Measurement of the Cosmic-Background Large-Scale Anisotropy in the Millimetric Region

R. Fabbri
Istituto di Fisica Superiore, Università di Firenze, I-50127 Firenze, Italy

and

I. Guidi
Unità di Ricerca, Gruppo Nazionale di Fisica Cosmica–Consiglio Nazionale delle Ricerche, I-50127 Firenze, Italy

and

F. Melchiorri and V. Natale
Gruppo Infrarosso, Istituto di Ricerca sulle Onde Elettromagnetiche del Consiglio Nazionale delle Ricerche, I-50127 Firenze, Italy
(Received 8 October 1979)

Dipole anisotropy in the cosmic background radiation in the 500–3000-μm wavelength region has been measured in a balloon-borne experiment. A dipole amplitude was found with $T_D = (2.9^{+1.3}_{-0.6})$ mK, at R. A. = 11h 24m ± 0h 40m, $\delta = 3° \pm 10°$, the errors arising essentially from detector and magnetometer calibrations. This Letter also reports the existence of a second harmonic $T_Q = (0.9^{+0.4}_{-0.2})$ mK.

PACS numbers: 98.70.Vc

A dipole anisotropy in the cosmic background radiation has been detected in the radio region by Wilkinson and co-workers[1] and by Smoot, Gorenstein, and Muller.[2] Attempts to measure such anisotropy in the far infrared have been made since 1974 by Muehlner and Weiss.[3] Their data were strongly contaminated by galactic emission as a consequence of their large beam separation.[4] We report here on an infrared measurement of the large-scale anisotropy. Using a beam separation of 6° we were able to obtain a large fraction of data unaffected by the galactic background. The experiment was performed at balloon altitude. The instrument, which was flown on 20 July 1978 from Trapani in Sicily, is schematically shown in Fig. 1. It consists of the following main parts[5]:

(a) A Ge-Ga bolometer with a condensing cone having a throughput of 0.15 cm^2 sr serves as the sensing element. The field of view of 5.2° is defined by a TPX lens and a set of baffles. The system is sensitive in the region 500–3000 μm.

(b) A large wobbling mirror explores the sky with a sinusoidal modulation of 6° at 30 Hz, at an elevation of 30° above the horizon.

(c) The detector and the wobbling mirror are fixed on an optical bench which may be tilted 0° to 30° above the horizon by telecommand. As the bench is tilted, the direction of modulation in the sky forms different angles with the horizon, allowing us to minimize the atmospheric offset as well as to introduce a known amount of atmospheric signal.

Our instrument presents an important advantage with respect to conventional large-angle isotropometers: Since it uses only one antenna coupled to the wobbling mirror, the delicate problem of balancing the emissions of two horns is avoided. Spurious anisotropies might be generated by ground radiation diffracted into the instrument, gondola oscillations, systematic latitude effect, as well as drifts of any residual instrumental offset. All such effects were negligible in the present experiment.[6]

The instrument was calibrated in the laboratory by the method described by Guidi *et al.*[7] The responsivity integrated over our bandwidth is R

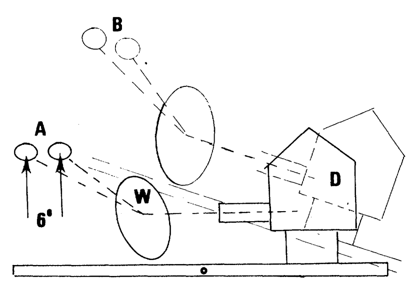

FIG. 1. Sketch of the experimental setup: W, wobbling mirror; D, Dewar containing the infrared detector; A and B, modulation directions when the optical bench is parallel to the horizon and tilted by 30°, respectively.

$=(8\mp 2)\times 10^5$ V/W, and the measured optical noise equivalent power is $P_{\text{N-eq}}=(3.5\pm 0.6)\times 10^{-14}$ W $\text{Hz}^{-1/2}$. During the flight the instrument was calibrated in two different ways: First we introduced an atmospheric offset by tilting the wobbling mirror, as outlined in point (c). Using the atmospheric data of Woody,[8] we found $R=(8.6^{+3.1}_{-1.3})\times 10^5$ V/W and $P_{\text{N-eq}}=(12^{+6}_{-4})\times 10^{-15}$ W $\text{Hz}^{-1/2}$. Then we checked the responsivity observing a few celestial sources, i.e., the galactic plane around $l=120°$ and $l=230°$, the Orion Nebula, W3, and the dark nebula L1262. The computed values of R agree with the previous calibrations, but the absence of standard celestial sources motivates the large calibration errors.

During the flight the gondola rotated freely, the instantaneous position being measured by a magnetometer. Each revolution lasted a few minutes. Each sky element was observed for a total time ranging from 10 to 40 secs. The maximum sensitivity in measuring the thermodynamic temperature difference between two adjacent $5°\times 5°$ spots is $\Delta T/T=0.24\Delta I/I+(3.5^{+1.7}_{-2.2})\times 10^{-5}$ at 1 standard deviation.[9] The observed region of the sky is shown in Fig. 2. When the beam cut the galactic plane or went close to it, we recorded strong signals, readily interpreted as dust emission.[3,4,10]

Unambiguous signals detected at high galactic latitudes show the presence of a large-scale anisotropy. In order to analyze it we divided the data into five strings, each covering an observing time of about 20 min. The galactic contribution to the large-scale anisotropy was studied for each string as follows:

(i) Only signals from regions of the sky more than 20° distant from the galactic plane were selected in order to fit a dipole-type anisotropy to the data.

(ii) Signals from the regions close to the galactic plane were also utilized. We subtracted the galactic emission assuming it to be concentrated in a layer of thickness 1°, negligible in comparison with our beamwidth. This rough approximation did not allow us to correct the data points corresponding to the Orion complex, W3, and the dark nebula L1262. Amplitude and azimuth of the dipole component on the horizon plane were found to be the same for both procedures, proving that the galactic disturbance is negligible for $|b|>20°$, with the exception of a few infrared sources.

In order to derive the right ascension, the declination, and the amplitude of the dipole anisotropy, we combined all the strings together, after exclusion of the data corresponding to $|b|<20°$.

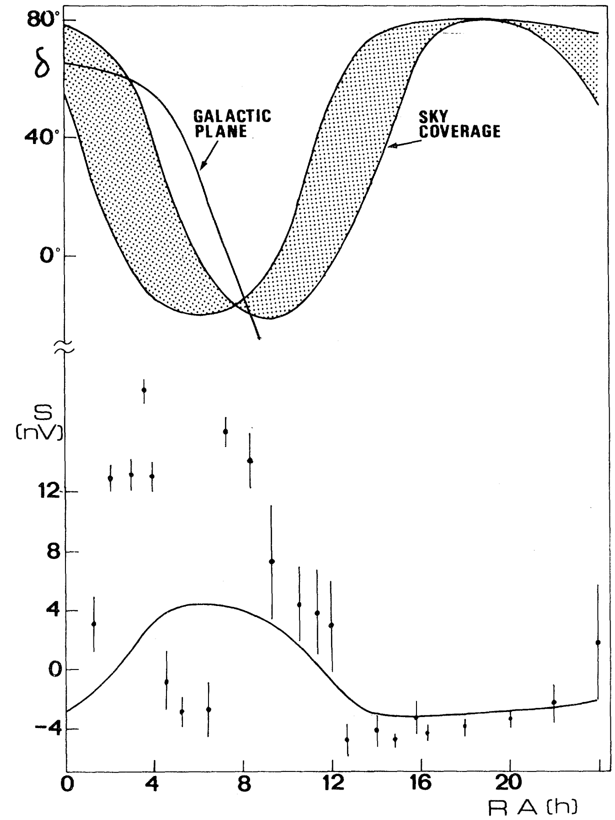

FIG. 2. Dotted region: the sky coverage of the present experiment. In the lower part we represent one string of the recorded data (20 min of observations, i.e., 20% of useful data). For the sake of clarity, data points are averaged over 15° in azimuth. Both the galactic contribution and the large scale anisotropy are shown. The full line gives the signal from a dipole with parameters R.A. = 11 h 24 m, $\delta=3°$, $S_D=50$ nV, namely $S=S_D\sin 6°\cos\theta$, where the 6° beam separation is taken into account.

The same data points were also analyzed by the method described by Smoot, Gorenstein, and Muller.[2] These procedures give consistent results within the statistical errors. A first-harmonic fitting produces in both cases a dipole amplitude $S_D=50\mp 2$ nV, R.A. = 11 h 24 m ± 0 h 10 m and $\delta=3°\pm 2°$, where the errors are statistical only (at 1 σ, following the method described by Lampton, Margon, and Bowyer).[11] By taking into account the uncertainties in bolometer and magnetometer calibrations, we get $T_D=2.94^{+1.30}_{-0.60}$ mk, R.A. = 11 h 24 m ± 0 h 40 m, $\delta=3°\pm 10°$. The dipole best-fit calculation shows the presence of a constant offset of about one tenth the dipole amplitude.[12]

The results are presented in Fig. 3 in terms of

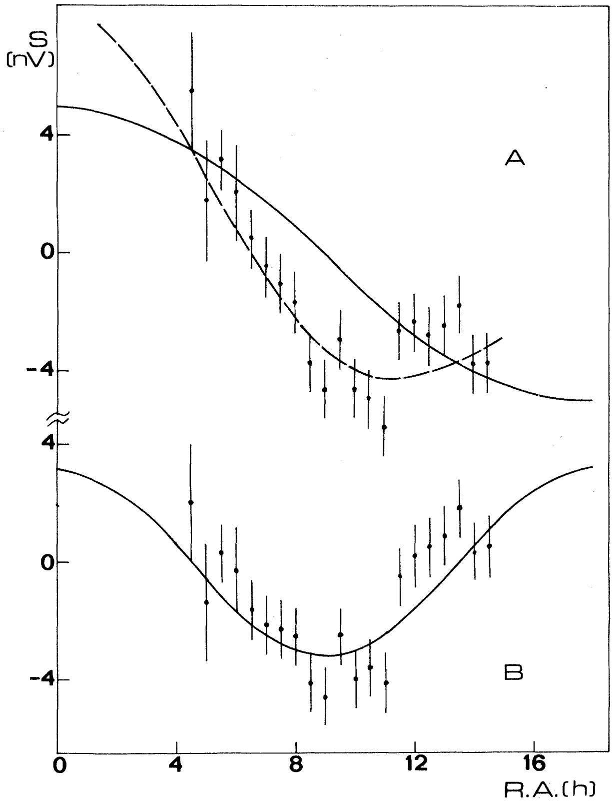

FIG. 3. (a) The full line represents a pure cosine fitting of the five strings with the signals averaged over 5°. The dashed line is the final fitting $S/\sin 6° = S_D \cos\theta + 2S_Q \cos(2\theta + \varphi)$, with $S_D = 50$ nV, $S_Q = 16$ nV, $\varphi = 0°$. (b) The signal after subtraction of the fitting dipole, and best fit corresponding to $S/\sin 6° = 2S_Q \cos 2\theta$.

the angle θ between the dipole direction and the vector $\vec{n}_1 - \vec{n}_2$, $\vec{n}_1$ and $\vec{n}_2$ being the two beam directions. Our results are consistent with those of Refs. 1 and 2, although we show better evidence of a distortion due to higher harmonics. The $\cos\theta$ fitting gives $\chi^2 = 111$ for 21 data points.[13] We tried then to fit the data with two Fourier terms, namely $S/\sin 6° = S_D \cos\theta + 2S_Q \cos(2\theta + \varphi)$. We find $\chi^2 = 24.6$ for the following best values: $S_D = 50 \pm 2$ nV, $S_Q = 16 \mp 1$ nV, $\varphi = 0° \mp 5°$. The distortion at $\theta = 100°-140°$ is also present in the data of Ref. 2, but it was attributed to galactic emission. In our case it appears at high galactic latitudes, which suggests the existence of a cosmological effect. Because of the limited sky coverage we could not perform a significant best fit with all of the second-order harmonics. Our $\cos 2\theta$ term should not be immediately identified with the quadrupole moment, but it is suggestive of a quadrupolelike anisotropy in the cosmic background radiation with amplitude $\sim \frac{1}{3}$ the dipole term.

A very stimulating discussion with Professor P. Boynton is gratefully acknowledged, as well as the help of all the members of the Italian Balloon Base at Trapani, Sicily. This work was supported by Servizio Attività Spaziali, Consiglio Nazionale delle Ricerche.

[1]B. E. Corey and D. T. Wilkinson, Bull. Am. Astron. Soc. 8, 351 (1976); E. S. Cheng, P. R. Saulson, D. T. Wilkinson, and B. E. Corey, Astrophys. J. 232, L139 (1979).

[2]G. F. Smoot, M. V. Gorenstein, and R. A. Muller, Phys. Rev. Lett. 39, 898 (1977).

[3]D. Muehlner and R. Weiss, in *Infrared and Submillimeter Astronomy*, edited by G. G. Fazio (Reidel, Dordrecht, Netherlands, 1976).

[4]M. A. Forman, Astrophys. J. 212, L1 (1977).

[5]R. Fabbri, I. Guidi, F. Melchiorri, and V. Natale, in Proceedings of the Second Marcel Grossman Meeting on Recent Developments of General Relativity, Trieste, Italy, 1979, edited by R. Ruffini (to be published).

[6]The ground problem was solved by use of metallic shields and a carefully designed optical layout. Ground effects in flight were found to be negligible when simulating a terrestrial hot spot by the sunrise. Gondola oscillations are generally smaller than 1′ [see W. F. Hoffmann, in *Infrared and Submillimeter Astronomy*, edited by G. G. Fazio (Reidel, Dordrecht, 1976), p. 164], and their effect averaged over 15 min is also negligible. Long-term drifts of gondola tilt were not detected while monitoring the signal for about 20 min when the balloon was nearly stationary in the sky. The systematic latitude effect arising from an atmospheric temperature gradient of about 0.3° per degree of latitude is unimportant for our 30° elevation.

[7]I. Guidi, B. Melchiorri, F. Melchiorri, and V. Natale, Infrared Phys. 18, 267 (1978).

[8]D. P. Woody, Ph.D. thesis, University of California at Berkeley, LBL Report No. LBL 4188, 1975 (unpublished).

[9]The data collected when the balloon was nearly steady in the sky have been used for a sensitive measurement of the anisotropy at scale of 6° (see Ref. 5) as well as to check possible instrumental drifts.

[10]E. Bussoletti, I. Guidi, B. Melchiorri, F. Melchiorri, and V. Natale, to be published.

[11]M. Lampton, B. Margon, and S. Bowyer, Astrophys. J. 208, 177 (1976).

[12]The offset values obtained from the analysis of the five data strings are the same within the statistical errors. This is further evidence for a constant offset, in agreement with the absence of long-term drifts.

[13]Because of small beam separation, the sensitivity

of our system to the second harmonic is twice the sensitivity to the first one. If our data were affected by the average error bar of Smoot, Gorenstein, and Muller, we would have derived a pure dipole fitting with $\chi^2 = 18$ for 21 data points, in good agreement with the Berkeley and Princeton experiments.

ERRATUM

COLORED MONOPOLES. Y. M. Cho [Phys. Rev. Lett. 44, 1115 (1980)].

Equation (14) on page 1117 should read

$$\hat{m} = \exp[-n'\varphi(\tfrac{1}{2}t_3 + \tfrac{1}{2}\sqrt{3}\,t_8)]\exp(-\theta_7) \times \exp[-(n - \tfrac{1}{2}n')\varphi t_3]\exp(-\theta t_2)\hat{\xi}_3. \qquad (14)$$