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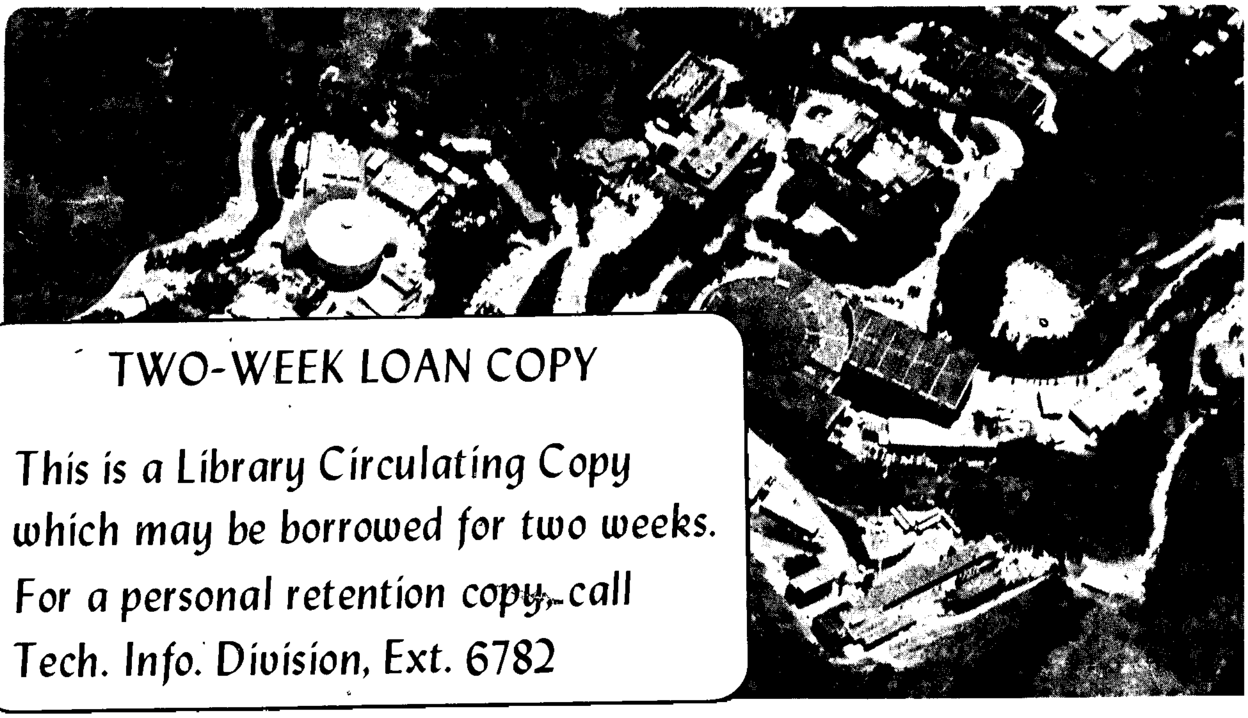

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SOUTHERN HEMISPHERE MEASUREMENTS OF THE ANISOTROPY IN THE COSMIC MICROWAVE BACKGROUND RADIATION

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ABSTRACT

A recent measurement of the anisotropy in the Cosmic Background Radiation from the southern hemisphere (Lima, Peru) is essentially in agreement with previous measurements from the northern hemisphere. The net anisotropy can be described as a first order spherical harmonic (Doppler) anisotropy of amplitude 3.1 ± 0.4 m°K with a quadrupole anisotropy of less than 1 m°K. In addition, measurements of the linear polarization yield an upper limit of 1 m°K, or one part in 3000, at 95% C.L. for the amplitudes of any spherical harmonic through third order.

Subject headings: Cosmic Background Radiation - anisotropy/polarization, - cosmology

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, Saulson, Wilkinson and Corey (1979). The smooth angular distribution of the anisotropy suggests that the anisotropy should be interpreted as a local effect caused by the motion of the sun relative to the background radiation. After subtraction of this first order spherical harmonic, no statistically significant anistropy remains. The observed isotropy of the cosmic background radiation at this level is the strongest evidence in support of the Cosmological Principle, the basic assumption of cosmology that the Universe is isotropic and homogeneous on a large scale.

When the measured anisotropy is interpreted as resulting from the solar velocity, the derived magnitude of approximately 350 km/sec seems quite reasonable; however, when the known velocity component due to galactic rotation is subtracted, we obtain a net velocity for the Milky Way of about 520 ± 75 km/sec in the direction $\alpha = 10.5 \pm 0.7$ hours and $\delta = -19° \pm 10°$ -- a velocity which is much higher than expected. The large magnitude of this velocity is somewhat disturbing, because the peculiar velocities for nearby galaxies are relatively small. For example, the relative radial velocity between the Milky Way and the Andromeda galaxy is only 80 km/sec, and the other local galaxies seem to have relative motions which are all under about 200 km/sec.

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 relative to the Virgo cluster is small; de Vaucouleurs (1978) has used a sample of 260 galaxies (5 Mpc to 20 Mpc distant) to obtain a solar velocity of 430 ± 60 km/sec towards $\alpha = 13^h$ and $\delta = 83°$. 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 but in roughly the same direction as the velocity we observe relative to very distant matter. However, when comparing a more distant sample of galaxies ($3500 \leq cz \leq 6500$ km/sec or $70 < d < 130$ Mpc for $H_o = 50$ km/sec/Mpc) V.C. Rubin and coworkers (1976) report a high velocity of 600 ± 125 km/sec with different direction $\alpha = 2^h$ and $\delta = 53°$. It is difficult to conceive of such large-scale volumes having non-Hubble flow, and difficult to reconcile the high kinetic energy of these galaxies with the belief that the Universe obeys the Cosmological Principle.

In earlier measurements of the angular distribution of cosmic background radiation, we used a 33 GHz twin-antenna Dicke radiometer (Gorenstein et al. 1978) flown in a series of flights from NASA-Ames aboard the U-2 Earth Survey Aircraft. From these measurements, we were able to place an upper limit of 1.1 m°K (Gorenstein and Smoot 1979) at the 95% confidence level on the existence of a second order (quadrupole) anisotropy. This limit refers to four of the five possible quadrupole components: the lack of southern hemisphere data resulted in an ambiguity between the polar axially symmetric quadrupole component and the polar first order spherical harmonic component.

The confused state of the velocity interpretation, the desire to uncouple 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. The sky coverage in the southern hemisphere is greatly restricted by the galactic center and the galactic plane, which produce a significant background emission and thus exclude large portions of the southern sky. However, flights originating from about 15° to 20° south latitude allow the possibility of threading the sky coverage through gaps in the galactic background, while remaining reasonably close to 30° south latitude, the optimum latitude for disentangling the first and possible higher-order anisotropies.

Through a series of negotiations, an agreement 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.

During the first flight on March 2, 1979, the roll monitor, a 54 GHz radiometer sensitive to atmospheric oxygen emission, did not function. Thus 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 successful analysis of the observations. We repaired the roll monitor, and it functioned properly thereafter.

The proper operation of the 33-GHz (anisotropy measuring) radiometer was confirmed by an in-flight moon calibration conducted on March 5. Using a sextant mounted in the U2, the pilot verified that the antenna was pointing directly at the moon. The moon signal observed was within 5% of that predicted from previous measurements.

Figure 2 shows the southern hemisphere data plotted with the predicted response based upon the data from the northern hemisphere. The results of fitting both these data and the measurements from the northern hemisphere are summarized in Table 1. All data are in reasonable agreement. Our southern hemisphere data are actually in better agreement with the Princeton results than with our own northern hemisphere results. We believe that systematic errors are now comparable to the statistical errors caused by our receiver noise so that our total errors need to be increased by about 10% over those produced by receiver noise alone in order to obtain reasonable χ^2 values for the fitted models. This increase corresponds to either an additional random error of 0.8m°K added to the 1.6m°K error for each of the 166 data points, or correlated systematic errors of 0.2 and 0.3m°K.

In regarding systematic errors, we are more concerned by the southern hemisphere data because of the greater possible significance of galactic background contamination and the more stringent operating conditions (particularly the colder temperatures at altitude). To allow for the possibility for greater systematic error, we have increased the quoted errors on the southern hemisphere data by 30%, instead of the 10% discussed above.

Our 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 allows us to predict that full-sky measurements of the cosmic background radiation will confirm a 3m°K first order anisotropy. The conclusion, in turn, supports the velocity interpretation of the first order anisotropy, indicating that the galaxy and local group are moving at the relatively high speed of 520 $\pm$ 70 km/sec towards ℓ = 264° and b = 33°. For this velocity to be consistent with the small local deviations from Hubble flow found by Peebles (1979) and Sandage, Tammann and Yahil (1979), requires either a significant flattening of the local supercluster (White and Silk 1979), or an additional density perturbation of slightly smaller magnitude but much larger scale in roughly the same direction as Virgo. In the latter case, the extra gravitational force is pulling not only the local group of galaxies, but also the whole supercluster, away from Hubble expansion trajectories.

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. Thus at the 95% confidence level, we can place an absolute limit of 1.0 m°K amplitude on any second order spherical harmonic (quadrupole) anisotropy. Similarly, if we remove the first order anisotropy and measure only the residual rms fluctuations, the sky roughness on an angular scale of about 7°, we find an upper limit of 1 m°K at a 95% confidence level (Gorenstein and Smoot 1979).

Limits on the amplitude of various spherical harmonic components translate into limits on parameters which describe effects of cosmological interest. The measurements of the overall isotropy verify that the Cosmological Principle is valid to one part in 3000 at the 95% confidence level. These results are consistent with Mach's principle, in that they place an upper limit on the rotation rate of the universe at 10^{-10} seconds of arc per century. The upper limit placed on the energy density of long wavelength gravity waves is given by:

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

The upper limit on any large-scale anisotropic Hubblie expansion is 10^{-5} to 10^{-8}, if the last scattering of the radiation occurred at a redshift between 7 and 1500. In general, we would expect that large-scale density variations are less than about one part in a thousand at present.

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, 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 fit a linear combination of spherical harmonics. The results of the fitting procedure provide an upper limit of 1 m°K at the 95% confidence level for any spherical harmonic component through third order.

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TABLE 1: SUMMARY OF FITTED ANISOTROPY PARAMETERS

	Amplitude (m°K)	Right Ascension α (hours)	Declination δ (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±10	
All our North data	3.5±0.5	11.2±0.5	16±7	138/113
Southern Hemisphere				
Uncorrected	2.4±0.7	12.5±1	2±13	69/47
Corrected	2.9±0.7	12.3±1	1±13	65/47
Our Combined Data	3.1±0.4	11.4±0.4	9.6±6	211/163

Component	Amplitude (m°K)[†]	Correlation Coefficients Matrix		
T_x	-3.01±0.24	1.00		
T_y	0.39±0.25	-0.07	1.00	
T_z	0.52±0.23	-0.14	-0.02	1.00

[†] Statistical Errors based on receiver noise only

TABLE 2: COMBINED DIPOLE & QUADRUPOLE MODEL PARAMETERS

χ^2 /DOF = 203/158

	Amplitude (m°K)	Error	Correlation Coefficients Matrix							
T_x	-2.78 ±	.28	1.00							
T_y	.66	.29	-.21	1.00						
T_z	-.18	.39	.13	-.25	1.00					
Q_1	.38	.26	.00	-.01	-.71	1.00				
Q_2	-.34	.29	-.34	-.03	.68	-.51	1.00			
Q_3	.02	.24	.08	-.44	-.35	.23	-.08	1.00		
Q_4	-.11	.16	.39	-.01	-.05	.07	-.12	-.05	1.00	
Q_5	.06	.20	-.31	.48	.07	.03	-.06	-.15	-.12	1.00

$$T(\alpha,\delta) = T_o + T_x \cos\delta \cos\alpha + T_y \cos\delta \sin\alpha + T_z \sin\delta$$

$$+ Q_1 \left(\frac{3}{2}\sin^2\delta - \frac{1}{2}\right) + Q_2 \sin 2\delta \cos\alpha + Q_3 \sin 2\delta \sin\alpha + Q_4 \cos^2\delta \cos 2\alpha + Q_5 \cos^2\delta \sin 2\alpha$$

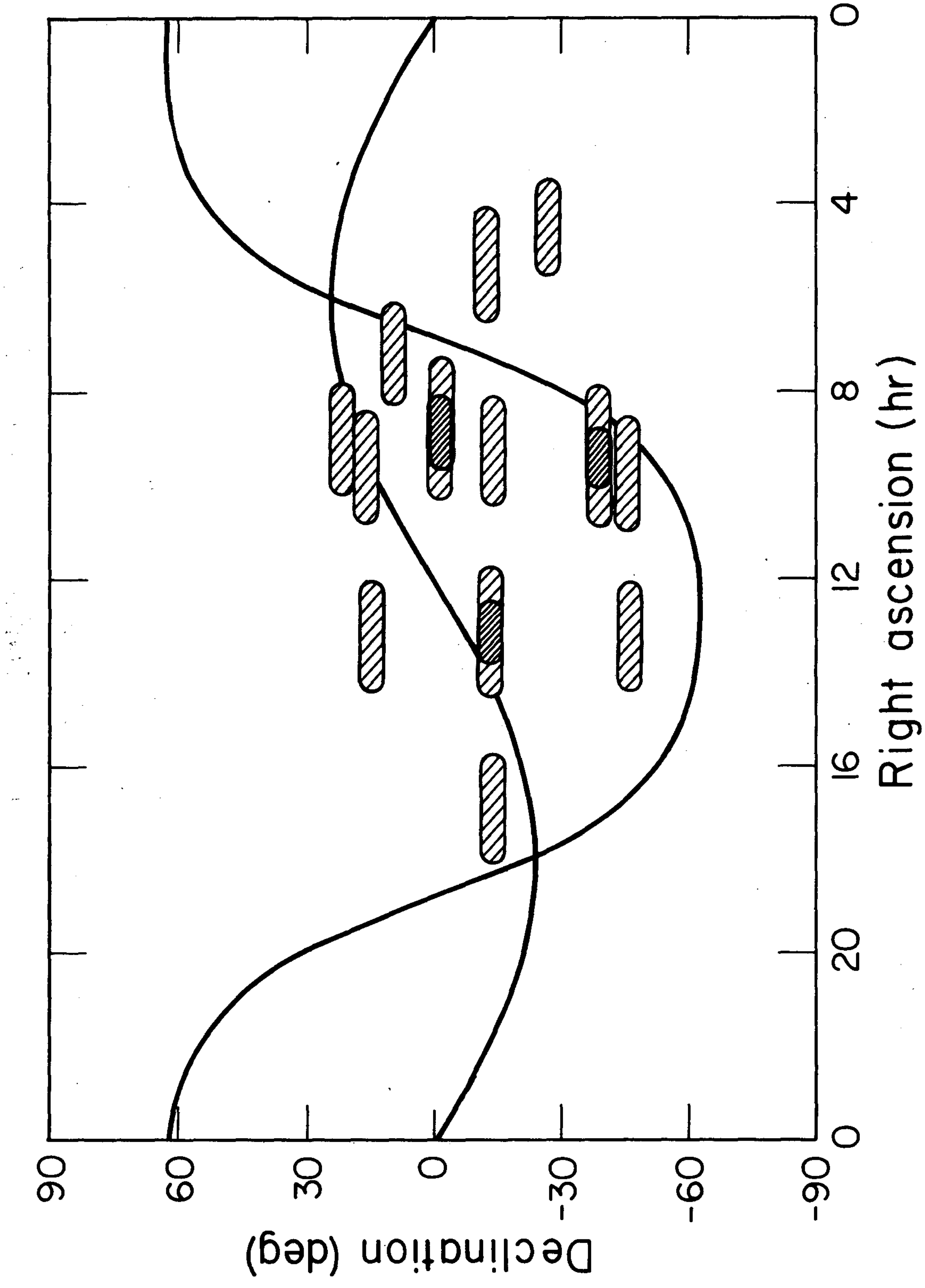
$\alpha \equiv$ Right Ascension

$\delta \equiv$ Declination

FIGURE CAPTIONS

Figure 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.

Figure 2. Comparison of southern hemisphere data with the anisotropy curve fit to northern sky data. The temperature difference $\Delta T = T(\hat{\theta}_1) - T(\hat{\theta}_2)$ observed is plotted versus the angle between the two vectors $(\hat{\theta}_1 - \hat{\theta}_2)$ and $\hat{n}$, the direction of maximum anisotropy ($\alpha = 11.2$ hrs. and $\delta = 16°$, as determined by 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.



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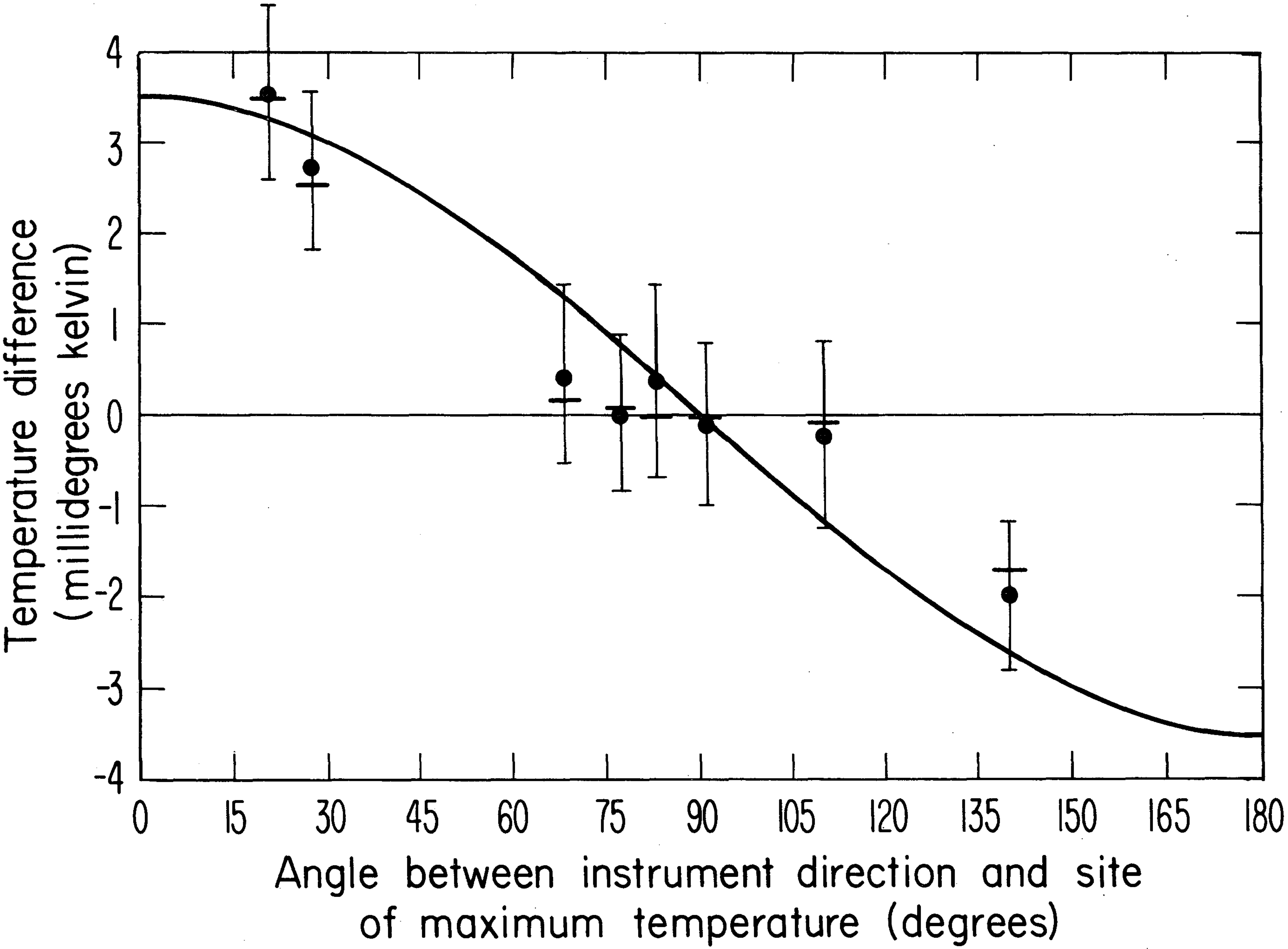

Temperature difference (millidegrees kelvin)
4
3
2
1
0
-1
-2
-3
-4
0
15
30
45
60
75
90
105
120
135
150
165
180
Angle between instrument direction and site of maximum temperature (degrees)

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