setting the spectral index of both to the theoretical value of 2, the second term \( S_2(\nu) \) of the SED in Eq. 4 becomes:

\[
S_2(\nu) = A_3 \left( \frac{\nu}{\nu_1} \right)^2 \frac{BB(\nu, T_c)}{\nu} + A_4 \left( \frac{\nu}{\nu_1} \right)^2 \frac{BB(\nu, T_w)}{\nu}
\]

where \( T_c \), \( T_w \) are the temperatures of the cold and warm components respectively and \( A_3 \) and \( A_4 \) the correspondent amplitudes. \( T_c \) is set to 10 K while \( T_w \) varies.

From the measured SED we estimate the parameters \( A_1, A_2, \alpha, \beta \) and \( T_d \) in the isothermal model, and the parameters \( A_1, A_3, A_4, T_c, \alpha \) in the two components model, using a Monte Carlo Markov Chain (MCMC) algorithm ([Christensen et al. 2001]; [Lewis & Bridle 2002]). Following Bayesian statistics, the probability to have a set of parameters \( p \) given a set of data \( d \) is

\[
P(p|d) \propto P(p)P(d|p),
\]

where \( P(p) \) is the a priori probability density of the parameters set \( p \) and \( P(d|p) \) is the probability density of data \( d \) given a set of parameters \( p \), named the likelihood function. The posterior probability \( P(p|d) \) is estimated using MCMC algorithm. Given a set \( p \), with likelihood \( L \) and posterior probability \( P(p|d) \), the MCMC algorithm generates an independent set \( p_{i+1} \) with likelihood \( L_{i+1} \) and posterior probability \( P(p_{i+1}|d) \). This second set is accepted according to a rule which also guarantees a good sampling of the posterior density in a reasonable computational time. For example in the Metropolis-Hastings algorithm the new set \( p_{i+1} \) is always accepted if

\[
\Lambda(i+1, i) = \frac{P(p_{i+1}|d)}{P(p_i|d)} = \frac{L_{i+1}P(p_{i+1})}{L_{i}P(p_i)} > 1
\]
Cirrus clouds with BOOMERanG

![Images of cirrus clouds observed by BOOMERanG at 245 and 345 GHz, as well as IRAS 100 µm and DIRBE 240 µm.]  

**Fig. 2.**—The BOOMERanG deep region observed, clockwise, by BOOMERanG at 245 GHz (top-left), BOOMERanG at 345 GHz (top-right), IRAS 100 µm (bottom-right) and DIRBE 240 µm (bottom-left).

<table>
<thead>
<tr>
<th>TABLE 3 PRIORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>α</td>
</tr>
<tr>
<td>T_d</td>
</tr>
<tr>
<td>T_w</td>
</tr>
<tr>
<td>β</td>
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<tr>
<td>A_1</td>
</tr>
<tr>
<td>A_2</td>
</tr>
<tr>
<td>A_3</td>
</tr>
<tr>
<td>A_4</td>
</tr>
</tbody>
</table>

List of *a priori* probability density imposed on parameter set.

We chose wide flat *a priori* probability densities of the parameters, as reported in Tab. 3. Three chains for each cloud have been run, starting from different points of the parameter space. The convergence has been checked using the test algorithm encoded in the GetDist software, available in the public CosmoMC package. The combination of the BOOMERanG scanning strategy and AC coupling induces an effective filtering to the sky signal. To take the induced bias into account, we applied the same effective filtering to all the other datasets as described in Section 2 and estimated its effect by means of simulations. Since filtering effects depend strongly on the scanning strategy, which translates in the map into a dependency on the position of the cloud and on the nearby structures, we produced for each cirrus cloud 100 simulations with the same shape, position and noise properties of the measured cloud, and processed each simulation through the pipeline applied to the data. Comparing the average output flux values with the input ones we obtain the bias factors the measured fluxes have to be corrected for. The factors show that approximately 20% of the sky signal is dumped by the pipeline. As expected, these factors depend on the dilution of the cirrus in the beam and on position and shape of the cloud itself.

http://cosmologist.info/cosmomc/
We can distinguish two sets of cirrus clouds: the first consists of four of the seven selected dust regions (marked with numbers 2, 3, 4, and 6 in Fig. 1) whose emission is clearly detected in the full range of analyzed frequencies; we are then able to derive both the thermal and non-thermal component. The SED for these clouds are shown in Fig. 5. The remaining three clouds (numbers 1, 5 and 7) form the second set and present the thermal component only, as plotted in Fig. 6. This can be seen in the values of the parameter $A_1$, and consequently of the non-thermal spectral index $\alpha$, which in the second set are un-determined.

4. RESULTS

Our analysis shows that the isothermal model of Eq. 4 and the two temperatures model of Eq. 5 are statistically equivalent and does not favour any. However, the 10 K component is poorly constrained in all clouds, as its amplitude $A_3$ in all cases is consistent with zero. The temperature of the warm component $T_w$ is always consistent with the temperature $T_d$ estimated with the isothermal fit. This consistency provides a further check on the temperature values obtained.

The characteristics of each cloud for the isothermal and the two temperatures model are reported in Tab. 4. One and two-dimensional posterior probability of parameters in Eq. 4 are shown for the cloud number 3, as example, in Fig. 7. In order to deeper investigate the presence of a cold temperature...
component in our sample we fit both the isothermal and the two temperatures model on the average fluxes for each frequency providing a better signal to noise ratio. In this case a 10 K component is detectable confirming the presence of cold dust at high latitude as already found close to the galactic plane (Netterfield et al. 2009). These results are reported in the last line of Tab. 4.

Assuming an isothermal model of dust emission the clouds have dust temperatures in the range $T_d \in [20;25]$ K, and emissivities $\beta \in [0.5;1.5]$. The two temperatures model leads to a general reduction of the temperature of the warm component: $T_w \in [17;23]$ K being $T_d$ and $T_w$ consistent within 1$\sigma$ error bars. When compared to all other maps, Region 2 has a significantly higher dust temperature. Looking more deeply in the IRAS 60 $\mu$m map, a source (IRAS 05519-4803) has been identified in this region: consequently the 60 $\mu$m band has been removed from the analysis of this cloud.

It’s worth noticing that including the IRAS 60 $\mu$m flux generates for each cloud a mild increase of the temperatures, which shifts towards higher values the best fit. However, the discrepancy remains within 1 sigma. One reason for that could be a non perfect parameterization, and consequently subtraction, of the zodiacal dust from the maps as suggested by Miville-Deschênes & Lagache (2003). Zodiacal light increases at shorter wavelengths and can contaminate the 60 $\mu$m band more than the 100 $\mu$m band.

In the next Sections and in the following analysis we will refer only to the isothermal model for the dust emission.

4.1. Temperature dependence of the spectral index

Dust emissivities and temperatures in the BOOMERANG deep field cover a range of values (see Tab. 4). The spectral shape of the thermal component of the dust emissivity (second term of Eq. 3) is strongly dependent on a combination of $T_d$ and $\beta$, whose two-dimensional posterior probability has a elongated, slant shape (Fig. 7), indicating a degeneracy between these two parameters. Two more degeneracy figures are obtained in the $A_2$-$\beta$ and $A_1$-$\alpha$ planes, as expected from the functional form. Previous works on Pronaos (Dupac et al. 2003) and Archeops (Désert et al. 2008) data which analyze many cold clouds find an inverse relation between the dust temperature and its spectral index, the former being expressed as a function of the latter. In order to compare our temperature results with previous analysis on diffuse clouds we run a new MCMC fixing the spectral index value to 2 (last column of Tab. 4). As expected from the inverse relation, fixing $\beta$ to higher value, the temperatures decrease and the clouds split into two sets: one “hot” component with $T \approx 20$ K and one “cold” component with $T \approx 14-16$ K in agreement with Lagache et al. (1998).

Given the shape of the posterior probability we find in our data, we want to investigate whether in our case the $\beta$-$T_d$ relation is a physical characteristic of the dust or just a consequence of the functional form and of measurements errors. We run then a MCMC on each region expressing, in Eq. 3 $\beta$ as a function of $T_d$ following the two models:

1. Désert et al. (2008), defined by the relation

\[
\beta = A \times T_d^\rho
\]  

TABLE 4

<table>
<thead>
<tr>
<th>Region #</th>
<th>$\alpha$</th>
<th>$T_d$ [K]</th>
<th>$T_w$ [K]</th>
<th>$\log A_1$</th>
<th>$\log A_2$</th>
<th>$\log A_3$</th>
<th>$\log A_4$</th>
<th>$T_d$ [K]</th>
<th>$\gamma$</th>
<th>$T_d^{\log A}[K]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>20.1 ± 2.7</td>
<td>1.3 ± 0.3</td>
<td>&lt;14</td>
<td>&lt; -2.5 ± 0.5</td>
<td>&lt; -1.1</td>
<td>&lt; -1.9 ± 0.5</td>
<td>17.3 ± 2.6</td>
<td>-</td>
<td>15.7 ± 0.5</td>
</tr>
<tr>
<td>2</td>
<td>-4.1 ± 0.7</td>
<td>20.0 ± 3.9</td>
<td>1.4 ± 0.4</td>
<td>0.2 ± 0.1</td>
<td>&lt; -1.3 ± 0.5</td>
<td>&lt; 1.7</td>
<td>&lt; -2.0 ± 0.3</td>
<td>19.2 ± 3.5</td>
<td>-1.6 ± 0.7</td>
<td>16.2 ± 0.7</td>
</tr>
<tr>
<td>3</td>
<td>-1.5 ± 0.8</td>
<td>24.8 ± 3.2</td>
<td>1.0 ± 0.4</td>
<td>0.4 ± 0.1</td>
<td>&lt; -2.1 ± 0.4</td>
<td>&lt; 0.03</td>
<td>&lt; -1.7 ± 0.3</td>
<td>22.9 ± 2.1</td>
<td>-1.9 ± 0.9</td>
<td>20.6 ± 1.7</td>
</tr>
<tr>
<td>4</td>
<td>-1.3 ± 0.7</td>
<td>24.5 ± 3.5</td>
<td>1.3 ± 0.5</td>
<td>0.3 ± 0.1</td>
<td>&lt; -2.4 ± 0.5</td>
<td>&lt; 0.9</td>
<td>&lt; -2.1 ± 0.3</td>
<td>23.0 ± 1.7</td>
<td>-1.8 ± 0.7</td>
<td>21.0 ± 1.7</td>
</tr>
<tr>
<td>5</td>
<td>-2.0 ± 1.9</td>
<td>1.2 ± 0.3</td>
<td>&lt; 0.7</td>
<td>-1.6 ± 0.4</td>
<td>&lt; 0.1</td>
<td>&lt; -1.3 ± 0.3</td>
<td>19.2 ± 1.5</td>
<td>&lt; 0.7</td>
<td>15.7 ± 1.6</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>-1.5 ± 0.9</td>
<td>24.2 ± 2.5</td>
<td>0.5 ± 0.3</td>
<td>0.5 ± 0.1</td>
<td>&lt; -2.4 ± 0.4</td>
<td>&lt; 1.3</td>
<td>&lt; -1.8 ± 0.4</td>
<td>21.4 ± 2.3</td>
<td>-2.0 ± 1.1</td>
<td>15.3 ± 2.0</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>20.0 ± 2.5</td>
<td>1.0 ± 0.3</td>
<td>&lt; 0.1</td>
<td>&lt; -2.2 ± 0.4</td>
<td>&lt; 0.4</td>
<td>&lt; -2.0 ± 0.4</td>
<td>19.8 ± 2.2</td>
<td>-</td>
<td>14.3 ± 0.6</td>
</tr>
</tbody>
</table>

Flux Average: $-1.2 ± 0.3$; 22.9 ± 1.1; 1.0 ± 0.1; 0.2 ± 0.05; 2.1 ± 0.2; 0.3 ± 0.1; 1.7 ± 0.1; 21.0 ± 0.7; -
2. [Dupac et al. (2003)], through the relation
\[
\beta = \frac{1}{\delta + \omega T_d}
\]
where \(A = 11.5 \pm 3.8\), \(\rho = -0.66 \pm 0.05\), \(\delta = 0.40 \pm 0.02\), \(\omega = 0.0079 \pm 0.0005\, K^{-1}\) are the values derived from the Archeops and Pronaos data respectively.

The probability that in a \(\chi^2\) distribution with \(N = 4\) degrees of freedom the \(\chi^2\) variable is smaller than the fitted ones is reported in Tab. 5. From these results, we can confirm that the standard model described in Eq. 4 fits our data better than the other models where the spectral index is expressed as a function of the temperature \(T_d\). This indicates that, with the data we have, we could not clearly identify a relation between dust temperature and spectral index, as suggested in previous analyses.

In order to check the concordance between BOOMERANG and the other considered experiments, we fit our sample using the two models quoted before (Eqs. 7 and 8) including the error induced by the degeneracy shape relation. We thus perform the fit on seven random points, one for each cirrus, within the 95% contour of the two-dimensional posterior probabilities. We repeat this procedure 60000 times for each model, a number of steps which allows a good sampling of the distributions of the parameters \(A\), \(\rho\), \(\delta\) and \(\omega\) in Eqs. 7 and 8 respectively. This technique allows a complete sampling of the degeneracy and not to be dominated by its shape in the final result. From the peaks and the standard deviations of the distributions we derive as best fits:
\[
\beta = \left(236^{+72}_{-53}\right) \times T_d^{-1} \quad \text{model 1}
\]
\[
\beta = \left(0.07^{+0.03}_{-0.02}\right) \times T_d^{-1} \quad \text{model 2}
\]
which actually do not match with the values measured by Pronaos and Archeops. Fig. 8 shows the points within the posterior probabilities 95% contour plot in the \(T_d—\beta\) plane, for all the analyzed structures together. The contours are also shown in dashed lines. The dashed and solid lines show BOOMERANG parameters using model 1 and 2 respectively. The circled and squared lines mark the best fits obtained by Archeops and Pronaos experiments respectively.

4.3. Spinning dust

There has been recent interest in spinning dust emission both theoretically [Draine & Lazarian (1998)] and observationally (e.g. de Oliveira-Costa et al. 2008; Gold et al. 2009). The data in Fig. 5 suggest the presence of a bump in the emission below 60 GHz, and we investigate whether this can be fit by a spinning dust component.

Large dust grains in cirrus clouds have a thermal emission which peaks at \(\sim 250\, \mu m\), but smaller grains emit transiently at higher frequencies, and could also produce rotational emission by spinning at microwave frequencies. This could be relevant below 60 GHz.

In order to investigate this possibility we fit the measured SED with a modified blackbody (second term of Eq. 10), which describes the thermal emission, and a generalized thermal spectrum which describes the rotational emission. We replaced Eq. 10 with Eq. 10 in Gold et al. (2009):
\[
S(\nu) = A_1 \frac{\nu^{\beta+1}}{e^{\nu \nu_s} - 1} + A_2 \left(\frac{\nu}{\nu_1}\right)^\beta \text{BB}(\nu, T_d) \quad (11)
\]
where \(\nu_s = 17\, \text{GHz}\). This formula has been used to fit data of regions 2, 4 and 6. Region 3 includes a radio source whose signal dominates over the dust rotational emission.

The dust parameters, assuming the low frequency emission to be generated by rotational dust emission, are reported in Tab. 5. A zoom of the low frequency part of the SEDs in these regions is shown in Fig. 9.

A chi-square analysis of the two different fits (Eqs. 10 and 11) indicates that for our dataset the spinning dust model is statistically equivalent to the non thermal power law used in Section 3.1.

5. Conclusions

This paper analyzes the properties of Galactic cirrus clouds at high latitude combining the high frequency BOOMERANG dataset together with other three datasets, IRAS, DIRBE and WMAP. We located seven clouds in the deep survey area of BOOMERANG and for each of them we estimated dust
average fluxes for each frequency in order to improve the signal to noise value. The last line reports the any significant difference in the parameters value with respect to Eq. 4.

Table 5: Comparison among the models

<table>
<thead>
<tr>
<th>Region #</th>
<th>$P(\beta, T_d)$</th>
<th>$P(\beta = 2, T_c, T_d)$</th>
<th>$P(\beta = AT_d^{-\omega})$</th>
<th>$P(\beta = AT_d^{-\omega})$</th>
<th>$P(\beta = 2)$</th>
<th>$P(\beta_{SD}, T_d)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.52</td>
<td>0.46</td>
<td>0.63</td>
<td>0.63</td>
<td>0.57</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>0.77</td>
<td>0.92</td>
<td>0.92</td>
<td>0.96</td>
<td>0.91</td>
<td>0.86</td>
</tr>
<tr>
<td>3</td>
<td>0.69</td>
<td>0.58</td>
<td>0.80</td>
<td>0.81</td>
<td>0.83</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>0.49</td>
<td>0.51</td>
<td>0.63</td>
<td>0.64</td>
<td>0.58</td>
<td>0.52</td>
</tr>
<tr>
<td>5</td>
<td>0.72</td>
<td>0.44</td>
<td>0.83</td>
<td>0.83</td>
<td>0.76</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>0.55</td>
<td>0.37</td>
<td>0.69</td>
<td>0.70</td>
<td>0.94</td>
<td>0.54</td>
</tr>
<tr>
<td>7</td>
<td>0.59</td>
<td>0.59</td>
<td>0.71</td>
<td>0.73</td>
<td>0.59</td>
<td>-</td>
</tr>
</tbody>
</table>

Flux Average: 0.99

Table 6: Spinning dust model

<table>
<thead>
<tr>
<th>Region #</th>
<th>$T_c$ [K]</th>
<th>$\beta$</th>
<th>$\log A_1$</th>
<th>$\log A_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>18.6 ± 2.2</td>
<td>1.6 ± 0.3</td>
<td>0.5 ± 0.1</td>
<td>-1.5 ± 0.3</td>
</tr>
<tr>
<td>4</td>
<td>24.3 ± 2.6</td>
<td>1.3 ± 0.3</td>
<td>0.6 ± 0.1</td>
<td>-2.4 ± 0.4</td>
</tr>
<tr>
<td>6</td>
<td>23.4 ± 1.5</td>
<td>0.6 ± 0.3</td>
<td>1.0 ± 0.1</td>
<td>-2.3 ± 0.3</td>
</tr>
</tbody>
</table>

Dust temperature, spectral index and amplitude in the regions with a significant emission below 60 GHz. This emission is assumed to be generated from the spinning on dust grains, and it is then described by a generalized thermal spectrum. The errors correspond to 68% confidence interval. We do not find any significant difference in the parameters value with respect to Eq. 4.

Fig. 9.— SED of cirrus with a significant emission below 40–60 GHz. The low frequency emission is well approximated with a generalized thermal spectrum peaking at ~30 GHz (solid line). This suggests that it could be generated by spinning dust. We find that this hypothesis is statistically equivalent to that of a non-thermal origin (see text).

13. Cumulative distribution function $P$ of a $\chi^2$ distribution with the proper number of degrees of freedom. The ideal fit should have $P \sim 0.5$; $P < 0.5$ is an indication of overestimated error bars; $P > 0.5$ indicates that the fitting function is not a good model. Here $P$ values are reported for all the models assumed. 2nd column: isothermal model in Eq. 4; 3rd column: two temperatures model in Eq. 5; 4th column: model which links $\beta$ and $T_c$ using the [Desert et al. 2008] model. 5th column: same of previous column but following the [Dupac et al. 2003] model. 6th column: isothermal model setting $\beta = 2$. 7th column: low frequencies emission dominated by spinning dust (SD) (see Eq. 11) in clouds with a significant low frequencies signal. The last line reports the $P$ values estimated on the average fluxes for each frequency in order to improve the signal to noise value.

The low frequency emission is well approximated with a generalized thermal spectrum peaking at ~30 GHz (solid line). This suggests that it could be generated by spinning dust. We find that this hypothesis is statistically equivalent to that of a non-thermal origin (see text).

14. Taking into consideration the shape of the joint posterior probability of the parameters estimated with the isothermal model for each observed object, our data cannot confirm a model in which temperature and spectral index are inversely correlated, as was suggested in previous analyses on Pronaos [Dupac et al. 2003] and Archeops [Desert et al. 2008] data. This may be due to the absence of a physical relation but also to the limited number of objects considered and to the noise in the data. Moreover, we are studying high latitude clouds whose grains could be different from those in lower latitude clouds.

A comparison to the extrapolation of IRAS data from [Finkbeiner et al. 1999] indicates that this prediction has limited accuracy in the range of frequencies observed with BOOMERANG. In particular, the model seems to underestimate the dust brightness at 345 GHz by a factor of ~2.

At lower frequencies we detect a signal in the observed regions but the sensitivity is not sufficient to provide a clear distinction among the different emission mechanisms we considered: synchrotron, free-free and spinning dust.

From this analysis it is clear that new data are required to improve the knowledge of properties of high Galactic latitude cirrus clouds, and of dust in general. The method developed in this paper allows to identify the location and shape of dust clouds, and to extract the flux from observations with different instruments at different wavelengths and angular resolutions. This technique can be profitably used to analyze the forthcoming Planck and Herschel datasets, which will provide higher sensitivity, wider spectral range and, in the case of Planck, full sky coverage.

6. ACKNOWLEDGEMENT

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