Analysis of Spots in the COBE DMR First Year Anisotropy Maps

Sergio Torres

ICRA - International Center for Relativistic Astrophysics, Università di Roma, Piazzale Aldo Moro, 5 - 00185, Rome, Italy

ABSTRACT

After the detection of structure in the microwave sky, the characterization of the observed features may be a useful guide to current and future experiments. The first year COBE DMR sky maps were analyzed in order to identify the most significant hot and cold spots. The statistical significance of potential spots of cosmic origin was evaluated with Monte Carlo simulations. The area, eccentricity, and location of the most significant spots are given.

1. INTRODUCTION

Anisotropies in the cosmic microwave background (CMB) at large angle scales have been detected by the Differential Microwave Radiometers (DMR) on board the COBE satellite [1, 2] and by the FIRS experiment [3]. Identifying and characterizing hot spots becomes now more relevant, and experiments (such as TENERIFE) can design survey strategies so as to look for a particular hot spot. Knowing the geometry of hot spots may also be of great potential for testing the ‘mixing of geodesics’ effect [13]. However, due to the low signal-to-noise ratio on the DMR maps, what appears as a hot spot is not necessarily a legitimate hot spot (i.e. one of cosmological origin or one that can be attributed to a local source).

In an ideal experiment, with noiseless instruments, a radiometer looking at the CMB fluctuations should see hot regions which behave as unresolved sources. It has been suggested that even noise limited experiments may observe the hottest spots [4]. The expected number density of these hot spots and their geometric characteristics have been derived for 2D homogeneous Gaussian random fields [5, 6, 7, 8, 9, 10, 11, 12].

The excursion set of a random temperature field is the domain of all points in which the field takes on values \( T \geq T_\nu = \nu \sigma \), where \( \sigma \) and \( \nu \) are the field standard deviation and threshold, respectively. For high threshold levels (\( \nu > 1 \)), the excursion set is characterized by non-connected regions (hot spots) whose shape approaches a circle as the threshold increases. Similarly, a cold spot can be defined as the region where the temperature takes on values \( T \leq -T_\nu \). A negative \( \sigma \) is used to indicate these cold spots.

1. On leave from Universidad de los Andes and Centro Internacional de Física, Bogotá, Colombia. E-mail: 40174::torres, torres@celest.lbl.gov
2. ANALYSIS

Data from the 53 and 90 GHz DMR radiometers, the two with the best sensitivity, were used. The maps were scaled to thermodynamic temperature, the dipole was fitted and removed, the $2\mu K$ kinematic quadrupole was removed, and finally the maps were Gaussian smoothed ($\theta_s = 2.9^\circ$). A comparison of the fitted dipole and quadrupole with the results of Smoot et al. [4] provided a test for the integrity of the data and the analysis software. The contribution of the galaxy is taken into account by excluding the equatorial band $|b| \leq 20^\circ$, where $b$ is galactic latitude. After galactic cut 65% of the sky remains available for analysis. Sum (A+B) and difference (A–B) maps are the sum and difference of the two DMR maps at each frequency. Galactic and cosmic signals cancel out in the (A–B) maps. The mean temperature is subtracted after galactic cut. The resulting temperature standard deviation of the 53 and 90 sum maps are 51 and 69 $\mu K$ respectively. Only spots that appear at a threshold $|\nu| \geq 2.3$ were studied.

Hot and cold spots on DMR maps were analyzed by an algorithm that relies on the formation of tree data structures on binary maps [14, 15]. The statistical significance of a spot is estimated by means of Monte Carlo simulations that take into account instrument noise, sky coverage, pixelization scheme and the DMR beam characteristics [15]. The location of a hot spot is given by the coordinates of the barycenter of the spot. The ’eccentricity’ parameter, $\epsilon$, is defined as the ratio of the distances from the center of the spot to the closest and furthest points along its contour. This parameter coincides with the eccentricity of elliptical patterns for large thresholds, but has no straightforward interpretation at low thresholds where contours are highly convoluted. Shape information for spots smaller or equal than a pixel is lost, and a value of 1.0 is automatically assigned to its area and eccentricity. Areas are given in pixel units, which for DMR are $4\pi/6144 \approx 2.6^\circ \times 2.6^\circ$ per pixel.

Simulated sky maps of the microwave sky were generated using a spherical harmonic expansion for the sky temperature, $\Delta T/T = \Sigma_\ell \Sigma_m a_{\ell,m} W_\ell Y_{\ell,m}$, with Gaussian random coefficients $a_{\ell,m}$ of zero mean and model dependent variance. The weights $W_\ell$ for DMR given by Wright et al. [16] were used. Noise, determined by instrument sensitivity and the number of observations per pixel, is included in the simulations.

With a power spectrum of primordial density fluctuations $P(k) \propto k^n$, the variances of $a_{\ell,m}$ can be determined [8]. Figure 1 shows the number of spots for the DMR 53 (A+B) data and Monte Carlo results for noise and for a $n = 1$ model normalized to a quadrupole of $16 \mu K$. From Fig. 1 it is clear that the number of spots descriptor of the DMR data is in good agreement with the presence of cosmic signal. Some of the spots on DMR maps must therefore be cosmic. Even though it is not possible to say whether a spot is real or not, one can assign a statistical significance to each spot using its height information in combination with the number of standard deviations that its area deviates from the expected area of spots on noise maps. The spot mean area and variance in noise maps are found with Monte Carlo simulations.

Due to noise alone, hot spots can appear on DMR maps. However, by the superposition of two or three maps, the probabilities of finding the same ‘noise spot’ in all maps is substantially reduced. Let $a_{\nu,i}$ denote the total area of the excursion set of
map $i$ at threshold level $\nu$. The intersection area of the excursion set of two maps, $A_{\nu,ij} = a_{\nu,i} \cap a_{\nu,j}$, is a quantity that can be used to indicate the presence of cosmic spots on a map.

Monte Carlo simulations of skies as seen by DMR, if no cosmic signal was present, were used to estimate $A_{\nu,ij}$ for noise alone. Figure 2 shows the intersection area with threshold for the superposition of the 53 and 90 sum and difference maps and the Monte Carlo data for simulations of noise. For large thresholds ($> 1.5\sigma$) the statistics is low, but for small $\nu$ there is a significant and systematic deviation of the $(A+B)$ data from what would be expected for noise. There are small differences among the Monte Carlo data and the $(A-B)$ points in Fig. 2. These can be attributed to the sensitivity of $A_{\nu,ij}$ to the level of smoothing of the maps, which depends on beam dilution (not taken into account in the Monte Carlo simulations) and the inaccurate estimation of beam smearing (due to spacecraft drift during the $1/2$ second observation time). If the $(A-B)$ points of Fig. 2 are used as an estimate of the expected $A_{\nu,ij}$ for noise, and in addition the Monte Carlo error bars are used, one finds that the excursion set intersection area of the 53 and 90 $(A+B)$ maps is 4.7, 3.1, and 1.7 standard deviations higher than expected for noise at threshold levels 1.5, 1.75 and 2.0 respectively.

The area, location and eccentricity of the most significant hot and cold spots are in Tables I and II. The spots are ordered according to a ‘significance parameter’ defined as $S = \sum_\nu |\nu| s_\nu$, where $s_\nu$ is the number of standard deviations the spot area deviates from the mean spot area of noise maps at threshold $\nu$. If $s_\nu < 1.0$ it is set to 1.0 when computing $S$. No absolute meaning should be given to $S$, it is only an assessment of the relative probability that a spot may be of cosmic origin.

At the $2.3\sigma$ level there are no spots seen simultaneously on the three $(A+B)$ DMR maps. Only one hot spot (No. 4) and one cold spot (No. 4) consistently appear on both 53 and 90 $(A+B)$ maps. Hot spot No. 1 in 53 $(A+B)$ map is clearly associated with the galactic bulge at $l = 0^\circ$ seen in this map. The only features on the 31 GHz sum map that may be significant are a hot spot coincident with hot spot No. 6. and one cold spot coincident with cold spot No. 10. With the exception of hot spot No. 2 and the two spots that appear in two maps (Hot No. 4 and Cold No. 4) at high $\nu$, all other features are marginaly significant. Eliminating hot spot No. 1 (galaxy) and all spots below $\nu = 2.6$ there remains 9 hot spots and 11 cold spots, consistent with the expected results from simulations of cosmic signal ($n = 1, 16 \mu K$ Quadrupole). With the four year DMR data the signal-to-noise ratio will be greater than one, thus cosmography will become even more relevant, and it will be possible to confirm or discard the identified spots. Bennet et al. [17] have shown that the features on the first year maps are not correlated with known astronomical sources, thus if the spots are real, their most likely origin is cosmic.

Acknowledgments: I thank Prof. R. Ruffini for his hospitality at ICRA. This work has been supported by Colciencias of Colombia, project No. 1204-05-007-90 and the European Community under contract No. CI1-CT92-0013. The COBE datasets were developed by the NASA Goddard Space Flight Center under the guidance of the COBE Science Working Group and were provided by the NSSDC.
References

[1] Bennett, C., et al., COBE-Preprint 94-01 (1994) and astro-ph/9401012
[2] Smoot, G.F. et al, ApJ, 396, L1 (1992)
[3] Ganga, K., Cheng, E., Meyer, S. & Page, L., ApJ, 410, L57 (1993)
[4] Sazhin, M. V., MNRAS, 216, 25p (1985)
[5] Adler, R. J., The geometry of Random Fields (New York: Wiley) (1981)
[6] Bond, J. R., & Efstathiou, G., MNRAS, 226, 655 (1987)
[7] Vittorio, N. & Juszkiewicz, R., ApJ, 314, L29 (1987)
[8] Coles, P. & Barrow, D., MNRAS, 228, 407 (1987)
[9] Coles, P., MNRAS, 231, 125 (1988)
[10] Coles, P., MNRAS, 234, 509 (1988)
[11] Gott, J. R., et al., ApJ, 352, 1 (1990)
[12] Martínez-González, E., & Sanz, J. L., MNRAS, 237, 939 (1989)
[13] Gurzadyan, V. G., Kocharyan, A. A., Europhys. Lett., 22, 231 (1993)
[14] Torres, S., ApJ Letters (in press) (1994) and astro-ph/9311067
[15] Torres, S., in The CMB Workshop, Edts. N. Mandolesi, et al., Capri, (in press) (1993)
[16] Wright, E. L., et al., ApJ, 420, 1 (1994)
[17] Bennett, C. L., et al., ApJ, 414, L77 (1993)
Figure Captions

FIGURE 1. Number of spots on the $4\pi$ sphere for Monte Carlo noise (squares, upper curve), a $n = 1$ model (squares), and the DMR (A+B) maps (crosses) scaled to the $4\pi$ sphere.

FIGURE 2. a) Excursion set intersection area for Monte Carlo noise (squares), 53 and 90 DMR sum maps (dots) and difference maps (crosses), b) same as a) with different scale. Area is in pixel units.
| N | S   | M   | $\nu$ | A     | $s_{\nu}$ | $\epsilon$ | $l$   | $b$ |
|---|-----|-----|-------|-------|-----------|-----------|------|-----|
| 1 | 141.5 | 53  | 2.33  | 26    | 29.1      | 0.33      | 4.4  | 25.5|
|   | 53   | 2.67| 16    | 15.3  | 0.36      | 4.8       | 24.8 |
|   | 53   | 3.00| 12    | 8.6   | 0.26      | 4.0       | 24.4 |
|   | 53   | 3.33| 2     | 0.1   | 0.50      | 2.6       | 22.5 |
|   | 53   | 3.67| 1     | -0.6  | 1.00      | 1.3       | 22.6 |
| 2 | 45.4 | 53  | 2.33  | 12    | 11.2      | 0.60      | 5.19 | 65.7|
|   | 53   | 2.67| 8     | 6.1   | 0.70      | 54.2      | 65.6 |
|   | 53   | 3.00| 2     | -0.3  | 0.50      | 47.3      | 65.6 |
| 3 | 15.2 | 53  | 2.33  | 7     | 4.8       | 0.37      | 184.4| -52.3|
|   | 53   | 2.67| 4     | 1.5   | 0.56      | 46.4      | 38.9 |
| 4 | 14.5 | 53  | 2.33  | 6     | 3.5       | 0.74      | 50.3 | 38.6|
|   | 53   | 2.67| 4     | 1.5   | 0.54      | 51.1      | 38.6 |
|   | 90   | 2.33| 4     | 0.9   | 0.72      | 46.4      | 38.9 |
| 5 | 8.0  | 53  | 2.33  | 1     | -2.9      | 1.00      | 160.1| -21.3|
|   | 53   | 2.67| 1     | -2.0  | 1.00      | 160.1     | -21.3|
|   | 53   | 3.00| 1     | -1.2  | 1.00      | 160.1     | -21.3|
| 6 | 8.0  | 53  | 2.33  | 2     | -1.6      | 0.50      | 206.8| -20.5|
|   | 53   | 2.67| 2     | -0.8  | 0.50      | 206.8     | -20.5|
|   | 53   | 3.00| 2     | -0.3  | 0.50      | 206.8     | -20.5|
| 7 | 5.0  | 53  | 2.33  | 4     | 1.0       | 1.00      | 194.6| 44.1 |
|   | 53   | 2.67| 1     | -2.0  | 1.00      | 195.6     | 42.3 |
| 8 | 5.0  | 53  | 2.33  | 2     | -1.6      | 0.50      | 212.6| -22.1|
|   | 53   | 2.67| 1     | -2.0  | 1.00      | 214.1     | -21.9|
| 9 | 5.0  | 53  | 2.33  | 3     | -0.3      | 0.37      | 258.2| -22.1|
|   | 53   | 2.67| 1     | -2.0  | 1.00      | 258.2     | -22.1|
| 10 | 5.0 | 90  | 2.33  | 2     | -1.6      | 0.50      | 7.9  | -25.1|
|   | 90   | 2.67| 2     | -0.8  | 0.50      | 7.9       | -25.1|
| 11 | 2.3 | 53  | 2.33  | 1     | -2.9      | 1.00      | 340.3| 51.3 |
| 12 | 2.3 | 53  | 2.33  | 1     | -2.9      | 1.00      | 208.6| 30.7 |
| 13 | 2.3 | 53  | 2.33  | 1     | -2.9      | 1.00      | 310.5| 35.7 |
| 14 | 2.3 | 53  | 2.33  | 1     | -2.9      | 1.00      | 175.0| -49.6|
| 15 | 2.3 | 53  | 2.33  | 1     | -2.9      | 1.00      | 14.8 | -48.8|
| 16 | 2.3 | 90  | 2.33  | 2     | -1.6      | 0.50      | 248.6| 51.0 |
| 17 | 2.3 | 90  | 2.33  | 4     | 0.9       | 0.95      | 164.1| 23.1 |
| 18 | 2.3 | 90  | 2.33  | 1     | -2.9      | 1.00      | 194.9| 33.1 |
| 19 | 2.3 | 90  | 2.33  | 1     | -2.9      | 1.00      | 175.5| -46.5|
| 20 | 2.3 | 90  | 2.33  | 2     | -1.6      | 0.50      | 160.7| -60.4|

**NOTE** - Hot spot characteristics as appear at different threshold levels ($\geq 2.3$). The ‘significance’ $S$ and $s_{\nu}$ parameter are defined in the text. The DMR map is indicated by M. The area, A, is in DMR pixel units. The spot eccentricity is $\epsilon$, and $l$, $b$ are the galactic longitude and latitude in degrees. The estimated error in pixel location is $\pm 1.5^\circ$. 
### TABLE II. Most significant cold spots

| N | S  | M  | $\nu$ | $A$  | $s_{\nu}$ | $\epsilon$ | l  | b  |
|---|----|----|------|------|-----------|-----------|----|----|
| 1 | 45.2 | 53 | -3.33 | 1  | -0.8 | 1.00 | 242.6 | 46.4 |
|   | 53 | -3.00 | 5 | 2.1 | 0.64 | 242.9 | 45.2 |
|   | 53 | -2.67 | 8 | 5.9 | 0.50 | 240.7 | 44.3 |
| 2 | 32.6 | 90 | -3.00 | 4 | 1.3 | 0.84 | 236.5 | 36.8 |
|   | 90 | -2.67 | 5 | 2.1 | 0.60 | 237.3 | 37.3 |
|   | 90 | -2.33 | 11 | 9.9 | 0.64 | 238.0 | 36.0 |
| 3 | 23.1 | 90 | -3.00 | 5 | 2.1 | 0.58 | 126.1 | -51.3 |
|   | 90 | -2.67 | 5 | 2.1 | 0.58 | 126.1 | -51.3 |
|   | 90 | -2.33 | 7 | 4.8 | 0.46 | 126.8 | -51.1 |
| 4 | 16.7 | 53 | -2.33 | 1 | -2.8 | 1.00 | 256.3 | 64.0 |
|   | 90 | -2.67 | 4 | 1.2 | 0.97 | 247.6 | 70.1 |
|   | 90 | -2.33 | 7 | 4.8 | 0.44 | 250.3 | 68.2 |
| 5 | 14.7 | 53 | -2.67 | 4 | 1.4 | 0.51 | 336.0 | -20.9 |
|   | 53 | -2.33 | 7 | 4.7 | 0.44 | 336.5 | -22.1 |
| 6 | 13.6 | 53 | -2.67 | 1 | -1.9 | 1.00 | 280.0 | 55.5 |
|   | 53 | -2.33 | 7 | 4.7 | 0.42 | 281.2 | 55.8 |
| 7 | 13.6 | 53 | -2.67 | 1 | -1.9 | 1.00 | 275.1 | 75.5 |
|   | 53 | -2.33 | 7 | 4.7 | 0.52 | 277.3 | 74.3 |
| 8 | 5.1 | 90 | -2.33 | 5 | 2.2 | 0.42 | 100.9 | -67.6 |
| 9 | 5.0 | 53 | -2.67 | 2 | -0.8 | 0.50 | 302.3 | 41.8 |
|   | 53 | -2.33 | 3 | -0.3 | 0.83 | 302.7 | 42.7 |
| 10 | 5.0 | 90 | -2.33 | 4 | 1.0 | 0.50 | 242.4 | 22.9 |
|   | 90 | -2.67 | 2 | -0.8 | 0.50 | 243.2 | 23.0 |
| 11 | 5.0 | 90 | -2.33 | 4 | 1.0 | 0.50 | 254.6 | 39.2 |
|   | 90 | -2.33 | 2 | -1.6 | 0.50 | 253.3 | 39.0 |
| 12 | 2.3 | 53 | -2.33 | 2 | -1.6 | 0.50 | 288.4 | 66.4 |
| 13 | 2.3 | 53 | -2.33 | 1 | -2.8 | 1.00 | 70.0 | -26.7 |
| 14 | 2.3 | 53 | -2.33 | 1 | -2.8 | 1.00 | 72.8 | -24.3 |
| 15 | 2.3 | 53 | -2.33 | 1 | -2.8 | 1.00 | 146.3 | -41.3 |
| 16 | 2.3 | 53 | -2.33 | 1 | -2.8 | 1.00 | 351.0 | -52.5 |
| 17 | 2.3 | 53 | -2.33 | 2 | -1.6 | 0.50 | 87.0 | -46.5 |
| 18 | 2.3 | 90 | -2.33 | 1 | -2.8 | 1.00 | 301.4 | 54.8 |
| 19 | 2.3 | 90 | -2.33 | 2 | -1.6 | 0.50 | 270.0 | 61.8 |
| 20 | 2.3 | 90 | -2.33 | 1 | -2.8 | 1.00 | 345.4 | -27.4 |
| 21 | 2.3 | 90 | -2.33 | 1 | -2.8 | 1.00 | 358.7 | 28.2 |
| 22 | 2.3 | 90 | -2.33 | 1 | -2.8 | 1.00 | 88.6 | -40.2 |
| 23 | 2.3 | 90 | -2.33 | 1 | -2.8 | 1.00 | 197.3 | -27.1 |
| 24 | 2.3 | 90 | -2.33 | 1 | -2.8 | 1.00 | 84.0 | -55.8 |

**NOTE:** See note of Table I.