3-mm Anisotropy Measurement and the Quadrupole Component in the Cosmic Background Radiation

Philip M. Lubin
Space Sciences Laboratory and Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720, and Joseph Henry Laboratories, Physics Department, Princeton University, Princeton, New Jersey 08544

and

Gerald L. Epstein and George F. Smoot
Space Sciences Laboratory and Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 3 November 1982)

The large-scale anisotropy in the cosmic background radiation has been measured at 3-mm wavelength with a liquid-helium–cooled balloon-borne radiometer sensitive enough to detect the dipole in one gondola rotation (1 min). Statistical errors on the dipole and quadrupole components are below 0.1 mK with less than 0.1 mK galactic contribution. The authors find a dipole consistent with previous measurements but disagree with recent quadrupole reports. The measurement is also useful in the search for spectral distortions.

PACS numbers: 98.70.Vc, 98.80.Bp

The large-scale anisotropy in the cosmic background radiation is one of the best probes available for studying the global properties of the universe. To date the only well established[1-3] deviation from a strictly isotropic distribution is a first-order (dipole) anisotropy with an amplitude of 3 mK believed to result from our motion relative to the background radiation. The prospect of finding a higher-order anisotropy, such as a quadrupole, which would reflect large-scale structure in the universe has stimulated many searches. Recently Fabbri *et al.*[4] and Boughn, Cheng, and Wilkinson[5] have reported a quadrupole anisotropy with 1-mK amplitude which, if confirmed, would be an important discovery and a new cosmological tool. Current theories suggest a natural interpretation for this type of anisotropy as arising from density fluctuations in the universe[6,7]; however, the theoretical basis for a quadrupole at the level reported is questionable as it depends on the matter autocorrelation function at large scales where it is not well understood.[8] In addition both the Princeton and Florence data are taken at wavelengths where the emission from our galaxy is a significant contaminant. One motivation for our experiment at 3 mm is to search for anisotropies at a wavelength where galactic contamination is substantially reduced.

Another motivation for this experiment is to look for the effects of the spectral distortions. By measuring the dipole amplitude at several frequencies the temperature of the radiation or its deviation from a blackbody spectrum can be determined.[9,10] Since the magnitude of the dipole anisotropy induced by our motion through the radiation depends on both the intensity and the spectral shape (derivative),[10] a distorted spectrum would give a different dipole amplitude than a blackbody. The data of Woody and Richards[11] suggest that the cosmic-background radiation spectrum may be distorted at our wavelength. A precise prediction of the dipole amplitude from their data is not possible because of their flux uncertainty and spectral resolution. However, a smooth spectrum through their data yields an estimated 20% to 40% enhancement of the dipole at our wavelength over that expected from a 2.7-K blackbody. In fact, comparison of our data at 3 mm with recent dipole measurements[12] at 12 mm does not give very good agreement with a 2.7-K blackbody. Because of this we quote our results in antenna temperature (as measured) and do not convert to thermodynamic temperature which requires knowing the spectrum. Calibration errors and various possible systematic errors in both experiments limit a more definitive statement. We will publish the results of this analysis separately.

A schematic of the instrument is shown in Fig. 1. It is a Dicke radiometer which uses a rotating mirror to chop the 7° beam between two positions in the sky 90° apart and 45° from vertical with an output proportional to their temperature difference. The receiver is a 90-GHz liquid-helium–cooled low-doped Schottky-diode mixer and GaAs

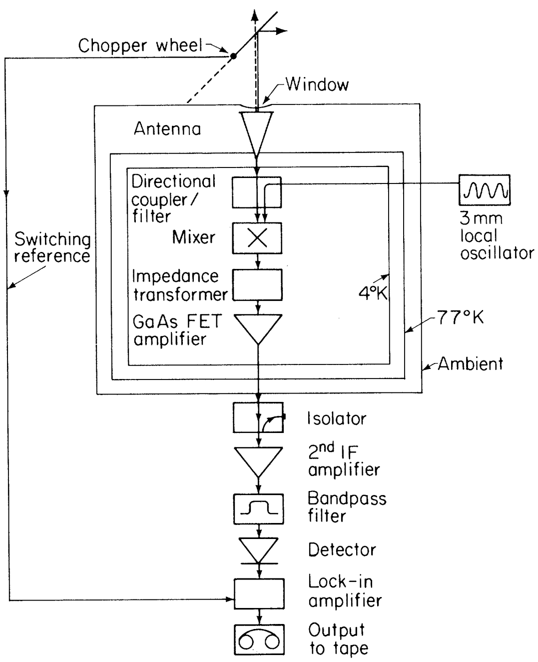

FIG. 1. Schematic of 3-mm radiometer.

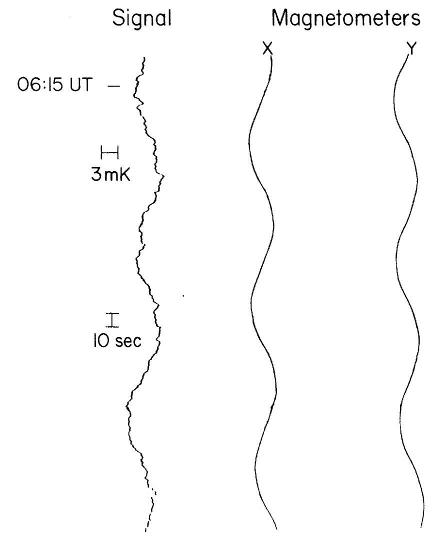

FIG. 2. Section of telemetered data from April 1982 flight taken at 06:15 h universal time (UT). This time corresponds to a zenith right ascension of 14.20 h. The signal was smoothed with a 55-s RC time constant. The dipole anisotropy is clearly evident as a modulation synchronous with the rotation of the gondola.

field-effect transistor (FET) IF based on a design by Kerr.[13] The exceptionally low-noise diode was supplied by R. Mattauch of the University of Virginia. The minimum spot noise of the mixer plus IF is 80 K with a system double-sideband noise figure of 125 K over a 600-MHz bandwidth which gives a receiver rms sensitivity of 13 mK/Hz$^{1/2}$. The measured emissivity of the chopper is $\epsilon = (9 \pm 1) \times 10^{-4}$ derived from the in-flight offset of about 200 mK. This is in good agreement with the theoretical emissivity of $\epsilon = (2\delta/\lambda_0)\cos\theta$ for a metal reflector with the electric field normal to the plane of incidence, where δ is the skin depth, λ_0 is the free space wavelength, and θ is the angle of incidence, 45°. Using the dc conductivity of aluminum gives $\epsilon_{\rm theor.} \simeq 1\times 10^{-3}$ which is consistent with the measured value. The offset is very stable with a typical time derivative of 1 mK/h.

The package rotates at 1 revolution per minute with a resultant sensitivity of about 1 mK in one revolution. Since the dipole anisotropy is about 3 mK in amplitude it can be seen in real time as the package rotates. Figure 2 shows a section of telemetered data which clearly shows the dipole. The radiometer is calibrated on the ground with liquid-nitrogen and ambient-temperature targets and is calibrated in flight every half-hour with a small ambient-temperature blackbody target. Currently we are limited to an absolute calibration error of 5% though we plan to reduce this in the future. The gain of the system is stable to better than 2% during flight.

There are a number of sources of potential systematic errors. Atmospheric emission is one of them. At our altitude of 30 km we estimate a residual vertical atmospheric emission of 10 mK. O_2 emission dominates as there are no known ozone lines in our bandwidth which is centered at 90.0 GHz. The atmospheric contribution to our signal is minimized by symmetrical beam paths. Combined with a typical gondola wobble amplitude of $\frac{1}{4}°$, atmospheric emission contributes less than 0.1 mK to the signal. The magnetic field of the Earth can be another source of spurious signal because some components are magnetically sensitive. The instrument was tested to have a magnetic field dependence of less than 0.1 mK for a field equivalent to the Earth's. Thermal emission from the Earth is reduced to less than 0.1 mK by the use of ground shields and a low side-lobe antenna.

Emission from the galaxy is a possible source of error in all anisotropy measurements and is a particular problem in searching for a quadrupole since the galactic emission is qualitatively a quadrupole in the northern celestial sky. Figure 3 shows the estimated galactic emission as a function of wavelength. Galactic emission in the centimeter wavelength region, where the

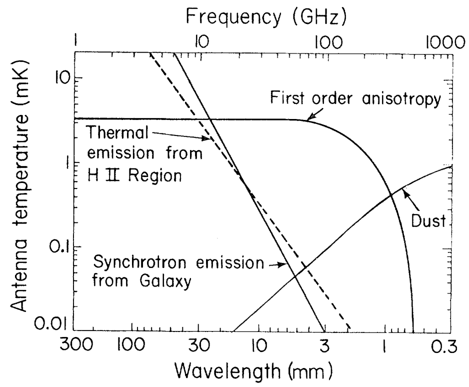

FIG. 3. Estimated galactic emission as a function of wavelength. The first-order anisotropy (dipole) for a 3-K blackbody is shown for comparison.

Princeton data were taken, is dominated by synchrotron and bremsstrahlung emission whereas at submillimeter wavelengths, where the Florence data were taken, interstellar dust emission is thought to dominate. Synchrotron and bremsstrahlung emission decrease (in antenna temperature) with increasing frequency while dust emission increases. Near 3 mm wavelength there is a natural galactic minimum or window which we are trying to exploit.

The instrument has flown three times though the first flight returned only engineering data. The second and third flights were flown on the nights of 4 November 1981 and 26 April 1982, lasting 8 and 10 h, respectively. On the first two flights we flew on the gondolas of D. Wilkinson of Princeton University and R. Weiss of Massachusetts Institute of Technology, respectively. We have surveyed most of the northern hemisphere and down to 14° S declination as shown in Fig. 4.

All three flights were launched from Palestine, Texas, at the National Scientific Balloon Facility (latitude 31.8° N).

Following the convention of Smoot and Lubin[3] the data have been fitted by first- and second-order spherical harmonics. Table I summarizes the various fits and errors. Because the data are taken from one latitude the axially symmetric first-order $[T_z\ (Y_{10})]$ and second-order $[Q_1\ (Y_{20})]$ spherical harmonics cannot be decoupled in a significant manner. The statistical errors are between 60 and 100 μK on the various dipole and quadrupole parameters. The effect of the galaxy on the various dipole and quadrupole parameters appears to be 70 μK or less, and so contamination by the galaxy does not seem to be a problem at our wavelength. Modeling galactic emission with a $(\sin b)^{-1}$ distribution (truncated at galactic latitude $b = 5°$) gives a marginally significant fit with a pole ($b = 90°$) value of 50 ± 20 μK. Excluding data within 5° of the galactic plane gives a result consistent with no galactic emission, indicating that the dust is probably more localized than a $(\sin b)^{-1}$ model.

Our data do not show a significant quadrupole amplitude, contrary to previous reports. The quadrupole reported by the Princeton and Florence groups should give 10σ results (in Q_5) at our sensitivity. New data from the Princeton group[12] using a maser at 1.2 cm and a new galactic model also show no significant quadrupole while further analysis of the Florence data[14,15] still shows a quadrupole with part but not all of it possibly due to a local source. Our data indicate that there is no quadrupole in the cosmic background radiation above the tenths-of-a-millikelvin level.

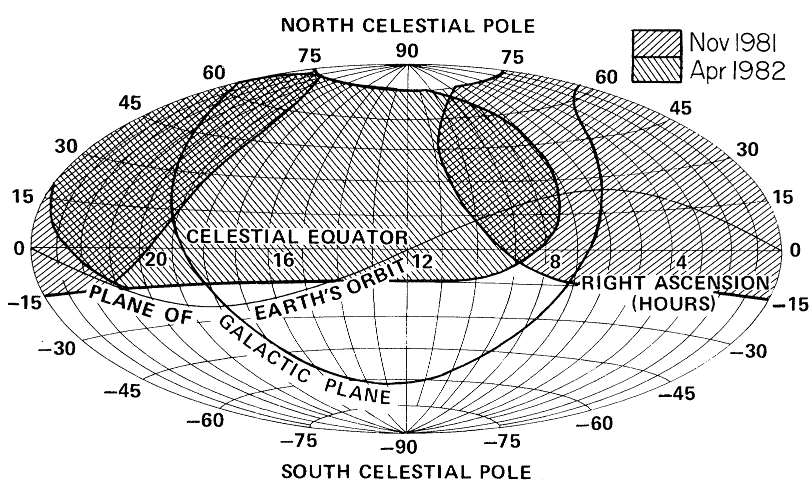

FIG. 4. Sky coverage obtained from flights.

TABLE I. Summary of fits in antenna temperature. To convert to thermodynamic temperature, multiply by 1.23 for T = 2.7 K or 1.19 for T = 3.0 K. Gal. Cut 5° refers to fits with data within 5° of the galactic plane deleted. $T = T_x \cos\delta \cos\alpha + T_y \cos\delta \sin\alpha + T_z \sin\delta + Q_1(\frac{3}{2}\sin^2\delta - \frac{1}{2}) + Q_2 \sin 2\delta \cos\alpha + Q_3 \sin 2\delta \sin\alpha + Q_4 \cos^2\delta \cos 2\alpha + Q_5 \cos^2\delta \sin 2\alpha$.

Function	Fit (mK) All Data	Fit (mK) Gal. Cut 5°	Statistical Error (mK)	Total Error (mK)	Correlation Coefficients[a]						
				Dipole Only							
T_x	-2.89	-2.94	0.07	0.14	1.00	0.11	0.01				
T_y	0.51	0.57	0.07	0.08		1.00	-0.10				
T_z	-0.27	-0.31	0.07	0.08			1.00				
				Dipole and Quadrupole							
T_x	-2.90	-2.94	0.09	0.15	1.00	-0.07	0.03	-0.39	0.23	-0.02	0.05
T_y	0.50	0.55	0.09	0.10		1.00	-0.02	0.27	-0.32	-0.11	0.02
T_z	-0.23	-0.28	0.08	0.09			1.00	0.03	0.10	-0.02	0.20
Q_2	0.19	0.12	0.10	0.11				1.00	-0.11	-0.08	0.05
Q_3	0.22	0.16	0.09	0.10					1.00	-0.01	0.09
Q_4	-0.08	-0.07	0.07	0.08						1.00	0.00
Q_5	0.05	0.07	0.06	0.07							1.00

[a] Correlation coefficients for full data set, no galaxy cut.

This project would not have been possible without the encouragement and assistance of B. Price, D. Wilkinson, and R. Weiss. Special thanks go to N. Boggess, R. Kubara, and the entire staff of the National Scientific Balloon Facility for their support and assistance during our flights. This work was supported by the California Space Institute under Contract No. CS 48-81, by the National Aeronautics and Space Administration under Contract No. NAGW-66, and by the National Science Foundation under Contract No. SPI 8166057. One of us (P.M.L.) is the recipient of a National Science Foundation postdoctoral fellowship and one of us (G.L.E.) is the recipient of a Fannie and John Hertz Foundation fellowship.

[1] B. Corey and D. Wilkinson, Bull. Am. Astron. Soc. 8, 351 (1976).

[2] G. Smoot, M. Gorenstein, and R. Muller, Phys. Rev. Lett. 39, 14, 898 (1977).

[3] G. Smoot and P. Lubin, Astrophys. J. Lett. 234, L83 (1979).

[4] R. Fabbri, I. Guidi, F. Melchiorri, and V. Natale, Phys. Rev. Lett. 44, 1563 (1980), referred to as "Florence."

[5] S. Boughn, E. Cheng, and D. T. Wilkinson, Astrophys. J. Lett. 243, L113 (1981), referred to as "Princeton."

[6] P. J. E. Peebles, Astrophys. J. Lett. 243, L119 (1981).

[7] J. Silk and M. Wilson, Astrophys. J. Lett. 244, L37 (1981).

[8] P. J. E. Peebles, Astrophys. J. Lett. 263, L1 (1982).

[9] P. Lubin, NASA COBE Report No. 5020, 1980 (unpublished).

[10] P. Lubin, in Proceedings of the International School of Physics "Enrico Fermi" Course on Gamow Cosmology, Varenna, 1982 (to be published).

[11] D. Woody and P. Richards, Phys. Rev. Lett. 42, 925 (1979).

[12] D. J. Fixsen, E. S. Cheng, and D. T. Wilkinson, following Letter [Phys. Rev. Lett. 50, 620 (1983)].

[13] H. Cong, A. R. Kerr, and R. J. Mattauch, IEEE Trans. Microwave Theory Tech. 27, 3, 245 (1979).

[14] C. Ceccarelli, G. Dall'Oglio, B. Melchiorri, F. Melchiorri, and L. Pietranera, Astrophys. J. 260, 484 (1982).

[15] R. Fabbri, I. Guidi, and V. Natale, in Proceedings of the Royal Society Meeting on The Big Bang and Element Creation, March 1982 (to be published).