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DETECTION OF ANISOTROPY IN THE COSMIC BLACKBODY RADIATION*

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ABSTRACT

We have detected anisotropy in the cosmic blackbody radiation with a 33 GHz (0.9 cm) twin-antenna Dicke radiometer flown to 20 km altitude aboard a U-2 aircraft. In data distributed over two-thirds of the northern hemisphere, we observe an anisotropy which is well-fit by a first-order spherical harmonic with an amplitude of $(3.5 \pm 0.6) \times 10^{-3}$°K, and direction (11.0 ± 0.6 hrs R.A. and 6° ± 10° dec). This observation is readily interpreted as due to motion of the earth relative to the radiation with a velocity of 390 ± 60 km/sec.

The observed isotropy of the 3°K cosmic blackbody radiation to about one part in 10^3 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. Anisotropy at the 10^{-3} to 10^{-4} level is expected to exist from the Doppler shift due to the motion of the earth with respect to the ancient matter which emitted the radiation.[1] Anisotropies would also exist if there were non-symmetric expansion of the universe or large scale irregularities in the distribution of matter or energy. Until recently, interference from galactic emissions had prevented anisotropy in the cosmic blackbody radiation from being unambiguously observed.[2] Preliminary reports of a positive effect have been made now by Corey and Wilkinson[3] and by this group.[4] We present here the results of a survey spanning approximately two-thirds of the northern hemisphere, taken at 0.9 cm, a wavelength at which the galactic background is small.

The experiment was conducted in a series of flights aboard the NASA-Ames Earth Survey (U-2) Aircraft. Anisotropy in the cosmic radiation was detected with a twin antenna Dicke radiometer which measured the difference in sky temperature between two regions 60° apart and on opposite sides of the zenith. The central frequency of the system was 33 GHz with a bandwidth of 2 GHz. Its sensitivity was limited by thermal noise with an RMS fluctuation of 0.044°K for an integration time of one second, or about 1 millidegree Kelvin (m°K) for a half hour. The apparatus is shown schematically in Figure 1; details of its design and construction are published elsewhere.[5]

Effort was made in the design of the apparatus to reduce all expected systematic errors well below the millidegree-Kelvin level. To achieve the desired sensitivity, the apparatus was r.f. and magnetically shielded, and carefully thermally stabilized.[5] The antennas were specially designed (dual-mode corrugated cones) with a beam pattern 7° wide (FWHM). The measured antenna gain in the direction of the earth was below 10^{-7}; anisotropic emission from the earth and aircraft contributed less than 0.2 m°K. A second twin-antenna radiometer operating at 54 GHz was used to monitor and eliminate anisotropic atmospheric background. This second system was sensitive to the strong oxygen emission region centered at 60 GHz and was calibrated at altitude by banking the airplane at angles of 5° to 25°. The monitor showed that the autopilot maintained level flight during data-taking periods to better than 0.2° of bank; the resulting spurious signal at 33 GHz due to aircraft tilt is less than 0.2 m°K.

Spurious anisotropies were detected and eliminated through a hierarchy of reversals. Rapid switching (100 Hz) between the two antennas reduced the effects of gain fluctuations (1/f noise). Spurious anisotropy generated by imbalance in the two arms of the radiometer (≈60 m°K) was canceled by interchange of the two antennas through a rotation of the apparatus by 180° about the vertical every 64 seconds. Spurious anisotropy associated with the rotation state of the antennas (≈2 m°K) was eliminated by reversing the flight path of the airplane every 20 minutes.

The data reported here were taken on eight flights between December 1976 and May 1977. Each flight yielded about 3.5 hours of data taken at altitude; Figure 2 shows the total sky coverage. A typical flight plan consisted of six pairs of "legs" flown in opposite directions along the ground. In addition to the data legs, when possible the flights included a "moon leg" in which one antenna pointed directly at the moon for a few minutes; this allowed us to determine our absolute calibration at altitude to about 5%.

The data were fit by a least-squares method to a sum of spherical harmonics. Only the first spherical harmonic is necessary to obtain a good fit (χ^2 = 91 for 80 data points). Thus the temperature in the direction $\hat{\Theta}$ is given by:

$$T(\hat{\Theta}) = T_o + T_1 \cos(\hat{\Theta}, \hat{n}) \qquad (1)$$

Here T_o is the average blackbody temperature (not measured in this experiment), T_1 ard $\hat{n}$ are the parameters of the fit and $(\hat{\Theta}, n)$ is the angle made by the unit vectors $\hat{\Theta}$ and $\hat{n}$. The best fit is obtained for T_1 = 3.2 ± 0.6 m°K and $\hat{n}$ = (10.8 ± 0.5 hr R.A.; 5 ± 10° dec). In galactic coordinates $\hat{n}$ = (54° ± 10° lat.; 245° ± 15° long.).

Inclusion of second-order spherical harmonics in the fit changes the values of T_1 and $\hat{n}$ by much less than one standard deviation. An additional fit was made in which background contributions from the galaxy, the atmosphere, the motion of the earth around the sun, the antenna sidelobes, and residuals in the apparatus were calculated and subtracted for each leg prior to the least-squares minimization. These corrections individually and cumulatively were less than 0.5 m°K per leg and were small compared to the signal. We will discuss these corrections in more detail in a subsequent paper. The resulting best-fit values were $T_1 = 3.5 \pm 0.6$ m°K and $\hat{n}$ = (11.0 ± 0.5 hr R.A.; 6° ± 10° dec).

The data, with and without corrections, are plotted in Figure 3, along with the best fit curve to the uncorrected data. The residuals are small; to a 70% confidence level they are $\lesssim 10^{-3}$°K. Thus, *except for a component that varies as cosine* $(\hat{\Theta},\hat{n})$, the cosmic blackbody radiation is isotropic to one part in 3000.

The cosine anisotropy is most readily interpreted as due to the motion of the earth relative to the rest frame of the cosmic blackbody radiation, what Peebles calls the "new Aether Drift". Using 2.7°K for T_o and the fit to the corrected data, we calculate that the earth is moving at a velocity of $v = (T_1/T_o) \times c$ = 390 ± 60 km/sec in the direction $\hat{n}$, towards the constellation Leo. This result differs from the preliminary result reported by Corey and Wilkinson by less than twice their reported errors.[6] In addition it differs substantially from the values of the peculiar velocity for the motion of the sun measured with respect to nearby galaxies by Ford and Rubin[7] and by Visvanathan and Sandage.[8] If we subtract from our measured velocity the component due to the rotation of the Milky-Way galaxy[9] ≈300 km/sec, we calculate the net motion of the Milky-Way with respect to the canonical reference frame of cosmology to be ∿600 km/sec in the direction (R.A. = 10.4 hr, dec. = -18°). These various velocities are summarized in Table I. The large peculiar velocity of the Milky Way galaxy is unexpected, and presents a challenge to cosmological theory.

The limits on the second and higher order spherical harmonics place new constraints on several phenomena of cosmological importance. Hawking and Collins have shown[11] that vorticity, equivalent to a net rotation of the universe, can contribute a second order spherical harmonic due to the transverse Doppler shift. The limit one can place on this rotation depends strongly on the model of the Universe that is assumed. Using a semi-classical model, and assuming the blackbody radiation has not scattered since it was emitted at a redshift z, the rotation of the universe contributes a second order harmonic of amplitude:[12]

$$T_2 = \frac{T_o \omega_o^2 (1+z)^4}{8 H_o^2 (1+2 q_o z)} \qquad (2)$$

where ω is the present value for the angular velocity of the universe. If we take $H_o^{-1} = 2 \times 10^{10}$ yrs for the present value of Hubble's constant, $q_o = 0.03$ for the deceleration parameter, $T_o = 2.7°K$ for the present temperature of the radiation, $z = 1500$, and $T_2 \leqslant 10^{-3}°K$, we calculate that the rotation of the Universe is presently less than 10^{-9} seconds of arc per century.

Our limit on the second order spherical harmonic also puts a constraint on the existence of large wavelength gravitation radiation. Using the calculation of Burke,[13] we conclude that the mass-density of such radiation in the Universe is $\lesssim \rho_c$, where ρ_c is the critical mass density necessary to close the universe.

TABLE I

Peculiar Velocities (km/sec)

Reference	V(km/sec)	R.A.(hrs)	dec	galactic (long. & lat.) ℓ	b
MOTION OF SUN RELATIVE TO COSMIC BLACKBODY RADIATION					
Corey and Wilkinson[3]	270 ± 70	13 ± 2	-25° ± 20°	306	38
This work	390 ± 60	11 ± 0.6	6° ± 10°	248	36
Muehlner and Weiss[15]	$\lesssim$350				
MOTION OF SUN RELATIVE TO NEARBY GALAXIES					
deVaucouleurs & Peters[14]	299 ± 45	7.3	51°	167° ± 13°	25° ± 6°
Rubin et al.[7]	600 ± 125	2 ± 1	53° ± 11°	135°	-8°
Visvanathan & Sandage[8]	300 ± 25	21.2	48°	90°	0°
Yahil, Tammann and Sandage[9]	308	23.1	51	107 ± 4°	-8° ± 5°
Schecter[10]	346 ± 76	18	45°	72°	28°
MOTION OF SUN IN ORBIT AROUND MILKY-WAY GALAXY					
Rotation of Galaxy[8]	300 ± 50	21.2	48°	90°	0°
MOTION OF MILKY-WAY GALAXY RELATIVE TO COSMIC BLACKBODY					
This work and rotation of galaxy	603	10.4	-18°	261°	33°

In summary, we have observed anisotropy that varies as cosine $(\hat{\Theta}, \hat{n})$. Excluding this component, the cosmic blackbody radiation is isotropic to one part in 3000. The cosine component is most readily interpreted as due to the motion of the earth with respect to the radiation with a velocity of 390 ± 60 km/sec (the "new Aether Drift"), but we cannot eliminate the possibility that some of the anisotropy is due to an intrinsic variation of the cosmic blackbody radiation itself.

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REFERENCES AND FOOTNOTES

1. P.J.E. Peebles, "Physical Cosmology" (Princeton: Princeton University Press 1971); S. Weinberg, "Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity" (John Wiley and Son, Inc., N.Y. 1972).

2. Both E.K. Conklin [Nature 222, 971 (1969)] and P. Henry [Nature 231, 516 (1971)] claimed to observe a first-order harmonic. However in both experiments backgrounds were much larger than the observed effect, and the resulting fits were very poor. [See A. Webster, Mon. Not. R. Astr. Soc. 166, 355 (1974)]. In both experiments the one-standard-deviation errors in the direction of the earth's velocity cover a large part of the sky. (Conklin quotes probable errors, not standard-deviations.).

3. B.E. Corey and D.T. Wilkinson, Bulletin of the AAS 8, 351 (1976).

4. G.F. Smoot, invited talk, APS Conference, 28 April 1977, Washington D.C.

5. G.F. Smoot, M.V. Gorenstein, R.A. Muller, J.A. Tyson, submitted to the Reviews of Scientific Instruments.

6. The reported errors in the preliminary results of Corey and Wilkinson (Ref. 3) at 19 GHz were statistical only. Newer results (300 ± 70 km/sec, 12 ± 2 hrs, -10° ± 20°) from their group (D. Wilkinson, private communication) are in closer agreement with our results.

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FIGURE CAPTIONS

1. Schematic view of the apparatus mounted in the upper hatch of the U-2 aircraft. The anisotropy reported in this paper was detected with the 33 GHz radiometer; the 54 GHz radiometer monitored the oxygen anisotropy above the aircraft.

2. Sky coverage for the eight flights is indicated by the shaded regions. Each oval region consists of several "legs" from the same flight. The width of each region was determined from the antenna pattern (7° FWHM), and the length was set by the motion of the U-2 and the rotation of the earth.

3. Comparison of the data with the fit to Eq. 1. The temperature difference $\Delta T = T(\hat{\Theta}_1) - T(\hat{\Theta}_2)$ is plotted versus the angle between the vectors $(\hat{\Theta}_1 - \hat{\Theta}_2)$ and $\hat{n}$ = (10.8 hr R.A.; 5° dec.) the direction of maximum temperature. Data from legs at nearly equal angles were combined; each data point plotted represents ~2 hrs of data. The large dots represents the uncorrected data; the horizontal bars show the data with expected systematic effects subtracted out. The errors shown are statistical only.

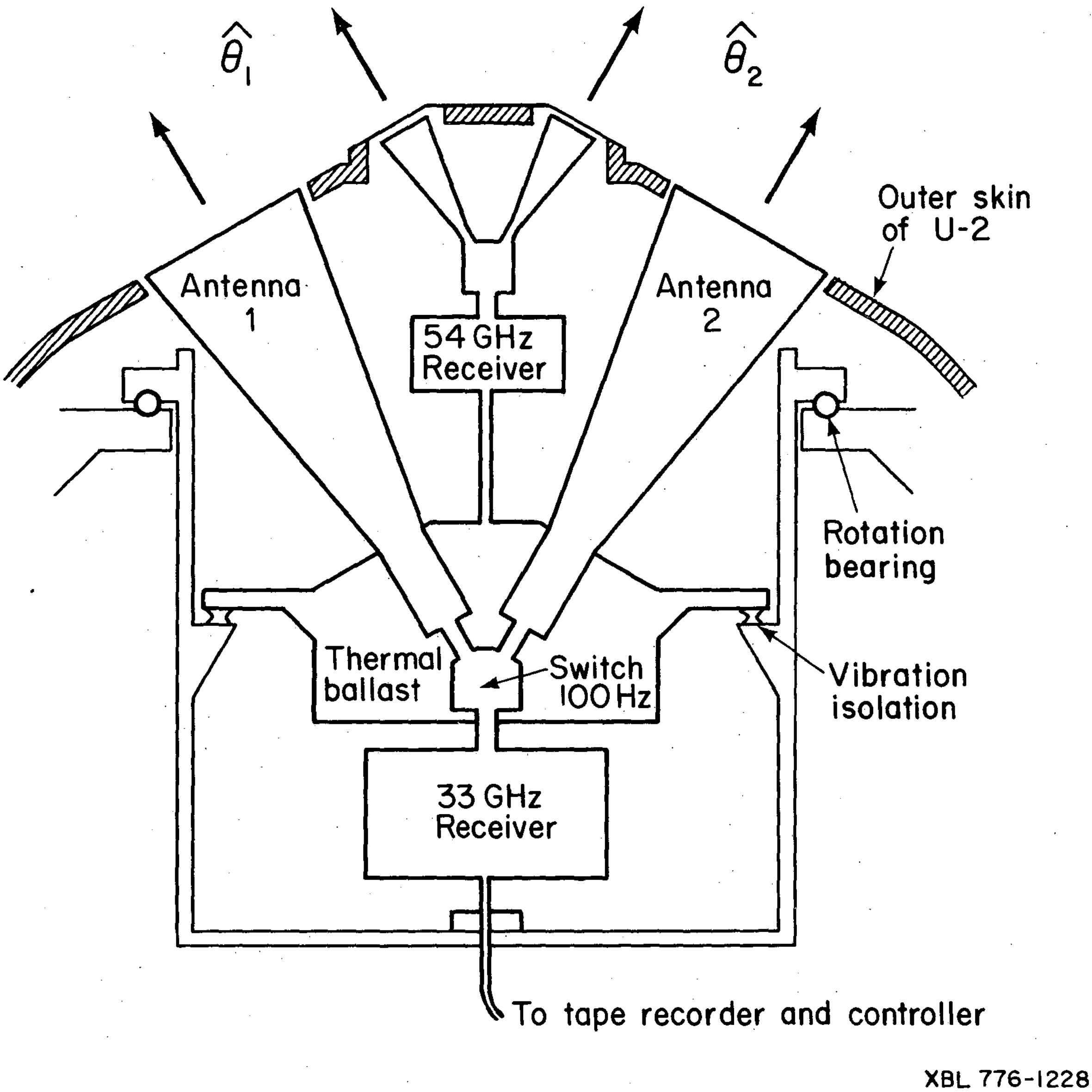

$\hat{\theta}_1$
$\hat{\theta}_2$
Outer skin of U-2
Antenna 1
Antenna 2
54 GHz Receiver
Rotation bearing
Thermal ballast
Switch 100 Hz
Vibration isolation
33 GHz Receiver
To tape recorder and controller
XBL 776-1228

Fig. 1

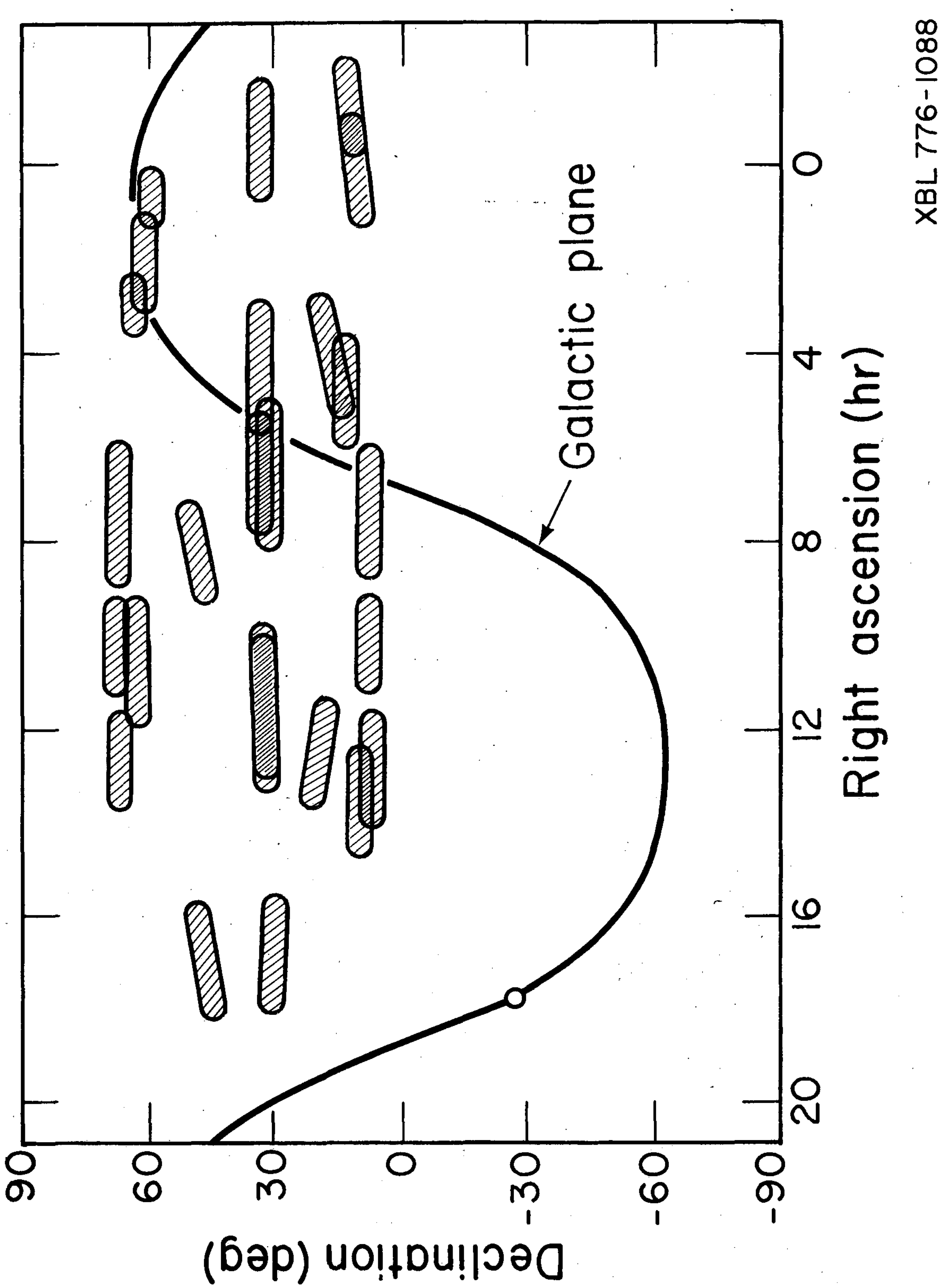
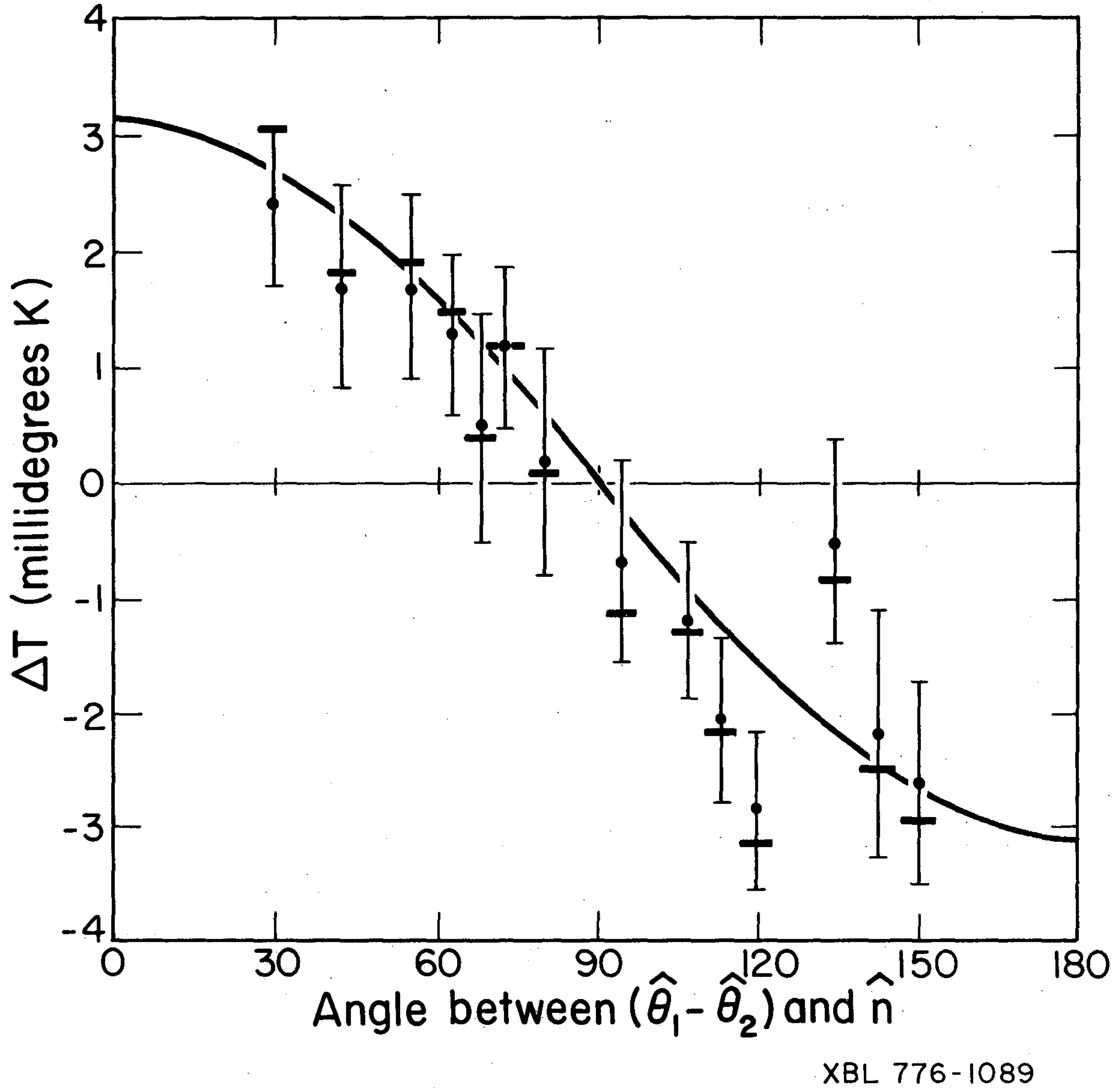

Galactic plane
Declination (deg)
90
60
30
0
-30
-60
-90
Right ascension (hr)
20
16
12
8
4
0
XBL 776-1088

Fig. 2



ΔT (millidegrees K)
4
3
2
1
0
-1
-2
-3
-4
0
30
60
90
120
150
180
Angle between $(\hat{\theta}_1 - \hat{\theta}_2)$ and $\hat{n}$
XBL 776-1089

Fig. 3

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