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SOUTHERN HEMISPHERE MEASUREMENTS OF THE ANISOTROPY IN THE COSMIC MICROWAVE BACKGROUND RADIATION

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ABSTRACT

A recent airborne measurement of the large-angular-scale anisotropy in the cosmic background radiation from the southern hemisphere (Lima, Peru) is in essential agreement with previous measurements from the northern hemisphere. The net anisotropy from the combined data can be described by a first-order spherical harmonic (Doppler) anisotropy of amplitude 3.1 ± 0.4 mK with a quadrupole component of less than 1 mK. Additional ground-based measurements of the linear polarization yield an upper limit of 1 mK, or one part in 3000, at 95% confidence level for the amplitudes of any spherical harmonic through third order.

Subject headings: cosmology — cosmic background radiation — polarization

I. INTRODUCTION

The large-angular-scale distribution of the cosmic background radiation is a sensitive probe of several phenomena of cosmological interest, including the isotropy of the Hubble expansion, the possible rotation of the universe (Collins and Hawking 1973), the existence of very long-wavelength gravitational radiation (Burke 1975), and density inhomogeneities at the time of decoupling.

Anisotropy in the background radiation has now been clearly observed from the northern hemisphere by Smoot, Gorenstein, and Muller (1977) and by Cheng *et al.* (1979). Our data from the northern hemisphere indicate a first-order dipole anisotropy of amplitude 3.5 ± 0.6 mK and an upper limit of 1.1 mK at 95% confidence level on any second-order (quadrupole) anisotropy (Smoot, Gorenstein, and Muller 1977; Gorenstein and Smoot 1979). Because of the lack of southern hemisphere data, the above limit on the second-order anisotropy refers only to four of the five quadrupole components.

The first-order anisotropy is readily interpreted as resulting from a 350 ± 60 km s^{-1} motion of the Sun relative to the background radiation, whereas the lack of a second-order anisotropy demonstrates the intrinsic isotropy of the background radiation. Taking into account the rotational motion due to rotation of our Galaxy, a net velocity for the Galaxy of 550 ± 100 km s^{-1} is derived relative to the background. This velocity is much higher than expected, and raises a number of cosmological problems.

The unsettled state of the velocity interpretation, the desire to distinguish unambiguously the various possible anisotropies (dipole, quadrupole, etc.), and a belief that the anisotropy should be measured more accurately, motivated us to mount an expedition to make measurements in the southern hemisphere.

II. DATA COLLECTION

The possible sky coverage in the southern hemisphere is greatly restricted by emission from the galactic center and the galactic plane. However, flights originating from about 10° to 20° south latitude allow the possibility of obtaining data through gaps in the galactic background, while remaining reasonably close to 30° south latitude, the optimum latitude for distinguishing the first and possible higher-order anisotropies.

After a series of negotiations, a decision was finally reached to conduct a series of four flights from Lima, Peru. Difficulties in finalizing the arrangements delayed our operations two weeks. This delay, along with logistical problems, resulted in a final sky coverage that was less than ideal. Despite various operational difficulties, however, we were able to sample a significant portion of the southern sky and achieve most of our goals. The sky coverage from the four flights is shown in Figure 1.

The measurements were taken with a 33 GHz Dicke radiometer essentially identical to that used for the northern hemisphere measurements (Gorenstein *et al.* 1978). The instrument was flown aboard a NASA-Ames U-2 aircraft at an altitude of 20 km. Orienting the aircraft such that one of the radiometer's antennas pointed at the Moon during the flight on March 5 calibrated the radiometer. The signal observed agreed to within 5% of that seen in previous northern hemisphere flights.

During the first flight on 1979 March 2, the roll monitor, a 54 GHz radiometer sensitive to atmospheric oxygen emission, did not function. We have no independent check of the aircraft stability for this data set, and only the pilot's log to determine bank times. Our previous experience and the succeeding flight data indicate that this is sufficient information for a success-

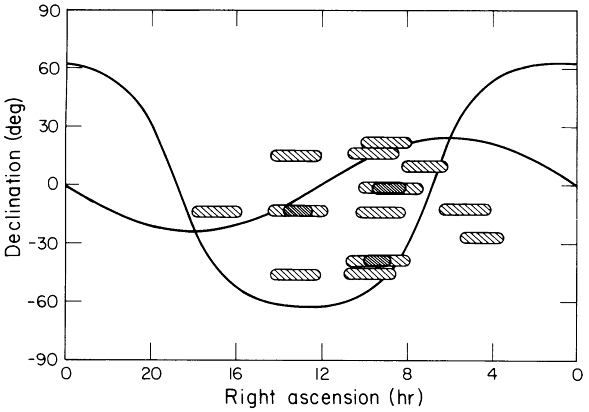

FIG. 1.—Sky coverage for the four flights originating from Lima, Peru, is indicated by the shaded regions. The width of each region is set by the 7° FWHM antenna beam pattern, and the length is set by the rotation of the Earth and the motion of the U-2 back and forth along its flight path. The galactic and ecliptic planes are shown for reference.

ful analysis of the observations, because the U-2 flies sufficiently level for the roll corrections to be negligible. We repaired the roll monitor, and it functioned properly on the remaining three flights.

III. RESULTS

Figure 2 shows the southern hemisphere data plotted with the predicted response based upon the Berkeley data from the northern hemisphere. The results of fitting the southern data, the previous northern data, and the combined data are summarized in Table 1. Because of the uncertainty in the subtraction of galactic emission and because of the more stringent operating conditions (particularly the colder atmospheric temperatures in flight), we have increased the quoted errors on the southern hemisphere data by 30% to allow for possible systematic effects. The primary conclusion is that we have detected an anisotropy in the southern hemisphere which is consistent with the first-order anisotropy measured in the northern hemisphere. This conclusion is based on an entirely independent data set, and as such is an important check on the northern hemisphere data.

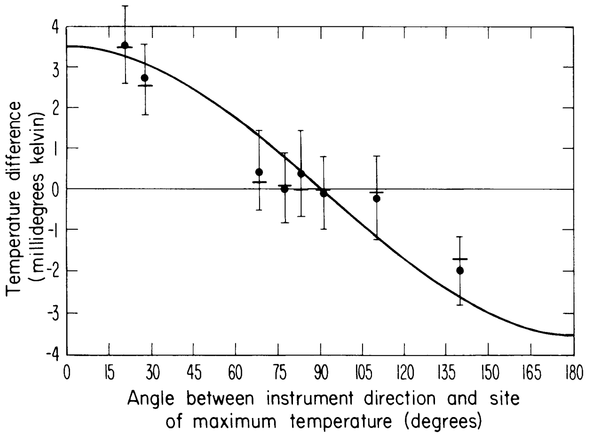

FIG. 2.—Comparison of southern hemisphere data with the anisotropy curve fitted to northern sky data. The temperature difference $\Delta T = T(\boldsymbol{\theta}_1) - T(\boldsymbol{\theta}_2)$ observed is plotted versus the angle between the two vectors ($\boldsymbol{\theta}_1 - \boldsymbol{\theta}_2$) and $\boldsymbol{n}$, the direction of maximum anisotropy ($\alpha = 11.2$ hr and $\delta = 16°$, as determined by the Berkeley northern sky data). The heavy horizontal bars represent the uncorrected data, while the dots show the data with estimated systematic effects removed (primarily galactic synchrotron radiation and H II emission). One standard deviation error bars are included.

TABLE 1

SUMMARY OF FITTED ANISOTROPY PARAMETERS

	Amplitude (mK)	R.A. (hours)	decl. (degrees)	χ^2/DOF
Northern hemisphere:				
Cheng *et al.* 1979	3.0 ± 0.3	12.3 ± 0.4	-1 ± 6	...
Smoot *et al.* 1977	3.5 ± 0.6	11.0 ± 0.6	$+6\pm10$	...
Berkeley north data[a] to date	3.5 ± 0.5	11.2 ± 0.5	$+16\pm7$	138/113
Southern hemisphere:				
Uncorrected	2.4 ± 0.7	12.5 ± 1	$+2\pm13$	69/47
Corrected for galactic emission	2.9 ± 0.7	12.3 ± 1	$+1\pm13$	65/47
Berkeley combined data	3.1 ± 0.4	11.4 ± 0.4	9.6 ± 6	211/163

Component	Amplitude (mK)[b]	Correlation Coefficients Matrix		
T_x	-3.01 ± 0.24	1.00		
T_y	$+0.39\pm0.25$	-0.07	1.00	
T_z	$+0.52\pm0.23$	-0.14	-0.02	1.00

[a] Includes all data in Gorenstein and Smoot (1979) plus one additional flight.

[b] Statistical errors based on receiver noise only.

The addition of the southern sky coverage substantially diminishes the correlation between spherical harmonics of low order. Table 2 presents the parameters and correlation coefficients for the combined dipole and quadrupole model. At the 95% confidence level, we can place a limit of 1.0 mK amplitude on all components with second-order spherical harmonic (quadrupole) anisotropy.

If we remove the first-order anisotropy and measure the residual rms fluctuations, we find an upper limit of 1 mK at a 95% confidence level (see also Gorenstein and Smoot 1979) for the sky roughness on the 7° angular scale of the antenna beamwidth.

During the same period in which the southern hemisphere anisotropy data were accumulated, we measured the linear polarization of the cosmic background radiation for declinations of 0°, $-19°$, and $-37°$. We used essentially the same apparatus, observing techniques, and data analysis described previously (Lubin and Smoot 1979). Combining these southern declination measurements with our measurements at $+63°$, $+53°$, $+38°$, and $+13°$, we fitted a linear combination of spherical harmonics. The results of the fitting procedure provide an upper limit of 1 mK at

TABLE 2

COMBINED DIPOLE AND QUADRUPOLE MODEL PARAMETERS[a]

	Amplitude and Error (mK)	Correlation Coefficients Matrix (χ^2/DOF=203/158)							
T_x......	−2.78±0.28	+1.00							
T_y......	+0.66±0.29	−0.21	+1.00						
T_z......	−0.18±0.39	+0.13	−0.25	+1.00					
Q_1......	+0.38±0.26	+0.00	−0.01	−0.71	+1.00				
Q_2......	−0.34±0.29	−0.34	−0.03	+0.68	−0.51	+1.00			
Q_3......	+0.02±0.24	+0.08	−0.44	−0.35	+0.23	−0.08	+1.00		
Q_4......	−0.11±0.16	+0.39	−0.01	−0.05	+0.07	−0.12	−0.05	+1.00	
Q_5......	+0.06±0.20	−0.31	+0.48	+0.07	+0.03	−0.06	−0.15	−0.12	+1.00

NOTE.—$T(\alpha, \delta) = T_0 + T_x \cos\delta \cos\alpha + T_y \cos\delta \sin\alpha + T_z \sin\delta + Q_1 (\frac{3}{2}\sin^2\delta - \frac{1}{2}) + Q_2 \sin 2\delta \cos\alpha + Q_3 \sin 2\delta \sin\alpha + Q_4 \cos^2\delta \cos 2\alpha + Q_5 \cos^2\delta \sin 2\alpha$, where $\alpha \equiv$ right ascension and $\delta \equiv$ declination.

[a] For all Berkeley data north and south.

the 95% confidence level for any spherical harmonic component through third order.

IV. INTERPRETATION

The conclusion that the anisotropy is first order and global, in turn, supports the velocity interpretation. When the measured anisotropy for our combined data is interpreted as the result of solar motion, the derived magnitude of approximately 350 km s^{-1} seems quite reasonable; however, when the known velocity component due to galactic rotation is subtracted, we obtain a net velocity for our galaxy of about 520 ± 75 km s^{-1} in the direction α = 10.5 ± 0.7 hours and $\delta = -19° \pm 10°$ (l = 264° and b = 33°)—a velocity which is much higher than expected. The large magnitude of this velocity is somewhat disturbing, given that the peculiar velocities for nearby galaxies are relatively small. For example, the relative radial velocity between our Galaxy and the Andromeda galaxy is only 80 km s^{-1}, and other local galaxies seem to have relative motions which are all under about 200 km s^{-1}.

Astronomers have measured solar motion with respect to various galaxy samples by measuring their redshift distribution on the sky. Peebles (1979) has concluded that the peculiar (non-Hubble) velocity of our Galaxy relative to the Virgo cluster is small; de Vaucouleurs (1978) has used a sample of 260 galaxies (5–20 Mpc distant) to obtain a solar velocity of 430 ± 60 km s^{-1} toward $\alpha = 13^h$ and δ = 83°. Sandage, Tammann, and Yahil (1979) report a net motion of the Galaxy relative to galaxies which are within a sphere of radius 80 Mpc (about 4 times the distance to the Virgo cluster) at about half the magnitude (245 ± 60 km s^{-1}) but in roughly the same direction (l = 205°, b = 31°) as the velocity we observe. However, when comparing a more distant sample of galaxies ($70 < d < 130$ Mpc), V. C. Rubin *et al.* (1976) report a high solar velocity of 600 ± 125 km s^{-1} with a different direction, $\alpha = 2^h$ and δ = 53°. For our measured velocity to be consistent with the small local deviations from Hubble flow found by Peebles (1979) and Sandage, Tammann, and Yahil (1979) the local supercluster must undergo a significant flattening (White and Silk 1979), or there must be an additional density perturbation of slightly smaller magnitude but on a much larger scale in roughly the same direction as Virgo. In the latter case, the extra gravitational force would pull not only the local group of galaxies but also the whole supercluster away from their Hubble expansion trajectories.

The upper limits on the amplitude of various spherical harmonic components translate into limits on parameters which describe effects of cosmological interest. The overall isotropy is valid to one part in 3000 at the 95% confidence level, verifying the cosmological principle. The results are also consistent with Mach's principle, in that they place an upper limit on the rotation rate of the universe at 10^{-11} seconds of arc per century (Collins and Hawking 1973). The upper limit placed on the energy density of long-wavelength gravity waves is given by (Smoot 1979)

$$\rho_{\rm GW} \leq \rho_{\rm CRITICAL}\, (8\ {\rm Mpc}/\lambda_{\rm GW})^2\,.$$

The upper limit on any large-scale anisotropic Hubble expansion is $\Delta H_0/H_0 \lesssim 10^{-5}$ or 10^{-8}, if the last scattering of the radiation occurred at a redshift of 7 or 1500, respectively (Rees 1968). In general, since the temperature variations are less than one part in three thousand, we would expect that large-scale density variations are less than about one part in a thousand at present (Silk 1968).

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