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LARGE-SCALE ANISOTROPY IN THE 2.7 K RADIATION[1]

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ABSTRACT

We report the results of two balloon flights, covering half the sky, to measure the large-scale anisotropy of the 2.7 K cosmic radiation. Radiometers at three wavelengths give results which are well fitted by a dipole distribution with amplitude 2.99 ± 0.34 mK and direction R.A. = $12^{h}.3 \pm 0^{h}.4$ and decl. = $-1° \pm 6°$. An upper limit of 2 mK (95% confidence) is found for the amplitudes of nonpolar components of a quadrupole distribution.

Subject headings: cosmic background radiation — cosmology

I. INTRODUCTION

Within 2 years of its discovery the 2.7 K radiation had been shown to be isotropic to about 0.1% (Partridge and Wilkinson 1967), lending support to the primeval fireball model. Since then, work on large-scale anisotropy has been directed toward (1) finding intrinsic anisotropy in the early universe, and (2) detecting the solar motion through the radiation. Early attempts at precision anisotropy measurements (see Table 2) were hampered by atmospheric noise, large corrections for galactic radiation, and limited sky coverage. But in retrospect it seems likely that the solar motion was being seen 10 years ago (Conklin 1969; Henry 1971). More convincing results have come from the Berkeley group (Smoot, Gorenstein, and Muller 1977), who flew their 33 GHz receiver in a U-2 aircraft, and from the earlier of the balloon flights reported here (Corey and Wilkinson 1976; Corey 1978). Low sidelobe horn antennas, careful radiometer design, and high observing frequencies minimized the systematic errors that had plagued earlier measurements.

This *Letter* reports the results of two balloon flights to look for large-scale anisotropy of the 2.7 K radiation. The first was in 1975 May with a 19.0 GHz radiometer; the second was in 1978 August and had radiometers at 24.8 GHz and 31.4 GHz.

II. OBSERVATIONS

The data were taken with three microwave radiometers having frequency, rms noise, and beamwidth (FWHM) as follows: 19.0 GHz, 100 mK $\text{Hz}^{-1/2}$, and 10°; 24.8 GHz, 51 mK $\text{Hz}^{-1/2}$, and 8°; 31.4 GHz, 45 mK $\text{Hz}^{-1/2}$, and 6°. Each radiometer measures the difference in the power received by two horn antennas which are pointed 90° apart in the sky; each horn points 45° down from the zenith.

To minimize atmospheric radiation, the radiometers are carried by a balloon to an altitude of about 27 km. The radiometer frequencies were chosen to avoid ozone lines (because ozone is patchy), and the residual atmospheric water and oxygen contribute less than 10 mK to the antenna temperatures. Observations are made at night and within 5 days of new Moon. A typical flight lasts from sunset to sunrise and gives a total integration time of 8 to 10 hours.

The radiometers are rotated about the zenith at 1 rpm, so the antennas scan a circle 90° across; orthogonal Hall magnetometers are used to measure the rotation angle to $\pm 1°$. Earth rotation scans the rotation axis in right ascension, α; and since flights are made from the National Scientific Balloon Facility at Palestine, Texas, the balloon zenith stays near declination $\delta = +32°$. Thus each balloon flight scans about 35% of the sky. Half the sky was covered by the two flights reported here.

The radiometers are calibrated before and after each flight with a room temperature absorber. Preflight and in-flight gain is monitored by measuring the receiver rms noise. The calibration is good to $\pm 5\%$ for the 24.8 GHz and 31.4 GHz data and $\pm 10\%$ for the 19.0 GHz data. These are included by quadrature in the final results.

III. DATA ANALYSIS AND RESULTS

a) Data Reduction

The raw data are edited to remove obvious contamination due to telemetry dropout and commands; typically less than 5% of the observing time is lost. The magnetometer data are then used to determine the radiometer orienta-

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tion ϕ (relative to true north) for each 1 s data sample. The radiometer data are divided into strings about 1 hour long and averaged as follows. (1) The data from each rotation cycle are fitted to the function

$$\sum_{n=0}^{m} (A_n \cos n\phi + B_n \sin n\phi)$$

for m up to 10; ϕ is measured from north, with west = $\pi/2$. (2) Each amplitude, A_1 and B_1, is averaged (over about 60 rotation cycles) to give a mean and a standard deviation in the mean for each hour. (3) These hourly mean amplitudes, $\langle A_1 \rangle$ and $\langle B_1 \rangle$, are assigned to a position on the sky (α, δ) equal to the balloon's zenith at the middle of the data string. (4) Higher harmonics of ϕ are examined for statistically significant amplitudes. None have been found. (It is important that no signals are found for even n. Since the radiometers measure the *difference* in horn powers, real signals cannot give even harmonics of ϕ; their existence would indicate a serious systematic error signal.)

$\langle A_1 \rangle$ and $\langle B_1 \rangle$ are next corrected for known sources of galactic radiation. The corrections are estimated by extrapolating long-wavelength measurements of (1) discrete sources, (2) nonthermal diffuse background, (3) thermal emission near the galactic plane, and (4) the Cygnus X region (Altenhoff *et al.* 1970; Pauliny-Toth and Shakeshaft 1962; Seeger *et al.* 1965; Wendker 1970; other references in Corey 1978). In no case was the galactic correction larger than the statistical error in $\langle A_1 \rangle$ or $\langle B_1 \rangle$. Finally, the measured amplitudes are corrected for the effect of the Earth's motion about the Sun, so the results refer to the anisotropy measured in the barycentric reference frame.

b) *Dipole Model*

Large-scale anisotropy in the 2.7 K radiation will appear in the results as a change in $\langle A_1 \rangle$ and $\langle B_1 \rangle$, as the rotation axis moves across the sky. Positive values of $\langle A_1 \rangle$ ($\langle B_1 \rangle$) indicate that the north (west) side of the 90° scan circle is warmer. Figure 1 shows $\langle A_1 \rangle$ and $\langle B_1 \rangle$ plotted against the right ascension of the radiometer rotation axis.

If the deviation from isotropy is dipole, the excess temperature can be written as $\boldsymbol{T}\cdot\hat{r} = T\cos\theta$, where $\hat{r}$ is a unit vector in the direction of observation, and $\boldsymbol{T}$ points to the warm pole. For our antenna geometry, the dipole model predicts

$$\langle A_1 \rangle = 2^{1/2}(-T_x \sin\delta\cos\alpha - T_y \sin\delta\sin\alpha + T_z\cos\delta)$$

$$\langle B_1 \rangle = 2^{1/2}(T_x \sin\alpha - T_y\cos\alpha)\ , \qquad (1)$$

where T_x, T_y, and T_z are the components of $\boldsymbol{T}$ in the directions (α, δ) = (0, 0), (6^h, 0), and (0, 90°), respectively. Equation (1) shows that the 24 hour components of $\langle A_1 \rangle$ and $\langle B_1 \rangle$ give the equatorial components of $\boldsymbol{T}$, while the polar component T_z causes a constant offset in $\langle A_1 \rangle$.

$\boldsymbol{T}$ is determined by a least-squares fit of equation (1) to $\langle A_1 \rangle$ and $\langle B_1 \rangle$. The results of fitting to five different data

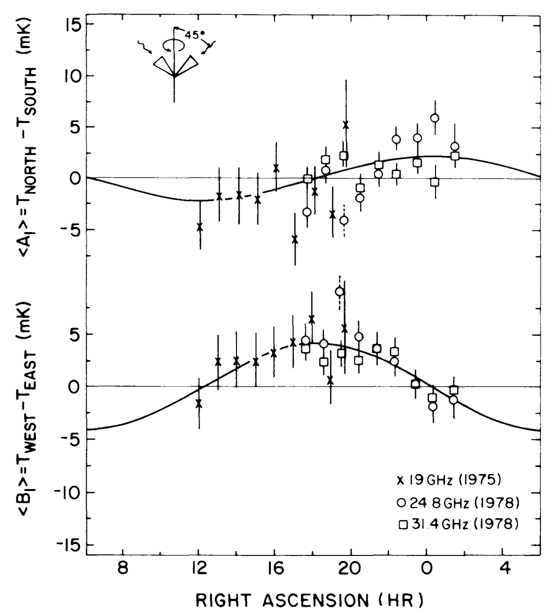

FIG. 1.—Hourly averages of the differential radiometer signals, synchronous with radiometer rotation. Errors are computed from internal scatter. The solid curve is the best-fit dipole model (fit 2, Table 1).

sets are given in Table 1. Fit 1 includes all the data from both flights; fits 3, 4, and 5 each uses the data from a single radiometer. The 24.8 GHz radiometer exhibited some instability during the third hour of the 1978 August flight; this hour has (1) the only visible nonrandom noise feature in the entire chart record, and (2) excessive low-frequency noise in the power spectrum. Excluding those two points from the fit (fit 1) reduces χ^2 by 18. We regard fit 2 as the best result.

The residuals in Figure 1 look peculiar. Taken separately, the residuals in $\langle A_1 \rangle$ are too large and those in $\langle B_1 \rangle$ too small. We cannot think of a systematic error which would be primarily north-south, and all together the residuals satisfy Gaussian statistics. We believe that the predominance of large residuals in $\langle A_1 \rangle$ is a statistical accident.

c) Quadrupole Model

The good fits achieved by the dipole model indicate that the use of more complex models should not be expected to improve the fit significantly. However, the limited sky coverage of the data can allow a rather large quadrupole effect to be masked by the dipole, and one must fit a combined model to evaluate possible quadrupole effects. If we express the quadrupole anisotropy as

$$\sum_{m=-2}^{2} (a_{2m} + ib_{2m}) Y_{2m} ,$$

the combined fit gives

$$(T_x, T_y, T_z + 0.71a_{20}) = (-3.27 \pm 0.57, -0.17 \pm 0.73, -0.10 \pm 0.72)\ \text{mK} ,$$
$$(a_{22}, b_{22}, a_{21}, b_{21}) = (-0.06 \pm 0.46, 0.29 \pm 0.49, -0.28 \pm 0.65, 0.34 \pm 0.87)\ \text{mK} . \quad (2)$$

Since all of our data were taken at essentially the same δ, the polar components T_z and a_{20} are highly correlated. The fitted quadrupole parameters are not significant. Comparing the results in equation (2) and Table 1 (fit 2), one sees that adding the quadrupole terms did not change the dipole result significantly. The combined fit gives $\chi^2 = 47$ for 45 degrees of freedom—a fit slightly worse than that of the dipole model by itself. Finally, the value of χ^2 obtained by fitting the quadrupole model alone to the data is 94 for 47 degrees of freedom. We can reject the hypothesis that the data are adequately described by a quadrupole anisotropy alone.

d) Statistical and Systematic Errors

For the 1978 data, radiometer noise alone would contribute 1.1 mK statistical errors to $\langle A_1 \rangle$ and $\langle B_1 \rangle$; the measured standard deviations range from 1.1 to 1.7 mK. Those points with excess statistical noise correlate well with periods when the 24.8 GHz radiometer exhibits excess low-frequency noise—mainly early in the flight. For the 1975 data, the standard deviations in the hourly means $\langle A_1 \rangle$ and $\langle B_1 \rangle$ should be 2.4 mK if the only error source is radiometer noise. The observed values all lie in a range (2.0 to 2.9 mK) consistent with the expected value.

Systematic errors are generated by effects which are modulated by the radiometer rotation, for example, coupling to the Earth's magnetic field. All ferrite components in the radiometers are magnetically shielded. We find in the laboratory that the magnetic sensitivity is less than 0.4 mK gauss^{-1}, so the nearly constant bias on $\langle A_1 \rangle$ and $\langle B_1 \rangle$ due to the horizontal component of the Earth's field is less than 0.1 mK.

Anisotropy of ground radiation can also cause error signals. Measured antenna patterns and ground screen diffraction calculations give an antenna temperature of less than 4 mK from ground radiation. For nighttime flights over land the largest ground asymmetry comes from attenuation by clouds which are colder than the ground. We esti-

TABLE 1

FITS OF DIPOLE MODEL

Fit No.	Data Set	T_x (mK)	T_y (mK)	T_z (mK)	χ^2(DOF)[a]	P[b] (%)
1..........	All data	-3.25 ± 0.30[c]	-0.33 ± 0.30	-0.28 ± 0.30	66(51)	8
2[d]..........	All data except 24.8 GHz at 19ʰ.5	-2.98 ± 0.30	-0.24 ± 0.30	-0.06 ± 0.31	48(49)	53
3..........	31.4 GHz data	-2.35 ± 0.43	-0.28 ± 0.41	$+0.11 \pm 0.44$	13(15)	57
4..........	24.8 GHz data except point at 19ʰ.5	-3.78 ± 0.60	-0.27 ± 0.54	$+0.05 \pm 0.57$	16(13)	26
5..........	19.0 GHz data only	-2.96 ± 0.86	-0.06 ± 1.01	-0.98 ± 0.94	12(15)	69
2..........	Correlation coefficients	+1.000	...	...	...	...
		−0.265	+1.000			
		+0.392	−0.409	+1.000		

[a] Chi-square and degrees of freedom of fit.

[b] Probability that repeated experiments would give a larger χ^2 provided that the residuals (data − model) are due to statistical errors only.

[c] Thermodynamic temperature. Errors are statistical only.

[d] Regarded as best result.

mate that the worst case could give a ground signal of 0.2 mK in the 24.8 GHz radiometer. The effect is smaller at the other frequencies which are farther from the water-vapor absorption line.

Large anisotropy signals (possibly 100 mK) could be produced by high power radar interference, especially if the balloon is being tracked. There is no evidence in the data of interference signals switching on or off, and it is unlikely (but possible) that all radar signals would *always* hide in the noise. Furthermore, the signal from a point source near the horizon has a unique signature. The nonaxisymmetric antenna patterns and the differential radiometer technique combine to give a point-source response containing strong third and fifth harmonics of ϕ, whereas the measured harmonic signals are consistent with zero. We do not believe that radar interference was a problem on these two flights.

Atmospheric emission and emission or reflection (of ground radiation) by the balloon are small and make negligible contributions to the differential signals. The radiometers are shielded against radio interference in the intermediate frequency band (e.g., TV and FM stations); this effect would also lead to harmonics of ϕ, which are not seen.

Systematic error due to incorrect estimates of the known galactic radiation is small. If no correction at all is made for galactic radiation, the results for fit 2 (Table 1) are $\boldsymbol{T} = (-2.88, -0.54, -0.04)$; the main effect is to make the galactic center region warmer by 0.30 mK. We believe that errors in the galactic radiation model do not affect the final result by more than 0.1 mK.

IV. DISCUSSION

Table 1 shows that the anisotropy in the 2.7 K radiation at three frequencies is well fitted by a dipole distribution on the sky. The adopted fit (no. 2) gives $\chi^2 = 48$ for 49 degrees of freedom, whereas the null hypothesis (isotropy) gives $\chi^2 = 164$ and can be rejected.

One should worry about whether there is a large-scale component to the galactic radiation, which would not have been detected in the long-wavelength maps. (Is the Vela supernova remnant a large, very faint, radio source? The direction is about right.) The agreement between fit 3 (31.4 GHz) and fit 5 (19.0 GHz) in Table 1 argues that the dipole asymmetry is produced by blackbody radiation ($T \propto \lambda^0$) and not by "nonthermal" ($T \propto \lambda^{2.8}$) or "thermal" ($T \propto \lambda^2$) radiation.

If the dipole effect is due to motion through the 2.7 K radiation, the implied solar velocity is given in Table 2, along with the earlier results. All results are in rough agreement. However, comparisons must be made with care, because the errors are highly correlated due to limited sky coverage in each measurement. The only two results with correlation coefficients given are Gorenstein (1978) and this work. Taking the difference of these results and comparing to the null vector gives $\chi^2 = 9.3$ for 3 degrees of freedom; there is only a 2.5% probability that statistical errors cause the results to disagree by this much. The largest discrepancy is in the polar component T_z; one of the experiments probably has a systematic error in this component.

The solar velocity has also been measured with respect to galaxies by measuring their redshift distribution on the sky. Rubin *et al.* (1976) find 600 ± 125 km s^{-1} toward $\alpha = 2^h$ and $\delta = 53°$ measured with respect to 96 Sc galaxies between 3500 km s^{-1} and 6500 km s^{-1}. De Vaucouleurs (1978) uses 200 closer galaxies (5 Mpc to 20 Mpc) and obtains a solar velocity of 430 ± 60 km s^{-1} toward $\alpha = 13^h$ and $\delta = 83°$. The solar velocities measured with respect to galaxies disagree in magnitude and direction with that found in the 2.7 K experiments. Table 3 shows the results expressed in terms of the motion of the Local Group. The directions of all three vectors disagree by more than 60°. But perhaps the most puzzling is the 120° discrepancy between the Rubin *et al.* result and the 2.7 K result; one would expect distant galaxies to give a reference frame similar to that of the 2.7 K radiation. The resolution of this problem may require a new view of the large-scale structure in the universe. Two obvious possibilities are: (1) the 2.7 K radiation has an intrinsic dipole moment; or (2) there exist random motions of order 500 km s^{-1} on a very large scale (~100 Mpc).

Finally, no quadrupole effect can be found in the current 2.7 K radiation isotropy data. A simultaneous dipole + quadrupole fit gives an upper limit of 2 mK (95% confidence) on the magnitudes of nonpolar components.

TABLE 2

Velocity of Sun Through 2.7 K Radiation

v[a] (km s^{-1})	R.A. (hr)	Decl. (deg)	l (deg)	b (deg)	Frequency (GHz)	Reference
<300	...	(equatorial component)	...	...	9.4	Partridge and Wilkinson 1967
250±100	11	(equatorial component)	...	...	8.0	Conklin 1972
366± 90	10.5±4	−30±25	270	24	10.2	Henry 1971
336± 81	12.1±1.3	−18±19	288	43	19.0	Corey 1978
390± 60	11.0±0.6	+6±10	248	56	33.0	Smoot, Gorenstein, and Muller 1977
401± 60	11.23±0.46	+19.0±7.5	229	67	33.0	Gorenstein 1978
332± 36	12.3±0.4	−1±6	287	61	19.0, 24.8, 31.4	This *Letter*

[a] $v = c(T/2.7)$, assuming that all of dipole asymmetry is due to solar motion.

TABLE 3

VELOCITY OF LOCAL GROUP

Reference Frame	v_{LG}[a] (km s^{-1})	l (deg)	b (deg)
Galaxies, $3500 < v < 6500$ km s^{-1}[b]	450	160	−10
Galaxies, 5 to 20 Mpc[c]	310	180	+50
2.7 K Radiation (this work)	540	280	+30

[a] The measured solar velocities have been transformed to the Local Group frame by subtracting 300 km s^{-1} toward $l = 90°$, $b = 0°$.

[b] Rubin *et al.* 1976.

[c] De Vaucouleurs 1978.

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