CONSTRAINTS ON THE POLARIZATION OF THE ANOMALOUS MICROWAVE EMISSION IN THE PERSEUS MOLECULAR COMPLEX FROM SEVEN-YEAR WMAP DATA

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ABSTRACT

We have used the seven-year Wilkinson Microwave Anisotropy Probe (WMAP) data in order to update the measurements of the intensity signal in the G159.6-18.5 region within the Perseus molecular complex and to set constraints on the polarization level of the anomalous microwave emission in the frequency range where this emission is dominant. At 23, 33, and 41 GHz, we obtain upper limits on the fractional linear polarization of 1.0%, 1.8%, and 2.7%, respectively (with a 95% confidence level). These measurements rule out a significant number of models based on magnetic dipole emission of grains that consist of a simple domain as responsible for the anomalous emission. When combining our results with the measurement obtained with the COSMOSOMAS experiment at 11 GHz, we find consistency with the predictions of the electric dipole and resonance relaxation theory at this frequency range.

Key words: cosmic background radiation – diffuse radiation – ISM: individual objects (G159.6-18.5) – radiation mechanisms: general – radio continuum: ISM

Online-only material: color figures

1. INTRODUCTION

The dust-correlated microwave (10–60 GHz) emission detected by several cosmic microwave background (CMB) experiments in the two last decades (COBE (Kogut et al. 1996a, 1996b); OVRO at 14.5 and 32 GHz (Leitch et al. 1997); Saskatoon (de Oliveira-Costa et al. 1997); 19 GHz (de Oliveira-Costa et al. 1998); Tenerife (de Oliveira-Costa et al. 1999, 2004); COSMOSOMAS (Watson et al. 2005; Hildebrandt et al. 2007); Very Small Array (VSA; Scaife et al. 2007; Tibbs et al. 2010, and references therein)) suggests the existence of a new continuum microwave emission mechanism unlike the three well-known Galactic mechanisms: synchrotron, free–free, and thermal dust emission. A remarkable observational effort has been devoted to the understanding of the intensity and polarization properties of this “anomalous” microwave emission, among other reasons, because of the importance of an accurate foreground correction of the CMB maps at low frequencies.

Among the various scenarios proposed to explain this emission, electric dipole radiation (Draine & Lazarian 1998) from very small \( N \lesssim 10^3 \) atoms rapidly rotating \((\sim 1.5 \times 10^{10} \text{ s}^{-1})\) carbon-based molecules in the interstellar medium (the so-called spinning dust) appears to reproduce well the observational constraints (see, e.g., Watson et al. 2005; Casassus et al. 2006; Iglesias-Groth 2006; Dickinson et al. 2007; Tibbs et al. 2010). The detailed theoretical description of this family of models has been recently updated in Ali-Haimoud et al. (2009), and also include the effect of rotation of the dust grains around a non-principal axis and the effects of the transient spin-up due to discrete impacts (Hoang et al. 2010; Silsbree et al. 2010).

An alternative explanation based on magnetic dipole emission has also been proposed (Draine & Lazarian 1999). Measurements of the polarization properties of the anomalous microwave emission may potentially distinguish between these two models. According to Lazarian & Draine (2000), electric dipole radiation from spinning dust would be polarized at low frequencies, reaching a maximum (6%–7%) at 2–3 GHz and dropping to 4%–5% at 10 GHz and progressively decreasing at higher frequencies. Polarization from magnetic dipole emission predicts a different frequency behavior and stronger linear polarization depending on the composition and shape of the emitting particles.

From the observational point of view, there is little information in the literature about the polarization properties of the anomalous emission. Kogut et al. (2007) used the full-sky Wilkinson Microwave Anisotropy Probe (WMAP) three-year data to constrain the polarization fraction of a diffuse anomalous component traced by the dust morphology. They concluded that the polarized anomalous emission contributes less than 1% of the observed polarization signal variance in any of the five WMAP bands.

Only a few attempts have been made to determine the polarization of the anomalous microwave emission in individual objects and in the frequency range where this contribution is dominant (10–50 GHz). Battistelli et al. (2006), using data from the COSMOSOMAS experiment on the Perseus molecular complex, reported at 11 GHz \( \Pi = 3.4_{-1.9}^{+1.5} \% \) (95% confidence level (CL)). Using the Cosmic Background Imager (CBI) at 31 GHz, Casassus et al. (2008) obtained a limit on the total linear polarization level of 1.0% integrated over the Oph molecular cloud (MC), discarding the emission of magnetic dust. More recently, Mason et al. (2009), using the Green Bank Telescope at 9 GHz, obtained an upper limit for the linear polarization of 88 \( \mu \text{K} \) at 95.4% confidence in the Lynds 1622 dark cloud. Both the Perseus molecular complex and the Lynds 1622 cloud are regions where anomalous microwave emission appears to dominate over other emission processes in the frequency range 10–50 GHz.

In this work, we present new measurements of the polarization of the anomalous microwave emission in G159.6-18.5 (within the Perseus molecular complex) using the WMAP seven-year data. Although the results only provide upper limits to
the polarized emission in the region, they still constitute a strong constraint on the physical mechanism responsible for the emission.

2. THE G159.6-18.5 REGION

The Perseus molecular complex is a giant MC located at a distance of 260 pc (Cernicharo et al. 1985). Our region of interest is G159.6-18.5, a dust feature in this molecular complex, observed in the infrared interferometer spectrometer (IRIS) maps, which appears as a slightly broken ring with a diameter ≈1.5, and an intensity of the order of 100–200 MJy sr⁻¹ at 100 μm and 5–10 MJy sr⁻¹ at 12 μm (see Figure 1).

Originally, G159.6-18.5 was considered to be a supernova remnant (Pauls & Schwartz 1989; Fiedler et al. 1994), but later observations showed that this is an H ii region driven by the O9.5-B0 V star HD 278942, located at the center of the ring (de Zeeuw et al. 1999). More recent studies (Andersson et al. 2000; Ridge et al. 2006) concluded that G159.6-18.5 was indeed an expanding H ii bubble that has emerged from the outer edge of the cloud.

Watson et al. (2005, hereafter W05) carried out a detailed study of the spectral energy distribution (SED) of G159.6-18.5 in a wide frequency range, from 408 MHz to 3000 GHz. This study combined, among others, the observations performed with the COSMOSOMAS experiment at 11, 13, 15, and 17 GHz (Gallegos et al. 2001; Fernández-Cerezo et al. 2006), and the first year WMAP data (Bennett et al. 2003). The total emitting region in G159.6-18.5 was slightly resolved in COSMOSOMAS and WMAP data, and was modeled using an ellipse with Γ = 61° and P.A. = 51°, centered on R.A. = 55°:4 and decl. = +31°:8. The SED for that region showed clear evidence for anomalous microwave emission, with a peaked spectrum around 20–30 GHz, indicative of spinning dust. Indeed, W05 showed that an adequate fit to the SED can be achieved from 10 to 50 GHz only when including three components in the analysis: (1) optically thin free–free emission, (2) vibrational dust emission with T_dust = 19 K and emissivity index of 1.55, and (3) a combination of the spinning dust models of Draine & Lazarian (1998) for warm neutral medium and molecular cloud (0.8WNM + 0.3MC). No bright unresolved source that could be an ultra-compact H ii region or a gigahertz-peaked source could be found.

Detailed observations of G159.6-18.5 with the VSA interferometer at 33 GHz (Tibbs et al. 2010) and an angular resolution of 10–40 arcmin showed that the region consists of five distinct components, all of which are found to exhibit an emission at 33 GHz which is highly correlated with the far-infrared emission. The most interesting result is that the VSA resolved out most of the emission in the region, as those five components contribute to only ≈10% to the total flux density of the diffuse extended emission detected in W05. Therefore, the bulk of the anomalous emission in G159.6-18.5 is diffuse.

Concerning the polarization level of the anomalous microwave emission in the region, the only measurement at the relevant frequencies (10–30 GHz) done so far was presented in Battistelli et al. (2006). Using dual orthogonal polarizations with the COSMOSOMAS experiment, the resulting total polarization level in G159.6-18.5 at 11 GHz was found to be Π = 3.4±1.5% (95% CL). Based on this value, they concluded that this weak detection of polarization would be associated

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3 IRIS maps are improved versions of IRAS maps; for details, see Miville-Deschênes & Lagache (2005).

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Figure 1. IRIS images at 12 μm, 60 μm (middle), and 100 μm (bottom panel) of the G159.6-18.5 region, with a field of view of 4.5 × 4.5, and centered in R.A.(J2000) = 55°:4 and decl. = +31°:8. All maps are in units of MJy sr⁻¹. (A color version of this figure is available in the online journal.)
with the spinning dust grains. Recently, Reich & Reich (2009) suggested that G159.6-18.5 is acting as a Faraday screen (FS) hosting a strong regular magnetic field, which would rotate the background polarized emission. They suggest that an FS model with a rotation measure of \( RM = 190 \) rad m\(^{-2}\) would explain the 11 GHz observations, as well as their new 11 cm Effelsberg observations in the region (see Figure 6 in that paper). In any case, even if the Battistelli et al. (2006) result is only an upper limit to the polarization level of the anomalous emission, its amplitude favors the electric dipole emission model with resonance paramagnetic relaxation (see Lazarian & Draine 2000).

In this context, the seven-year WMAP data represent an opportunity to update the measurements of the intensity signal in the Perseus region, as well as to constrain the polarization level of the anomalous microwave emission in the frequency range where this emission is dominant (20–30 GHz). As shown by Tibbs et al. (2010), 90\% of the emission in the region is diffuse, so the angular resolution of WMAP data is sufficient to provide a reliable measurement.

3. DATA AND METHODOLOGY

3.1. WMAP Data

In this paper, we use the seven-year WMAP data products (Jarosik et al. 2010), which are available in the LAMBDA\(^4\) Web site in the HEALPix\(^5\) pixelisation scheme (Górski et al. 2005). In particular, we use the smoothed \( I, Q, \) and \( U \) maps, for each of the five frequency bands centered at 23, 33, 41, 61, and 94 GHz (K, Ka, Q, V, and W, respectively). The original angular resolution of these maps is approximately 0\(^\circ\)82, 0\(^\circ\)62, 0\(^\circ\)49, 0\(^\circ\)33, and 0\(^\circ\)21, respectively, but they are degraded to a common resolution of 1\(^\circ\). For each map, a full description of the noise covariances (II, QQ, UU, QU) is provided. This information will be used in our analyses. We would like to stress that the WMAP polarization maps are derived from the difference of two measurements. Thus, WMAP measures a double difference in polarized intensity, not the intensity of the difference of the electric field as with interferometers and correlation receivers

\(^4\)http://lambda.gsfc.nasa.gov/
\(^5\)http://healpix.jpl.nasa.gov

Figure 2. Neighborhood of the Perseus molecular complex as seen by WMAP-7 at 33 GHz (Ka band), with field of view of 23\(^\circ\) \times 23\(^\circ\) centered in the G159.6-18.5 region. All images (I, right panel; Q, center; and U, left panel) are smoothed to 1\(^\circ\) resolution and in units of mK (thermodynamic). The black circles define the circular apertures around the objects studied in this paper (see the text for details). (A color version of this figure is available in the online journal.)

3.2. Ancillary Data

3.2.1. Intensity

As a reference for the SED in G159.6-18.5, in this work we use the data points from Table 1 in W05. In that table, in addition to the COSMOSOMAS and WMAP measurements, there are also data points at 0.408 MHz (Haslam et al. 1982); at 1420 MHz (Reich & Reich 1988); and at 100, 140, and 240 \( \mu \)m, based on the DIRBE maps (Silverberg et al. 1993).

Here, we have re-evaluated the intensity measurements on the Haslam, WMAP, and DIRBE maps, using the methodology described in Section 3.3. The derived fluxes are slightly higher than those presented in W05 (by a factor of 5\%–13\%), although

| ID | A1 | A2 | A3 | A4 | A5 | A6 |
|----|----|----|----|----|----|----|
| R.A. (\(^\circ\)) | 52.19 | 47.30 | 50.21 | 46.88 | 60.39 | 59.70 |
| Decl. (\(^\circ\)) | 36.88 | 35.74 | 28.56 | 24.34 | 23.88 | 27.48 |

Note. The aperture used in all cases and at all frequencies is \( r_1 = 2\(^\circ\)\).

(for further details, see Page et al. 2007; Jarosik et al. 2007; Kogut et al. 2003).

From those \( Q \) and \( U \) maps at each frequency band, we can obtain the maps of the polarization intensity as

\[ P = \sqrt{Q^2 + U^2}, \]

while the angle between the polarization direction of the electric field and the Galactic meridian can be obtained as

\[ \gamma = \frac{1}{2} \arctan(U/Q). \]

Figure 2 shows a detailed view of the Perseus molecular complex as seen in the Ka band of WMAP (33 GHz). In this map, two strong sources are clearly visible: G159.6-18.5 (placed at the center of the image) and the H\( \alpha \) region NGC 1499. This later object will be used as a null hypothesis in our study, as free–free emission is known to be unpolarized. This null test was also used in the study of Battistelli et al. (2006). Finally, the figure also displays six nearby regions which have been selected due to their low emission in intensity. These regions will be used below to characterize the behavior of the background diffuse emission in the surroundings of G159.6-18.5.

| ID | A1 | A2 | A3 | A4 | A5 | A6 |
|----|----|----|----|----|----|----|
| R.A. (\(^\circ\)) | 52.19 | 47.30 | 50.21 | 46.88 | 60.39 | 59.70 |
| Decl. (\(^\circ\)) | 36.88 | 35.74 | 28.56 | 24.34 | 23.88 | 27.48 |
as pointed out below, this is probably due to the different methodology used for the flux determination in W05.

After W05, Semenova et al. (2009) used the RATAN-600 telescope to obtain independent measurements in the region. Although an estimate of the error bar of these new measurements is not provided in their paper, the overall shape of the SED in G159.6-18.5 in the frequency range 1–20 GHz is fully compatible with the results of W05, showing a rising spectrum in that frequency range.

Recently, Reich & Reich (2009) presented preliminary results of the emission in G159.6-18.5 at 11 cm and 6 cm with the Effelsberg and the Urumqi telescopes, respectively. These results support that the emission in the frequency range 2.7–5 GHz is compatible with an optically thin thermal gas, as expected from the SED in W05.

3.2.2. Polarization

The only reported measurement to date of the radio polarized intensity in G159.6-18.5 comes from the COSMOSOMAS experiment at 11 GHz (Battistelli et al. 2006). The measured fractional polarization is $\Pi = 3.4^{+1.5}_{-1.0}$% (95% CL).

Recently, Reich & Reich (2009) presented preliminary results of the polarized emission in G159.6-18.5 at 11 cm (~2.7 GHz) with the Effelsberg telescope. They reported a significant degree of polarization along the ring, which they interpreted as an indication that G159.6-18.5 acts as an FS rotating the polarization angle of the background emission in the region. However, this effect will be strongly suppressed at the peak frequencies of the anomalous emission (20–30 GHz) as discussed below.

Kogut et al. (2007) presented a full-sky model of the polarized Galactic microwave emission, considering in their analysis the polarization from the thermal dust and synchrotron emissions. The resulting polarized dust model obtained in that paper shows that the Perseus molecular complex lies near the boundaries of the P06 mask (see mask definition in Page et al. 2007), where the expected dust fractional polarization ($\Pi_{\text{dust}}$) reaches 6.4% ± 1.3% and 2.0% ± 1.4% for $|b| < 10$ deg and $|b| > 10$ deg, respectively, inside P06; and 3.6% ± 1.1% outside the P06 mask. This fractional degree of polarization will be of importance when studying the high frequency behavior of the polarized emission in the G159.6-18.5 region.

3.3. Determination of the Spectral Energy Distribution in Intensity and Polarization

Figures 2 and 3 show that there is no obvious structure seen within the G159.6-18.5 region in the polarization maps. In this case, we cannot apply a similar method to the one used in W05 for the flux determination. In that paper, a simple elliptical Gaussian model was used to describe the region, and fluxes were obtained using direct fitting to the data.

Here, we will adopt a direct aperture integration, or “ring analysis,” both for the intensity and polarization determinations. The practical implementation of this method has been previously used in other works (Bennett et al. 1993; Banday et al. 1996; Hernández-Monteagudo & Rubiño-Martín 2004). The basic idea is as follows. For a certain frequency map, we define a circular aperture around the object with radius $r_1$, subtending a solid angle $\Omega_1$ around the source. In order to correct for the background emission, a circular corona with radius $r_1 < r < r_2$ is used. In order to preserve a similar area both for the source and the background flux estimation, we use the relation $r_2 = r_1 \sqrt{2}$ between the two apertures. This method provides an efficient correction of the background emission around the source for apertures ($r_1$ values) comparable to the beam size, although for larger apertures might be biased due to the background or CMB contributions. The error bar associated with this measurement contains the quadratic sum of two contributions, the pure instrumental noise and the increase of the variance due to the CMB fluctuations. It is important to note that the evaluation of both contributions should account for correlation terms. In the case of the CMB, this is introduced by means of the two-point correlation function, which is evaluated using the (measured) WMAP angular power spectrum. In the case of the noise, the correlation between pixels shows up after the smoothing process and is taken into account in a pixel-by-pixel basis.

As we will see below, in the case of the selected aperture for G159.6-18.5 ($r_1 = 2'$) and the instrumental noise level of the WMAP data, the CMB contribution to the error bar is dominant for the $I$ Stokes parameter, while its contribution is negligible for Stokes $Q$ and $U$. Although the main focus of this paper is the polarization determination, for illustration purposes we have also considered how the intensity measurements change with our aperture method when a CMB correction is performed.
before the flux determination. For that discussion, we have used the Internal Linear Combination (ILC) map provided by the WMAP team in the LAMBDA Web site (Gold et al. 2010). Although this map does not provide an optimal separation of the CMB component, it provides a reasonable approximation which can be used to estimate its impact on the final intensity measurements.

4. RESULTS AND DISCUSSION

4.1. Control Regions

4.1.1. Characterization of the Background Emission

G159.6-18.5 is relatively close to the galactic plane, in a region with a non-negligible diffuse emission which varies markedly with the position. In order to characterize the behavior of this background emission, we have selected six regions with low emission in intensity in the surroundings of the Perseus molecular complex. The central coordinates of the six regions are shown in Table 1. Around each of them, we have chosen the same aperture as for G159.6-18.5 \( r_1 = 2\left(^\circ\right) \) for the flux determination.

Table 2 summarizes our results. In addition to the \( I, Q, \) and \( U \) determinations at each frequency, we also include in the last two columns the values for the fluxes inside the inner aperture \( (r_1) \) with no background correction. These numbers, quoted as \( Q_{\text{back}} \) and \( U_{\text{back}} \), will be used below for the analysis of the Faraday rotation in the region (Section 4.2). The table also includes an estimation of the total linear polarization \( P = \sqrt{Q^2 + U^2} \), and also the upper limit on this linear polarization \( P_0 \) that we would obtain in the null-hypothesis case using a zero signal \( (Q = U = 0) \) and the same noise levels. As in all the values where no detection is found, we quote upper limits which correspond to the 95% CL derived from a maximum likelihood approach based on the \( Q \) and \( U \) measurements.

We first note that at all frequencies, the main contribution to the error budget in intensity comes from the CMB part, which for illustration purposes is written separately in Table 2 (values in brackets in the second column). As one would expect, its relative contribution rises with approximately \( v^2 \) dependence, as the temperature sensitivity of WMAP is comparable in all channels. In the case of \( Q \) and \( U \), the CMB contribution is negligible and it is not included in the error bar.

Finally, as a summary of the results in Table 2, we present in Table 3 the peak-to-peak variations \( (I_{p-p}) \), means, and the root mean squares of these values for the six regions. We note that in the case of intensity, the variations in the three first frequencies \( (23, 33, \) and \( 41 \) GHz) are even larger than the expected CMB contribution, which implies that in addition there is a significant contribution to the error budget coming from the variations of the diffuse background in the surroundings. This effect is not seen in polarization, so in this case the error bars seem to be dominated by the instrumental noise contribution. However, we note that the average values of \( Q_{\text{back}} \) and \( U_{\text{back}} \) show a small degree of diffuse polarization in the background, which is very well-corrected by the ring analysis.

4.1.2. NGC 1499: Null Hypothesis in Polarization

The California Nebula is an \( \text{H II} \) region close to G159.6-18.5 (its optical coordinates are R.A.(J2000) = 04\textdegree 03\textquoteright 18\textquoteleft and decl. = +36\textdegree 25\textquoteleft 3). Since the dominant emission mechanism in diffuse \( \text{H II} \) regions at these frequencies is the free–free emission, they are expected to be practically unpolarized, so NGC 1499 will be our null hypothesis for the polarization.

California is also an extended object at this resolution. For consistency, we use the same aperture \( r_1 = 2\left(^\circ\right) \) for all frequency bands, which after visual inspection is found to fit well with the solid angle that defines the source. The central coordinates of the emission used for the flux integration are R.A. = 60\textdegree 40 and decl. = +36:3675, practically coinciding with the peak emission in the 33 GHz map. Our results on the \( I, Q, U \) measurements, and the derived upper limits on the linear polarization\(^6\) \( P \) and \( \Pi \), as well as the null-case \( P_0 \) and \( \Pi_0 \), are presented in Table 4.

A simple extrapolation of the DIRBE fluxes to the WMAP frequency range shows that the thermal dust emission is expected to be negligible between 20 and 100 GHz. Thus, we expect that the main emission mechanism is the free–free emission. To check this prediction, we have derived the spectral index that best fits the data obtained in the range 23–41 GHz, using a power-law model \( (I \propto v^\beta) \). We find \( \beta = 0.08 \pm 0.10 \), which is apparently in contradiction with the expected frequency behavior for an optically thin free–free emitting region at these frequencies \( (\beta \approx -0.1) \). However, this seems to be an effect of the residual CMB contribution to these measurements. If we correct the WMAP maps from the CMB emission by subtracting the ILC map, the flux estimates at 23, 33, and 41 GHz are now found to be 61.6, 59.6, and 59.5 Jy, respectively. Using these values, we find \( \beta = -0.07 \pm 0.11 \), which is now compatible with the expected value.

Concerning the polarization measurements, at all frequencies the Stokes \( Q \) and \( U \) parameters are found to be compatible with a zero level. The upper limits on \( P \) and \( \Pi \) at the 95% CL are similar to those obtained for the null-case hypothesis \( (P_0 \) and \( \Pi_0 \)). Indeed, the full posterior distributions for these parameters are found to be very similar, implying a non-detection of polarization in the region, as one would expect for an \( \text{H II} \) region.

4.2. Perseus

Figure 3 shows a detailed view of the G159.6-18.5 region. The circular aperture used for the flux determination corresponds to a radius of \( r_1 = 2\left(^\circ\right) \) and is centered at R.A.(J2000) = 55\textdegree 4 and decl. = 31\textdegree 8. Since G159.6-18.5 is an extended object, we have used the same aperture \( r_1 \) at all frequency bands. The subsets of pixels within the small aperture at the northwest of the center of G159.6-18.5 were removed for the flux determination, as they correspond to the location of the quasar 4C+32.14. This small aperture uses \( r_{\text{flux}} = 0.25 \) at all frequencies, and it is centered at R.A.(J2000) = 54:125 and decl. = 32:308. Table 5 summarizes the results obtained for the region.

4.2.1. Intensity Signal

The second column in Table 5 presents the results for the intensity measurements in the G159.6-18.5 region. A comparison with the results in W05 shows that our fluxes are between 5% and 13% higher in the first four channels (23 to 61 GHz) and 10% smaller in the last channel (94 GHz). This small discrepancy is probably due to the different methodologies used to derive the fluxes. In W05, an elliptical model for the region was adopted, so any departure of the actual shape of the region from this model might introduce these changes.

Figure 4 shows our results for the intensity signal in WMAP and DIRBE maps, together with the ancillary data described

\(^6\) \( \Pi \) is the fractional linear polarization, defined as \( \Pi \equiv 100 \frac{P}{I} \).
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DIRBE data we can fit the thermal dust emission with a modified blackbody function

in Section 3.2. Following W05, using the W band and the DIRBE data we can fit the thermal dust emission with a modified blackbody function

\[ I_{\text{dust}} \propto \nu^{\beta_{\text{dust}}} B(\nu, T_{\text{dust}}), \]

where \( T_{\text{dust}} \) is the dust temperature and \( \beta_{\text{dust}} \) is the dust emissivity index. The black dashed line represents the best-fit model of the thermal dust emission, which has parameters \( \beta_{\text{dust}} = 1.55 \) and \( T_{\text{dust}} = 19 \, \text{K} \).
in full agreement with W05. These values are expected for dust in a “warm neutral medium” (WNM).

The low-frequency behavior in Figure 4 is fitted by the dotted line to a free–free emission \( I_{\text{ff}} \propto \nu^{2/3} \), using the measurement at 1420 MHz (7.3 ± 2.0 Jy from W05) and the typical free–free spectral index \( \beta_{\text{ff}} = -0.12 \) for an optically thin region.

As in W05, the extrapolations of the thermal dust and free–free emissions cannot explain the rising spectrum between 10 and 23 GHz, and a third component (the anomalous emission) has to be included in the fit. Following W05, we consider a model based on a linear combination of the Draine & Lazarian (1998) models for WNM and MC. Using \( \tau_{\text{2000}} = 8.45 \times 10^{-4} \) (obtained from the fit thermal dust emission) and the canonical factor of \( 2.13 \times 10^{24} \) H \( \text{cm}^{-2} = 1 \text{ mm} \) (from Finkbeiner et al. 2004), we obtain the column number density of hydrogen \( N(H) = 1.8 \times 10^{21} \text{ cm}^{-2} \), which differs from the value obtained by W05 (1.3 \times 10^{22} \text{ cm}^{-2}) due to the dependence of \( N(H) \) on the solid angle. For illustration purposes, we plot the same model as in W05 for the fit of the anomalous emission: \( I_{\text{a}} \approx 0.8 \text{ WNM} + 0.3 \text{MC} \) (black dot-dashed line in Figure 4).

However, we note that here the model has been rescaled to our column density (\( N(H) \)) and solid angle (\( \Omega_\text{s} \)) values. For completeness, Figure 4 also shows the individual contribution of WNM, MC, and cold neutral medium (CNM) models. In a line of sight toward the Perseus anomalous microwave emission there is evidence for abundant molecular gas (Iglesias-Groth et al. 2010) and from optical spectroscopy of \( C_2 \), Iglesias-Groth (2010) has derived a gas kinetic temperature of \( T = 40 \) K and a density of \( n = 250 \pm 50 \text{ cm}^{-3} \). These values for \( T \) and \( n \) are well covered by the MC and CNM models displayed in the Figure.

The red solid line in Figure 4 corresponds to the co-added SED model \( I_{\text{tot}} \) for the three components \( (I_{\text{tot}} = I_\text{ff} + I_{\text{dust}} + I_{\text{a}}) \).

4.2.2. Polarization Signal

Table 5 summarizes our polarization measurements, which show that the polarized intensity in G159.6-18.5 is compatible with zero at the five frequency bands. Because of this reason, all quoted values in Columns 5–8 correspond to upper limits at the 95% CL. Nevertheless, these upper limits on the linear polarization fraction still provide extremely important constraints on the nature of the anomalous emission.

Figure 5 represents our upper limits from WMAP data, together with the 11 GHz result of Battistelli et al. (2006). For comparison, we also include the expected dust fractional polarization for three cases, namely, \( \Pi_{\text{dust}} \) equal to 6.0% (solid black line), 3.6% (solid blue line), and 2.0% (solid red line). This range of values for the polarized dust emission in the region is taken to be consistent with the estimates in Kogut.

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**Table 4**

| \( \nu \) (GHz) | \( I \) (Jy) | \( Q \) (Jy) | \( U \) (Jy) | \( P \) (Jy) | \( \Pi \) (%) | \( P_0 \) (Jy) | \( \Pi_0 \) (%) |
|----------------|------------|------------|------------|------------|-------------|-------------|-------------|
| 23             | 64.65 ± 0.13 (± 1.50) | 0.28 ± 0.16 | 0.12 ± 0.21 | <0.63 | <0.98 | <0.46 | <0.71 |
| 33             | 65.70 ± 0.23 (± 3.02) | −0.22 ± 0.30 | 0.44 ± 0.37 | <0.90 | <1.40 | <0.82 | <1.27 |
| 41             | 68.92 ± 0.32 (± 4.62) | 0.36 ± 0.41 | 0.15 ± 0.54 | <1.18 | <1.84 | <1.17 | <1.84 |
| 61             | 70.73 ± 0.79 (± 9.73) | 0.58 ± 1.01 | 0.21 ± 1.31 | <3.05 | <4.73 | <2.84 | <4.43 |
| 94             | 65.61 ± 1.93 (± 20.11) | 2.64 ± 2.45 | −1.55 ± 3.19 | <7.10 | <10.90 | <6.91 | <10.70 |

**Notes.** We use an aperture of \( r_1 = 2'' \) at all frequencies to integrate the fluxes for \( I, Q, \) and \( U \) Stokes parameters. The upper limits on \( P \) and \( \Pi \) are derived using a maximum likelihood analysis. Similarly, we get the upper limits \( P_0 \) and \( \Pi_0 \) for the null-case hypothesis \( Q=U=0 \). As in Table 2, for the intensity column the error budget is separated in two contributions, the instrumental noise and the CMB error (within parenthesis).

**Table 5**

| \( \nu \) (GHz) | \( I \) (Jy) | \( Q \) (Jy) | \( U \) (Jy) | \( P \) (Jy) | \( \Pi \) (%) | \( P_0 \) (Jy) | \( \Pi_0 \) (%) |
|----------------|------------|------------|------------|------------|-------------|-------------|-------------|
| 23             | 47.76 ± 0.13 (± 1.44) | −0.07 ± 0.16 | 0.01 ± 0.22 | <0.48 | <1.01 | <0.47 | <0.98 |
| 33             | 42.97 ± 0.23 (± 2.90) | 0.05 ± 0.29 | 0.43 ± 0.39 | <0.86 | <1.79 | <0.85 | <1.76 |
| 41             | 37.88 ± 0.33 (± 4.44) | −0.09 ± 0.42 | −0.41 ± 0.55 | <1.29 | <2.69 | <1.19 | <2.48 |
| 61             | 36.36 ± 0.80 (± 9.35) | 0.06 ± 1.01 | 0.67 ± 1.33 | <3.44 | <7.23 | <2.88 | <6.03 |
| 94             | 70.18 ± 1.94 (± 19.32) | 1.13 ± 2.46 | −2.06 ± 3.24 | <7.52 | <15.64 | <7.04 | <14.65 |

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**Figure 4.** Spectral Energy Distribution (SED) for the G159.6-18.5 region. The blue squares and black diamond correspond to measurements obtained in this paper (WMAP and DIRBE bands) and the ancillary data used (COSMOSOMAS and HASLAM bands), respectively. The SED is fitted with three contributions: (1) the free–free emission \( I_{\text{ff}} \), modeled as a power law with spectral index \( \beta_{\text{ff}} = -0.12 \); (2) the thermal dust emission, modeled as a modified black body \( (I_{\text{dust}}) \) with spectral index \( \beta_{\text{dust}} = 1.55 \) and temperature \( T_{\text{dust}} = 19 \) K; and (3) the spinning dust due to the electric dipole, modeled here as the linear combination of two Draine & Lazarian (1998) models for warm neutral medium (WNM) and molecular cloud (MC) described in W05. The red line represents the co-added SED model of the three contributions. For illustration, we also include the WNM, CNM (cold neutral medium), and MC (Draine & Lazarian 1998) models with an arbitrary amplitude of \( N(H) \approx 5 \times 10^{20} \text{ cm}^{-2} \), all normalized to our solid angle \( \Omega_\text{s} \).

(A color version of this figure is available in the online journal.)
et al. (2007). The conclusion is that our upper limits on the fractional linear polarization in G159.6-18.5 at these microwave wavelengths can be directly translated into upper limits on the anomalous emission, at least in the frequency range 23–41 GHz, while the dust contribution has to be taken into account at higher frequencies. Thus, the upper limits at 23 and 33 GHz of \( \Pi_{(23 \text{ GHz})} < 1.0\% \) and \( \Pi_{(33 \text{ GHz})} < 1.8\% \) (95\% CL) constitute the most stringent constraints on the polarization of this emission.

**Faraday screen model.** As mentioned in Section 2, Reich & Reich (2009) have recently suggested that G159.6-18.5 is acting as an FS hosting a strong regular magnetic field, which would rotate the background polarized emission, being the responsible mechanism of the signal detected in Battistelli et al. (2006). However, this mechanism produces negligible effects on the expected polarized emission at the WMAP frequencies. To show this, we can use the estimates of the background emission from the last two columns in Table 3 and take the rotation measure \( RM = 190 \text{ rad m}^{-2} \) as a face value to evaluate the effect. Being conservative, we can assume that the full background emission is rotated by the FS. In that case, for the relevant rotation angles (computed as \( \theta = RM \lambda^2 \)), we obtain that the expected polarization signal is smaller than 0.1 Jy (or 0.2\%) at 23 GHz and becomes even smaller at higher frequencies (Ka, Q, and V). Therefore, we can safely neglect its contribution at the WMAP frequency bands.

**Implications on the anomalous emission models.** Figure 6 illustrates the implications of our measurements on the existing models of anomalous emission. The figure also includes the value of Battistelli et al. (2006), because even in the case that this result only provides an upper limit to the polarization of the anomalous emission, it still is a very valuable constraint.

In Figure 6 we have considered two physical processes used by various authors to try to explain the anomalous emission: (1) the electric dipole (hereafter ED) emission and the resonance relaxation, proposed by Lazarian & Draine (2000) and (2) the magnetic dipole (hereafter MD) emission proposed in Draine & Lazarian (1999). For the first case, and for illustration purposes, we use here the CNM model. For the second case, here we will restrict ourselves to those models where the grains that dominate the 10–100 GHz emission consist of a single magnetic domain. These models were computed by Draine & Lazarian (1999) for metallic Fe and for a hypothetical material X4 (defined by them).

Both results will be used here, for three different grain shapes with axial ratios \( a/2a_2a_3 \), namely, 1:1.25:1.5 (dotted lines), 1:1.5:1.5 (dashed lines), and 1:2.2 (dot-and-dashed lines). For further details on these models, see Draine & Lazarian (1999).

We note that in addition to the anomalous emission, when plotting the different models in Figure 6 we have also included the contribution of the polarized thermal dust emission with a polarization fraction of \( \Pi_{\text{dust}} = 6.0\% \). In practice, this is done as described by this equation

\[
\Pi_m = \frac{P_a + P_{\text{dust}}}{I_a + I_{\text{dust}} + I_f},
\]

where the model for the linear polarization of anomalous and the thermal dust emission can be represented by \( P_a = I_a \Pi_a \) and \( P_{\text{dust}} = I_{\text{dust}} \Pi_{\text{dust}} \), respectively. The \( I_{\text{dust}} \), \( I_f \), and \( I_{\text{dust}} \) contributions were obtained in the previous section.

From Figure 6, we see that the measurement at 11 GHz cannot completely rule out the model of dust grains of X4 with semiaxes 1:1.5:1.5. However, when including the upper limits derived here from WMAP data, all the considered models based on magnetic dipole emission can be ruled out. In contrast, all these measurements are in agreement with the predictions of the polarization fraction from the electric dipole and resonance relaxation theory (Lazarian & Draine 2000) at this frequency range (see Figure 7).
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5. CONCLUSIONS

A detailed understanding of the physical mechanism responsible for the anomalous microwave emission is still needed. The polarization properties of those regions with anomalous emission, as in G159.6-18.5, are very useful tools to disentangle, among the different models proposed in the literature.

Here, we used the WMAP7 data to study the intensity and polarization properties of the emission in the G159.6-18.5 region. In intensity, our results confirm the presence of the anomalous microwave emission. We present an updated SED model that takes into account the contribution of the electric dipole emission of very small dust grains rapidly rotating (Draine & Lazarian 1998).

Concerning the polarization in the region, we present the first constraints on the polarization properties of the anomalous microwave emission at high frequencies (23–94 GHz). Due to the fact that more than 90% of the emission in G159.6-18.5 is diffuse and extended over scales larger than 40 arcmin (Tibbs et al. 2010), the angular resolution of WMAP is not a limitation when constraining the polarization degree of the emission in the region. Although we find no detection of polarization in any of the five frequency bands, the derived upper limits allow us to exclude a significant number of models based on the magnetic dipole emission of dust grains, where the orientation of the magnetic domains is aligned either parallel or perpendicular to the principal axis of largest moment of inertia (Draine & Lazarian 1999), as the physical process responsible for the observed polarization.

The main conclusion is that the combination of our constraints in the range 23–94 GHz with the measurement at 11 GHz from the COSMOSMAS experiment (Battistelli et al. 2006) is consistent with the expected linear polarization arising from the electric dipole model with resonance relaxation.

Further observations with higher sensitivity and angular resolution in this and other regions will be valuable to understand the nature of this anomalous emission in polarization.

Figure 7. Constraints on the grain alignment for both resonance and Davis–Greenstein relaxation models for grains in the cold interstellar medium as a function of the frequency. Both theoretical curves are taken from Lazarian & Draine (2000; see the text for details). For the resonance relaxation the saturation effects are neglected, which means that the upper curves correspond to the maximal values allowed by the paramagnetic mechanism. The data point corresponds to the Battistelli et al. (2006) result, while the three upper limits are the results in this paper.

(A color version of this figure is available in the online journal.)
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