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DIPOLE AND QUADRUPOLE ANISOTROPY OF THE 2.7 K RADIATION[1]

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ABSTRACT

Data from a third balloon flight give a dipole anisotropy in agreement with that measured on earlier flights and with the results of other groups. Combining our data gives a dipole anisotropy of 3.78 ± 0.30 mK in the direction R.A. = 11ʰ6 ± 0ʰ2, $\delta = -12° \pm 5°$. Measurements at four frequencies between 19.0 and 46.0 GHz give a spectral index ($T \sim \nu^{-\alpha}$) $\alpha = 0.04 \pm 0.28$, indicating that the dipole effect arises from (1) an intrinsic anisotropy in the temperature of the 2.7 K radiation, and/or (2) the first-order Doppler shift due to solar motion through the 2.7 K radiation. Quadrupole anisotropy is detected at the 4 σ level. Since known sources of galactic radio emission are too weak to produce the observed intensity, we believe that quadrupole effects are intrinsic to the 2.7 K radiation.

Subject headings: cosmic background radiation — cosmology

I. INTRODUCTION

It is now well established that the microwave background radiation has a dipole anisotropy of amplitude ~0.1% (Smoot, Gorenstein, and Muller 1977; Cheng *et al.* 1979, and references therein). Recent observations in the southern hemisphere (Smoot and Lubin 1979) and at millimeter wavelengths (Fabbri *et al.* 1980) support the earlier results. Some or all of this dipole anisotropy comes from the Doppler effect due to the Sun's motion with respect to the background radiation. The important question of how much of the dipole anisotropy is intrinsic to the 2.7 K radiation can be answered by measuring the solar motion with respect to other cosmological reference frames.

This *Letter* reports the results of a balloon flight in 1980 January which agree with the earlier results and extend the sky and frequency coverage of the observations. The data from three balloon flights now give (1) dipole and quadrupole parameters with statistical errors of ~0.2 mK and small correlations, (2) evidence that the spectrum of the dipole anisotropy is blackbody, and (3) a statistically significant quadrupole effect.

II. OBSERVATIONS AND DATA REDUCTION

The results reported here were obtained from data collected in three nighttime balloon flights from NSBF in Palestine, Texas. The dates and radiometer frequencies are 1975 May, 19.0 GHz; 1978 August, 24.8 and 31.4 GHz; and 1980 January, 24.8, 31.4, and 46.0 GHz. The radiometers have rms noise of 50 to 150 mK Hz$^{-1/2}$ and measure the temperature difference between two horn antennas pointed 90° apart and 45° from the zenith. Instrument rotation at 1 revolution per minute and Earth rotation scan about 35% of the sky on each flight.

Fourier coefficients are calculated from the data for each instrument rotation. These are then averaged over 1 hr intervals to obtain the Fourier coefficients $\langle A_1 \rangle$ and $\langle B_1 \rangle$ for each hour of the flight. After small corrections for known sources of Galactic radio emission, $\langle A_1 \rangle$ and $\langle B_1 \rangle$ are fitted by least squares to dipole and dipole plus quadrupole models for the temperature distribution across the sky. Thus, three dipole parameters ($\boldsymbol{T}$) and four quadrupole parameters[2] (Q_2–Q_5) are measured. The polar components Q_1 and T_z are highly correlated because of our antenna geometry and the approximately constant declination of the balloon zenith. See Cheng *et al.* (1979) for more details.

III. RESULTS

a) Dipole Model Fits at Each Frequency

Table 1 shows the results of fitting a dipole (only) model to $\langle A_1 \rangle$ and $\langle B_1 \rangle$ at each frequency. The radiometers at 24.8 and 31.4 GHz have lower system noise and better sky coverage (two flights) than the others. Therefore, the fitted parameters for 24.8 and 31.4 GHz have smaller statistical error and smaller correlations. Inspection of Table 1 indicates that the dipole results at all four frequencies are roughly in agreement. Figure 1 shows $\langle A_1 \rangle$ and $\langle B_1 \rangle$ versus the right ascension of the balloon zenith for each radiometer. The solid curves are the dipole models fitted individually to each data set. Again, the agreement of the dipole fits is apparent.

A more formal test for agreement among the dipole results was made by calculating the probability that the difference of each pair of vectors in Table 1 is con-

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[2] We adopt the Berkeley notation (Smoot and Lubin 1979) to minimize confusion. The Q's are related to the spherical harmonic coefficients (Cheng *et al.* 1979) as follows: $Q_1 = (5/4\pi)^{1/2}a_{20}$, $Q_2 = -Ca_{21}$, $Q_3 = Cb_{21}$, $Q_4 = Ca_{22}$, and $Q_5 = -Cb_{22}$, where $C = (15/8\pi)^{1/2}$. The sky temperature is then $T(\delta,\alpha) = T_x \cos\delta \cos\alpha + T_y \cos\delta \sin\alpha + T_z \sin\delta + Q_1 (\frac{3}{2}\sin^2\delta - \frac{1}{2}) + Q_2 \sin 2\delta \cos\alpha + Q_3 \sin 2\delta \sin\alpha + Q_4 \cos^2\delta \cos 2\alpha + Q_5 \cos^2\delta \sin 2\alpha$.

sistent with the null vector. The probabilities range from 17% to 90% that statistical errors would cause larger differences for repeated measurements. So, the chances are good that all radiometers measured a dipole distribution with a single blackbody temperature.

b) *Dipole plus Quadrupole Model Fit to All Data*

The dipole (only) fits at 24.8 and 31.4 GHz have poor χ^2 statistics (see Table 1). When four quadrupole parameters are added to the fits, the χ^2 values drop by 15.6 and 16.2 at 24.8 and 31.4 GHz, respectively. The new χ^2 values indicate reasonable probabilities (49% and 12%) that the combined dipole plus quadrupole model fits the data. Furthermore, the new dipole parameters agree with the ones in Table 1 to within statistical errors. Table 2 shows the results of the dipole plus quadrupole fit to the combined data at all four frequencies. We believe that this fit gives our best measurement of the dipole and quadrupole effects. The χ^2 of this fit is 124.4 for 119 degrees of freedom, down from $\chi^2 = 145.3$ (123) for a dipole (only) fit. The quadrupole part of the fit is statistically significant.

c) *Statistical and Systematic Errors*

Statistical errors in $\langle A_1 \rangle$ and $\langle B_1 \rangle$ are calculated from the scatter of single-rotation Fourier coefficients (~60 hr^{-1}). This method was chosen because it gives an accurate, impartial measure of the statistical errors and, thus, a meaningful χ^2 test of the model fits. The magnitude of the statistical error is consistent with that expected from radiometer noise.

The discussion of systematic errors in Cheng *et al.* (1979) applies here as well. In addition, there are effects due to small changes in radiometer offset—the residual imbalance when both horns view identical cold loads. Typically, the offset is 1 K. Random variations and drifts in offset only contribute to the statistical error in $\langle A_1 \rangle$ and $\langle B_1 \rangle$, but offset changes, synchronous with instrument rotation, are serious at the 0.02% level. Differential heating of the horns by anisotropic earthshine or the Sun is one such effect. The difference in the

TABLE 1

BEST FITS TO DIPOLE MODEL

Frequency (GHz)	T_x[a] (mK)	CC_{xy}[b]	T_y[a] (mK)	CC_{yz}[b]	T_z[a] (mK)	CC_{zx}[b]	χ^2/d.o.f.[c]
19.0.......	−2.90±0.85	+0.39	−0.03±1.00	−0.55	−0.93±0.92	−0.44	11.7/15
24.8.......	−3.99±0.26	−0.02	+0.41±0.26	+0.12	−0.16±0.25	−0.08	50.2/39
31.4.......	−3.54±0.24	−0.09	+0.91±0.25	+0.12	−0.52±0.23	+0.02	59.2/37
46.0.......	−3.78±1.00	−0.04	−0.43±0.97	+0.25	−0.84±0.94	−0.29	15.1/23

[a] Blackbody temperature. Errors are statistical only. Increase errors by 5% of amplitude (10% for 19.0 GHz) to include calibration error.

[b] Correlation coefficient of fit.

[c] Chi-square/degrees of freedom.

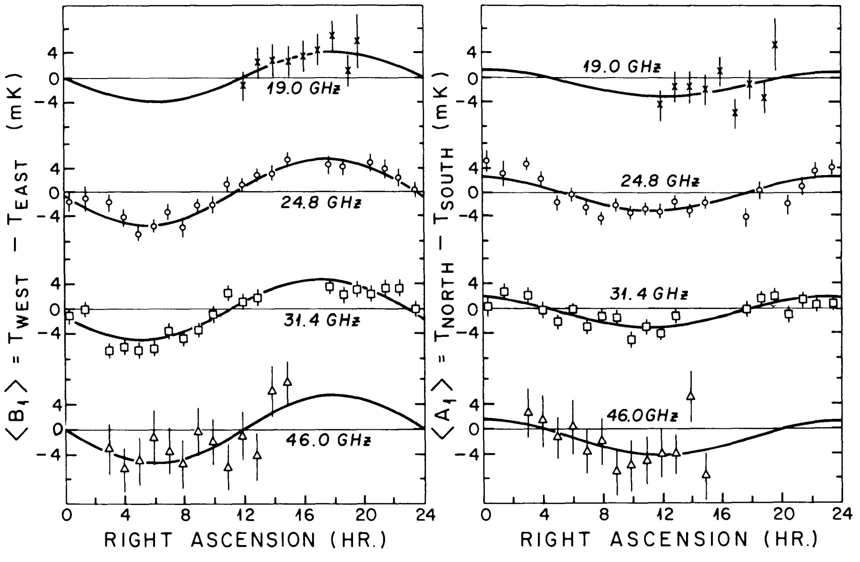

FIG. 1.—Hourly averages of the signal from each radiometer. Errors shown are statistical only. The solid curves are the best-fit dipole models from Table 1.

TABLE 2

Dipole plus Quadrupole Fit Parameters

Fitted Coefficients	Amplitude and Error[a] (mK)	Correlation Coefficients (χ^2/d.o.f. = 124.4/119)					
T_x	-3.68 ± 0.19	+1.00	...	...	...	...	...
T_y	$+0.43\pm0.19$	+0.01	+1.00	...	...	...	...
$T_z+1.12Q_1$	-0.39 ± 0.16	−0.05	+0.14	+1.00	...	...	...
Q_2	$+0.28\pm0.22$	−0.37	−0.08	+0.07	+1.00	...	...
Q_3	$+0.13\pm0.21$	−0.08	−0.37	−0.18	+0.04	+1.00	...
Q_4	-0.31 ± 0.15	+0.03	+0.12	+0.00	−0.12	−0.06	1.00
Q_5	-0.54 ± 0.14	−0.11	+0.06	−0.06	−0.03	+0.10	0.02

[a]Statistical error only. Increase by 3% of amplitude to include calibration error.

physical temperatures of the horn throats is accurately measured, and normally the synchronous component is less than 10 mK. However, near sunrise a temperature difference develops between horns, and subsequent data are not included in the fits. The 31.4 GHz horns showed synchronous heating before the others, probably because one of its baritone bells (used to apodize the horns) was not polished. The 31.4 GHz points for the last hour (R.A. = $13^{\rm h}_{.}9$) were the only data deleted from the 1980 flight.

We estimate that the error in radiometer calibration (mK per telemetry count) is less than ±5% (±10% for 19.0 GHz) which should be added to the statistical error in the results of each radiometer in Table 1. The fit to all data, however, averages these errors, and we estimate ±3% as the largest calibration error in the results in Table 2.

IV. DISCUSSION

a) *Dipole Anisotropy*

We have already mentioned that our data only measure the sum of the polar component T_z and Q_1. Smoot and Lubin (1979) have made southern hemisphere measurements which for the first time separate these parameters, although the correlation coefficient is still large (−0.71). Using their result, $Q_1 = 0.38 \pm 0.26$ mK, we get T_z from the value of $T_z + (3Q_1 \sin \delta)/2^{1/2}$ in Table 2. Adding the calibration errors, our best estimate of the dipole anisotropy is

$$\begin{aligned} T_x &= -3.68 \pm 0.30\ \text{mK}\,, \\ T_y &= 0.43 \pm 0.20\ \text{mK}\,, \\ T_z &= -0.82 \pm 0.35\ \text{mK}\,. \end{aligned} \tag{1}$$

In spherical coordinates

$$\begin{aligned} T &= 3.78 \pm 0.30\ \text{mK}\,, \\ \text{R.A.} &= 11^{\rm h}_{.}6 \pm 0^{\rm h}_{.}2\,, \\ \delta &= -12^\circ \pm 5^\circ\,. \end{aligned} \tag{2}$$

This dipole has a larger amplitude and points south and west of our earlier result (Cheng *et al.* 1979). It is now apparent that the 1979 dipole result was contaminated by quadrupole effects which could not be evaluated because of limited sky coverage. Besides the obvious problem with Q_1 interfering with T_z, Q_2 through Q_5 have large correlations with T_x and T_y, unless right ascension (α) is well covered. To see the effect graphically, look at the dipole fit to $\langle B_1\rangle$ in Figure 1, and note that the 1979 data covered $12^{\rm h} < \alpha < 2^{\rm h}$; the positive half-cycle at $18^{\rm h}$ was observed. Now look at Figure 2 where the quadrupole effect is shown separately, and note the negative effect in $\langle B_1\rangle$ at $18^{\rm h}$. Thus, quadrupole effects reduced the apparent dipole amplitude in the 1979 data. Similarly, dipole (only) fits to the 1980 data give anomalously large amplitudes due to the negative quadrupole effect near $\alpha = 6^{\rm h}$. In general, partial sky coverage causes each spherical harmonic Y_{lm} to be contaminated by higher-order harmonics. For our sky coverage, the strongest correlation is between components with $\Delta l = 1$, $\Delta m = 0$.

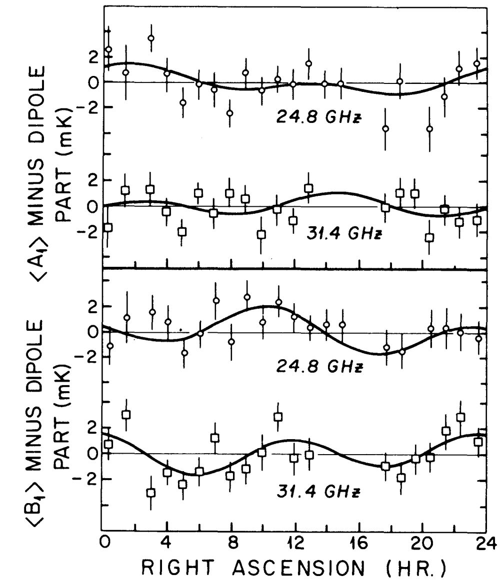

Fig. 2.—Quadrupole fits at 24.8 and 31.4 GHz. The dipole part of the combined fit has been subtracted from the data points, and the solid curves show the quadrupole part of the best fit at each frequency. The radiometers see similar quadrupoles, especially the 12 hr components (Q_4 and Q_5) which have the smallest correlations to the dipole effect (Table 2).

The dipole anisotropy given in equation (1) can be compared to the latest result of the Berkeley group (Smoot and Lubin 1979); $T = (-2.78 \pm 0.28; 0.66 \pm 0.29; -0.18 \pm 0.39)$. While our measurement of the dipole amplitude increased, theirs decreased, the two results crossing. Changes and differences in measured dipole moments are probably due mainly to interference from higher-order moments windowed by partial sky coverage.

b) *Spectrum of the Dipole Anisotropy*

Could part of the dipole anisotropy be due to some large-scale, faint radio source—a nearby supernova remnant, for example? Such a source would be expected to have a spectrum similar to Galactic radio emission. Figure 3 shows the measured dipole amplitudes at four frequencies; clearly, the dipole spectrum is nearly blackbody. Fitting a power-law spectrum ($T \sim \nu^{-\alpha}$) to the points in Figure 3 gives $\alpha = 0.04 \pm 0.28$. Thermal ($\alpha \sim 2.1$) and nonthermal ($\alpha \sim 2.9$) spectra do not fit the dipole spectrum; at most, 10% of the dipole effect could be due to thermal emission. Figure 3 argues that the dipole anisotropy is due to (1) solar motion through the 2.7 K radiation and/or (2) an intrinsic anisotropy in the temperature of the radiation.

Recently Fabbri *et al.* (1980) have reported detecting a dipole anisotropy at 0.5 mm $< \lambda <$ 3 mm. The amplitude is 2.9 (+1.3, −0.6) mK in agreement with all longer wavelength measurements. Thus, the dipole anisotropy appears to be blackbody into the millimeter region. Including this result in the power-law fit gives $\alpha = 0.11 \pm 0.13$.

c) *Quadrupole Effect*

The least-squares fit of all our data to a dipole plus quadrupole model gives a 4 σ effect in the Q_5 component and a 2 σ effect in the Q_4 component, each with small correlations to other fitted parameters (see Table 2). Furthermore, similar quadrupole effects are apparent in separate fits to 24.8 and 31.4 GHz data (see Fig. 2). We believe that the radiometers have detected a real quadrupole distribution in the 2.7 K background radiation.

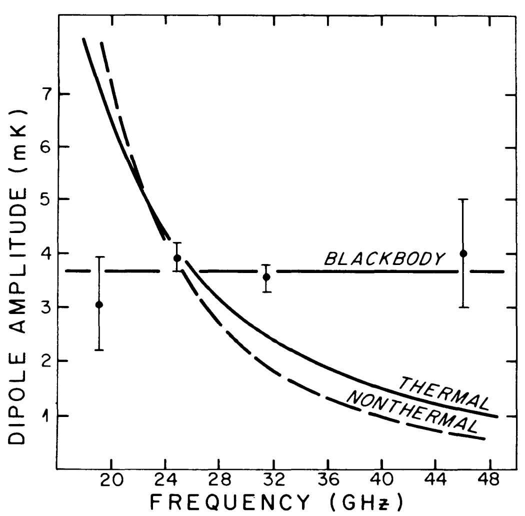

FIG. 3.—Spectrum of the dipole anisotropy. The best-fit thermal and nonthermal curves are for spectral indices of 2.1 and 2.9, respectively. Known sources of Galactic radiation are ruled out.

Could Galactic radio emission account for the observed quadrupole effects? Qualitatively, the spatial distributions are similar (Q_5 has warm lobes at $\delta = 0°$, R.A. = 9^h and 21^h), but known sources are too weak. Before fitting to models, the coefficients $\langle A_1 \rangle$ and $\langle B_1 \rangle$ are corrected for Galactic radiation due to (1) nonthermal emission, (2) thermal emission from H II regions, the galactic plane, and the Cygnus X region, and (3) discrete sources. The Galactic corrections contribute only −0.07 mK to Q_5 and −0.09 mK to Q_4, so Galactic corrections fall short by a factor of more than 5. We have looked for evidence of an unknown component of large-scale thermal emission by examining Hα maps, low-frequency radio maps, pulsar dispersion measures, and recombination line measurements. All indicate that on large angular scales the emission measure of the Galaxy is too small to give the observed quadrupole effects. Finally, unreasonable changes in the spectral index of the nonthermal emission are needed to make this component strong enough at $\lambda \sim 1$ cm.

The quadrupole result reported here is not in conflict with Cheng *et al.* (1979) ($Q_i < 2$ mK) or with the upper limit of 1 mK stated by Smoot and Lubin (1979). However, Table 2 of the latter paper gives $Q_5 = 0.06 \pm 0.20$, which is 3 σ smaller than our best-fit value. We cannot explain this discrepancy, but note that the Smoot and Lubin (1979) result has relatively large correlations with T_x and T_y, presumably owing to unfavorable sky coverage.

Fabbri *et al.* (1980) have reported a second harmonic signal which they tentatively identify with a "quadrupole-like anisotropy" of amplitude 0.9 (+0.4, −0.2) mK, aligned along the dipole axis. Very limited sky coverage (essentially a circle of diameter 120°, one side of which cuts the Galactic plane) prevents them from evaluating quadrupole components, or separating dipole from quadrupole effects in the first harmonic signal. This makes it difficult to compare our quadrupole result with theirs directly. However, we have tried to estimate their second harmonic signal using the quadrupole distribution of Table 2 and taking Q_1 from Smoot and Lubin (1979). Their signal[3] is larger than our estimate by a factor of 2, but the phases appear to be similar. Better sky coverage at millimeter wavelengths and better sensitivity at centimeter wavelengths are needed to test the spectrum of quadrupole and higher-order effects. If they prove to be intrinsic to the 2.7 K radiation, an important new cosmological tool is at hand.

[3] The horizontal axis on Figure 3 of Fabbri *et al.* (1980) is incorrectly labeled R.A.; it should be θ in units of 10°. A quadrupole signal is double valued when plotted against θ, so the phase comparison is ambiguous.

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