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POLARIZATION OBSERVATIONS OF THE ANOMALOUS MICROWAVE EMISSION IN THE PERSEUS MOLECULAR COMPLEX WITH THE COSMOSOMAS EXPERIMENT

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ABSTRACT

The anomalous microwave emission detected in the Perseus molecular complex by Watson *et al.* has been observed at 11 GHz through dual-orthogonal polarizations in the COSMOSOMAS experiment. Stokes U and Q maps are obtained at a resolution of ∼0.9° for a 30°x30° region including the Perseus Molecular complex. A faint polarized emission has been measured; we get $Q = -0.2 \pm 1.0\%$, while $U = -3.4^{+1.8}_{-1.4}\%$ both at 95% CL with a systematic uncertainty estimated to be lower than 1% determined from tests of the instrumental performance using unpolarized sources in our map as null hypothesis. The resulting total polarization level is $\Pi = 3.4^{+1.5}_{-1.9}\%$. These are the first constraints on the polarization properties of an anomalous microwave emission source. The low level of polarization seems to indicate that the particles responsible for this emission in the Perseus molecular complex are not significantly aligned in a common direction over the whole region, due to either a high structural symmetry of the emitting particle, or to a low-intensity magnetic field. Our weak detection is fully consistent with the predictions from electric dipole emission and resonance relaxation at this frequency.

Subject headings: diffuse radiation–dust,extinction–ISM:individual (G159.6-18.5)–radiation mechanisms:general–radio continuum:ISM–polarization

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1. Introduction

Since the COBE experiment first detected dust correlated microwave emission in its maps (Kogut *et al.* 1996), a significant effort has been made by the scientific community to understand the origin of this anomalous emission and characterize its properties. Further statistical evidence has been found in observations and analysis by Leitch *et al.* (1997), de Oliveira-Costa *et al.* (1997, 1998, 1999, 2002, 2004), Mukherjee *et al.* (2001, 2003), Lagache *et al.* (2003), Finkbeiner (2004a), Finkbeiner, Langston, and Minter (2004b) and Davies *et al.* (2005). Still, the underlying mechanism for this emission is a matter of discussion due to the lack of measurements about its properties, and different models have been proposed to explain its observed characteristics.

The COSMOSOMAS experiment[2] of the Instituto de Astrofisica de Canarias (IAC) is now able to fill the frequency and sky coverage gap needed to increase our understanding of the statistical and physical properties of the anomalous microwave emission (Fernández-Cerezo *et al.* , 2006; Hildebrandt *et al.* , in prep.). Watson *et al.* (2005) (W05 hereafter) have recently presented a direct detection of rising spectrum emission detected by COSMOSOMAS in the Perseus molecular cloud RA=$55^\circ.4$ and dec=$31^\circ.8$ (J2000) which is an order of magnitude higher than what can be explained with standard galactic mechanisms of emission (*i.e.* free-free, synchrotron and thermal dust) and that cannot be explained with any ultra-compact H II regions or gigahertz-peaked source. In this letter we present polarization measurements of this anomalous emission performed with the COSMOSOMAS experiment. It is worth stressing that the W05 detection refers to an extended region appearing diffuse also with the COSMOSOMAS angular resolution ($\sim 1^\circ$) and with a Gaussian FWHM fit over the emitting region of $\sim 2^\circ$. Our polarization measurements are characterized by the same angular resolution.

2. Anomalous microwave emission: interpretation and polarization properties

Comparison between anomalous emission detections and Hα maps have already ruled out the possibility that statistical and direct observations are due to free-free emission from ionized gas (see, for instance, Draine and Lazarian 1998a, 1998b; D&L hereafter). Ultra compact H II regions have also been invoked by McCullough and Chen (2002), to explain the direct tentative detection performed by Finkbeiner *et al.* (2002), as the superposition of a compact optically thick and extended optically thin H II regions both free-free emit-

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[2] http://www.iac.es/project/cmb/cosmosomas

ters. Bremsstrahlung emission is intrinsically unpolarized, although polarization may occur via Thomson scattering when photons are re-scattered within the H II region. This may occur in optically thick regions where the level of polarization can be at maximum 10% (Keating *et al.* 1998). Bennett *et al.* (2003) and Hinshaw *et al.* (2006) interpret the dust-correlated component as a synchrotron emission with a flatter spectral index. However, the results of the Tenerife Experiment (e.g. de Oliveira-Costa *et al.* 2004), or the analysis of Lagache (2003) are not consistent with this interpretation. In any case, polarization measurements are essential to probe this hypothesis, because the synchrotron emission is expected to be highly polarized.

D&L (1998a, 1998b) have proposed that the anomalous dust correlated emission is due to electric dipole emission from rapidly rotating small dust grains (*i.e.* spinning dust) in the interstellar medium. They have gone into the details of the mechanisms of excitation and damping, and concluded that their emission spectrum may fit well the observed signal and be responsible for this anomalous emission. Lazarian and Draine (2000) continued the study of spinning dust grains in the presence of weak magnetic fields and found that paramagnetic relaxation resonance, in a domain where classical paramagnetic relaxation is suppressed, may be efficient at producing an alignment of grains rotating faster than 1 GHz. This may result in the presence of an observable polarization as high as 5% at 10 GHz and rapidly decreasing at higher frequencies, in the anomalous emission, depending on the phase in sky of the magnetic field. Still, the level of alignment depends on factors like the efficiency of spin-lattice relaxation which is uncertain for very small grains (*i.e.* $< 10^{-7}$cm).

Magnetic dipole emission from dust grains has also been found to be of considerable interest at frequencies <100 GHz. D&L (1999) calculated the spectra of different grains candidates and found that ordinary paramagnetic grains exhibit emission spectra noticeably different from the observed anomalous emission. However, they proposed a model, adjusting the magnetic properties of the emitting material, involving strong magnetic material whose emission may account, at least in part, for the observed anomalous emission. For this model, ferromagnetic relaxation may efficiently act in aligning dust grains and produce strongly frequency- and shape-dependent polarized emission that could be as high as 30% at 10 GHz. A key signature of polarized emission from magnetic dipole, with respect to electric dipole, is the variation of its direction with frequency.

It is worth noting that both electric and magnetic dipole emissions are model-dependent making it difficult to effective predict their polarization properties. However, according to the model proposed by D&L (1999), in order to account for the observed spectrum a hypothetical material "X4" characterized by strong magnetic grains has to be considered. Therefore, asymmetric grains will be aligned even by a low intensity magnetic field like the Galactic filed, resulting in both a higher polarization level and a higher probability for alignment to occur with respect to electric dipole emission.

Iglesias-Groth (2005,2006) studied the rotation rates of hydrogenated fullerenes and electric dipole emission in the interstellar medium and found that the smallest of these molecules could be the origin of the anomalous emission detected by W05 in the Perseus molecular complex and by Casassus *et al.* (2006) in the dark cloud LDN 1622. Also, weak ferromagnetic properties exhibited by some of these molecules may lead to a consistent alignment and consequently to detectable polarization.

3. COSMOSOMAS observations

3.1. The instrument

The COSMOSOMAS experiment is located at the Teide observatory at 2400m a.s.l. in Tenerife (Spain). It is formed by two circular scanning instruments and generates two daily maps at 11 GHz (COSMO11 instrument) and 3 maps at 13, 15 and 16 GHz (COSMO15 instrument). The angular resolution is approximately 0.9°. The interested reader may refer to Gallegos *et al.* (2001) for a general description of the COSMO15 instrument and of the adopted observational strategy. COSMO11 has similar instrumental set-up to COSMO15. The optical configuration is identical (dimensions are scaled with wavelength) with a rotating primary flat mirror and a secondary parabolic mirror focusing the radiation into a cryogenically cooled receiver. The detectors are low noise HEMT amplifiers cooled to 20K.

The main difference between the two experiments is that COSMO11 is optimized for polarization measurements. An Ortho Mode Transducer (OMT) is used to separate two orthogonal polarizations after the radiation collector and before the HEMT which are followed by further amplification stages. This configuration allows to sample the sky performing measurements of 2 Stokes parameters at a time: I and Q (or U depending on the orientation in sky of the measured polarization planes). In order to completely characterize linear polarization of the measured emission, the sampled polarization planes have been rotated by 45° by simply rotating the front-end of the experiment allowing us to switch the receiver sensitivity from Q to U (and vice-versa). A detailed description of the instrument will be presented in Hoyland *et al.* (in prep.).

3.2. Data analysis

COSMO11 performs daily maps with full coverage in RA and $\sim 20^\circ$ in dec. Raw data are stacked in scan collections where the detected data, resulting from the adopted circular scan strategy, are saved as a function of the time. Each scan is the result of an average over 30 cycles (equivalent to 30 s). Atmospheric emission is evident in the scans as a pseudo-sinusoidal modulation due to changing air masses within the circles covered on the sky by the instrument. This modulation has been removed by calculating a template and subtracting it from our scans. The template has been calculated averaging over 2 hours, masking bright sources and the galactic plane, and iterating the procedure. The time over which the template has been calculated has been chosen by considering the final S/N as a function of time. This procedure allows a subtraction of slow day-night modulation, including 1/f noise as well as other fixed systematics like optical pick-up which is anyway strongly reduced by under-illuminating the primary mirror.We note that this data processing differs from the one adopted in W05, and Fernández-Cerezo *et al.* 2006, and it is aimed at preserving the large scales of the emission (i.e. to extend the window function to lower multipole ℓ). After the cleaning procedure we proceed to the projection of the scans into the sky map using bright sources to check for consistency in the pointing reconstruction. The final pixelization is $1/3^\circ \times 1/3^\circ$. After that we sum the daily maps into cumulated maps. The main calibration is performed with Cygnus A on daily basis. Absolute flux is taken from the model by Baars *et al.* (1977). The instrumental beam is also calculated using the main calibrator for each day. The overall beam is recalculated using the cumulated map, and afterwards we re-calibrate all the maps with fixed FWHM's with the Gaussian fits over the calibration source.

In the calculation of the source emission, we take great care in accounting for contaminations which might be due to the Sun or the Moon in the proximity of the target sources. We have adopted a conservative attitude removing from the analysis those data in which the sun is closer than $\sim 30^\circ$ to the interested regions. Our conservative attitude originates from our concern about possible (even very low) asymmetric pick-up resulting in a polarized signal. A significant effort has been made to track the instrument stability using radio-sources and H II regions emission and polarization with time. Among others, we have checked in the reconstructed map the coordinates of 4C 39.25 and 3C 345 outside the galactic plane, and 3C84 and IC405 in the galactic anti-center, close to the Perseus region of interest. These sources have allowed us to test possible effects arising from the distance to the calibration source in our maps, and to test that possible misalignment effects in the optical system of the instrument are not affecting the local reconstruction of the microwave sky in the region of interest. Also, the relatively close H II region NGC 1499 (California) has been used to test possible effects and systematics arising from measurements of extended sources compared to point-like sources. All the cited sources have shown a good level of stability or slow variation compatible with intrinsic flux variations. NGC 1499 has also been carefully studied to check for spurious effects and as a zero hypothesis test since diffuse H II regions are expected to mainly emit free-free radiation which is intrinsically unpolarized.

Possible diffuse polarized synchrotron emission has been checked using Wolleben *et al.* (2006) maps [3]. Wolleben *et al.* point out the presence of depolarized regions around H II regions. Fortunately this does't have an effect on the polarized emission of the Perseus molecular cloud which is known to be closer to us than NGC 1499. A detailed analysis of Wolleben *et al.* polarization maps, and the extrapolation toward COSMOSOMAS frequencies, show possible residual polarized signal lower than 1% in the NGC 1499 region even assuming a spectral index as high as -2.7. We have thus finally re-calibrated our Perseus emission with NGC 1499.

The coordinate convention adopted in this paper is to define the Q and U Stokes parameters is the following. At every point on sky, the X axis is pointing north, and the Y axis is pointing East. In the first COSMO11 configuration, we measure I_{0° (intensity along X axis) and I_{90° (intensity along Y axis), while in the second orientation of the system we obtain I_{+45° and I_{-45°. Our definition of Stokes parameters is $Q = I_{0^\circ} - I_{90^\circ}$ and $U = I_{45^\circ} - I_{-45^\circ}$. For each one of the two configurations, we have two determinations of the intensity, which we note as $I_Q = I_{0^\circ} + I_{90^\circ}$ and $I_U = I_{45^\circ} + I_{-45^\circ}$, respectively. Finally, the total polarization degree is defined as $\Pi = \sqrt{Q^2 + U^2}/I$.

Instrumental spurious polarization induced by oblique reflections in our off-axis system has been calculated, in a regime of ordinary skin effect, using the method presented in Renbarger, Dotson, and Novak (1998) and is found to be totally negligible compared to other systematics. The two channels have almost identical spectral response resulting in a negligible systematic effect due to the pass-band mismatch between observed calibrator and the Perseus region (*i.e.* the effect is canceled out). Further instrumental effects have been tested by rotating the front-end of the instrument by 90° and checking for consistency.

Q measurements have been taken over the period between March 2004 and May 2005 while U measurements are extracted from the measurements performed after this month. The time coverage is not uniform due to contaminations, to variation in the atmosphere conditions and to instrumental failures which have been reduced to the minimum thanks to a continuous monitoring of the instrumental performance. The integration time for the U measurements is smaller than that for Q, resulting in higher statistical errors. The residual systematics are monitored by NGC 1499 measurements using this H II region as a null-test.

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[3] http://www.drao-ofr.hia-iha.nrc-cnrc.gc.ca/26msurvey/data.html

This is done in two steps: by directly observing NGC 1499 on the Cygnus calibrated map, and then by considering the possibility of a faint polarization of the main calibrator which could result in an apparent polarization signal of the H II region. Tests on Wolleben *et al.* maps allowed us to check for this possibility and, after accounting for this, to constrain the systematics both for Q and for U directions at lower level with respect to the statistical uncertainties. In order to double-check this result we have carefully monitored 3C84 whose emission is expected to be variable with time but whose polarization is expected to be far below 1% [4]. We get a final polarization level lower than 1% which sets our systematic level.

4. Results and discussion

The effective polarized emission form the Perseus region has been calculated through a maximum likelihood analysis using the measurements of the partial stacked maps. This likelihood was built using a multivariate Gaussian distribution. Measurements at different epochs were assumed to be uncorrelated, so the covariance matrix in this case is diagonal. We describe the data with a two-parameter model, one for the value (assumed to be constant in time) for the polarization of the Perseus region, and another one for the calibration uncertainty. This latter parameter is marginalized over following the analytical prescription given in Bridle *et al.* (2002), assuming a Gaussian prior for its value with 10% width (overall calibration uncertainty). Note that in the case of the fractional polarization the calibration uncertainty does not enter. Once the likelihood curves are computed, the confident limits are derived from the 0.025, 0.5 and 0.975 points of the cumulative distribution function. Thus, our parameter estimate is the median of the marginalized posterior probability distribution function, and the confidence interval encompasses the 95% of the probability. In Figure 1 we report the map of the Perseus region emission and the two difference-maps of 90° polarization orientation describing the Q and U parameters.

We get a small polarization emission in both orientations: for the $0^\circ/90^\circ$ orientation we get $Q/I = -0.2 \pm 1.0\%$, while for the $45^\circ/-45^\circ$ one we get $U/I = -3.4^{+1.8}_{-1.4}\%$ both 95% CL, with a total polarization level of $\Pi = 3.4^{+1.5}_{-1.9}\%$. The polarization in the $0^\circ/90^\circ$ orientation is thus consistent with a null measurement within the systematic and statistical uncertainties. A polarization in U is possible both from a statistical and systematic point of view. From the considerations highlighted in the introduction, although model-dependent uncertainties are widely present, the low level of polarization in the Perseus anomalous emission appears to be inconsistent with magnetic dipole emission of particles highly oriented

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[4] See UMRAO database, at http://www.astro.lsa.umich.edu/

in the presence of a magnetic field, either because of a low-intensity of the field in the region, or because of the highly symmetric nature of the emitting particles. Our results favor electric dipole emission as responsible for this emission, whose emission properties are even more model-dependent, but whose polarization is limited to $\sim 5\%$. In particular, as presented by Lazarian and Draine (2000), paramagnetic relaxation resonance may produce an observable polarized signal of the same order of what observed by COSMOSOMAS for an equivalent radius of the grains $\lesssim 10^{-7} cm$. Our observations are limited both by the interpretation of the models and by our angular resolution. In fact, we cannot constraint magnetic-emitting grains characterized by low magnetic properties or by spherical shape, and we cannot monitor structures characterized by angular dimensions smaller then our angular resolution in the observed region. This latter problem is, however, somewhat lessened by the fact that the measurement of W05 is over an extended region and so we expect anomalous emission properties to characterize the entire region. Further polarization observations with higher sensitivity and angular resolution, as well as monitoring other frequencies of interest for the anomalous emission, will further help to understand the mechanism responsible for this emission.

5. Conclusions

We have observed the Perseus molecular cloud in order to extract information about polarization properties of the anomalous microwave emission observed by W05. A careful analysis and control of systematics lead us to the conclusion that this emission is characterized by a low level of polarization: $\Pi = 3.4^{+1.5}_{-1.9}\%$ 95% CL with systematic uncertainties limited to 1%. To infer the real emission mechanism for the anomalous emission, still local physical properties of the observed regions should be further investigated. However, the weak detected polarization seem to support the electric dipole emission model, with resonance relaxation, over the dipole magnetic emission hypothesis. Further information about the effective origin of this emission will be available with higher resolution/higher sensitivity/multifrequency observations already planned at the Teide observatory and, hopefully, planned by other instruments.

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REFERENCES

Baars, J.W.M., Genzel, R., Pauliny-Toth, I.I.K., and Witzel, A., 1977, A&A 61 99

Bennett, C.L., *et al.* , 2003, ApJS, 148, 1,97

Casassus, S., Cabrera, G.F., Frster, F., Pearson, T.J., Readhead, A.C.S., and Dickinson, C., 2006, ApJ, 639, 2, 951

Bridle, S.L., Crittenden, R., Melchiorri, A., Hobson, M.P., Kneissl, R., and Lasenby, A.N., 2002, MNRAS, 335, 1193

Davies, R.D., Dickinson, C., Banday, A.J., Jaffe, T. R., Gorski, K.M., and Davis, R. J., 2005, astro-ph/0511384

de Oliveira-Costa, A., Kogut, A., Devlin, M.J., Netterfield, C.B., Page, L.A., and Wollack, E.J., 1997, ApJ 482 L17

de Oliveira-Costa, A., Tegmark, M., Page, L.A., and Boughn, S.P., 1998, ApJ 509 L9

de Oliveira-Costa, A., Tegmark, M., Gutierrez, C.M., Jones, A.W., Davies, R.D., Lasenby, A.N., Rebolo, R., and Watson, R.A., 1999, ApJ 527 L9

de Oliveira-Costa, A., *et al.* , 2002, ApJ 567 363

de Oliveira-Costa, A., Tegmark, M., Davies, R.D., Gutirrez, C.M., Lasenby, A.N., Rebolo, R., and Watson, R.A., 2004, ApJ 606 L89

Draine, B.T., and Lazarian, A., 1998a, ApJ, 494, L19

Draine, B.T., and Lazarian, A., 1998b, ApJ 508 157

Draine, B.T., and Lazarian, A., 1999, ApJ 512 740

Fernández-Cerezo, S., *et al.* , 2006, MNRAS accepted for publication, astro-ph/0601203

Finkbeiner, D.P., Schlegel, D.J., Frank, C., and Heiles, C., 2002, ApJ 566 898

Finkbeiner, D.P., 2004a, ApJ 614 186

Finkbeiner, D.P., Langston, G.I., and Minter, A.H., 2004b, ApJ 617 350

Gallegos, J.E., Macías-Pérez, J.F., Gutiérrez, C.M., Rebolo, R., Watson, R.A., Hoyland, R.J., and Fernández-Cerezo, S., 2001, MNRAS 327 1178

Hinshaw, G., *et al.* , 2006, astro-ph/0603451

Iglesias-Groth, S. 2005, ApJL, 632, L25

Iglesias-Groth, S. 2006, MNRAS, accepted for publication

Keating, B., Timbie, P., Polnarev, A., and Steinberger, J., 1998, ApJ 495 580

Kogut, A., Banday, A.J., Bennett, C.L., Gorski, K.M., Hinshaw, G., Smoot, G.F., and Wright, E.I., 1996, ApJ 464 L5

Lagache, G., 2003, A&A 405 813

Lazarian, A., and Draine, B.T., 2000, ApJ 536 L15

Leitch, E.M., Readhead, A.C.S., Pearson, T.J., and Myers, S.T., 1997, ApJ 486 L23

McCullough, P.R. and Chen, R.R., 2002, ApJ 566 L45

Mukherjee, P., Jones, A.W., Kneissl, R., and Lasenby, A.N., 2001, MNRAS 320 224

Mukherjee, P., Coble, K., Dragovan, M., Ganga, K., Kovac, J., Ratra, B., and Souradeep, T., 2003, ApJ 592 692

Renbarger, T., Dotson, J.L., and Novak, G., 1998, APPLIED OPTICS 37 28 6643

Watson, R.A., Rebolo, R., Rubiño-Martín, J.A., Hildebrandt, S., Gutiérrez, C.M., Fernández-Cerezo, S., Hoyland, R.J., and Battistelli, E.S., 2005, ApJ 624 L89-L92

Wolleben, M., Landecker, T.L., Reich, W., and Wielebinski, R., 2006, A&A 448 441-424

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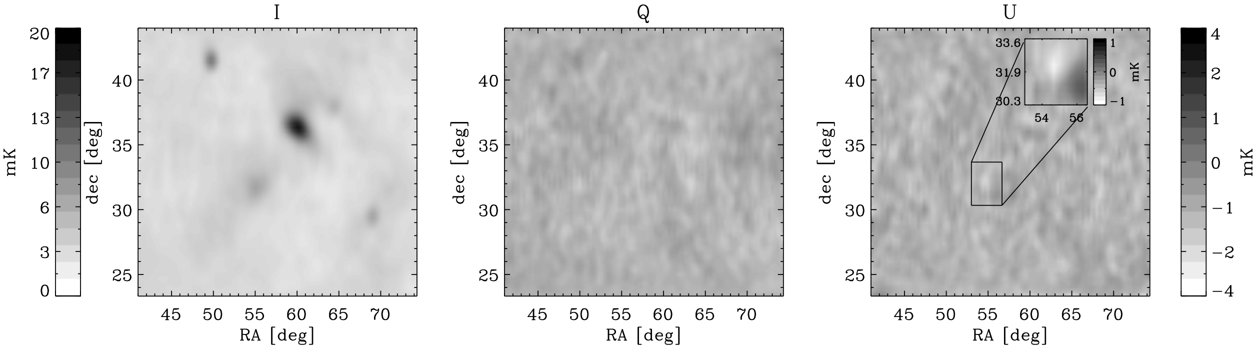

Fig. 1.— I, Q and U COSMOSOMAS 11GHz maps of the region around the Perseus molecular complex. In the I map, the brightest source is the NGC 1499 H II region. The fainter source at RA=55°.4 and dec.=31°.8 (J2000) is the observed (anomalously) emitting region. 3C84 is also visible in the intensity map with coordinates RA=49°.9 and dec.=41°.5 (J2000). The (grey-scale) color bar on the left refers to the I map, while the one on the right refers to both Q and U maps. The maps have been smoothed with a 3 pixel box-car. The inset in the U map refers to the faint detection performed in the Perseus molecular complex.