Detection of Anisotropy in the Cosmic Blackbody Radiation

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We have detected anisotropy in the cosmic blackbody radiation with a 33-GHz (0.9 cm) twin-antenna Dicke radiometer flown to an altitude of 20 km aboard a U-2 aircraft. In data distributed over two-thirds of the northern hemisphere, we observe an anisotropy which is well fitted 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 h right ascension (R.A.) and 6° ± 10° declination (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}–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 nonsymmetric 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 Wilkenson[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 eight flights aboard the NASA-Ames Earth Survey (U-2) Aircraft. Anisotropy in the cosmic radiation was detected at 33 GHz 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 best receiver, used on the final four flights, has a sensitivity limited by thermal noise with an rms fluctuation of 0.044°K/Hz$^{1/2}$. The receivers used on the earlier flights had rms fluctuations about twice as large. The apparatus is shown schematically in Fig. 1; details of its design and construction will be given elsewhere.[5]

Effort was made in the design of the apparatus to reduce all expected systematic errors well below the millikelvin level. To achieve the desired sensitivity, the apparatus was radio-frequency and magnetically shielded, and carefully thermally stabilized.[5] The antennas were specially designed (dual-mode corrugated cones) with a beam pattern 7° wide full width at half-maximum (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

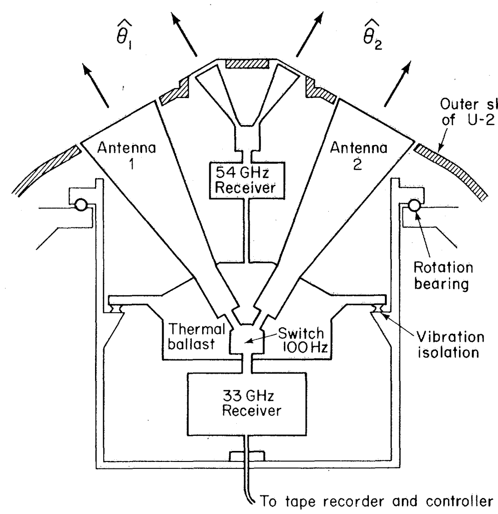

FIG. 1. Schematic view of the apparatus mounted in the U-2 aircraft. The anisotropy reported in this Letter was detected with the 33-GHz radiometer; the 54-GHz radiometer monitored the oxygen anisotropy above the aircraft.

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 sec. 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 min.

The data reported here were taken on eight flights between December 1976 and May 1977. Each flight yielded about 3.5 h of data taken at altitude; Fig. 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%.

Before the data were analyzed for astrophysical content, the signals recorded during aircraft banks, equipment rotation, moon-looking legs, and other "contaminated" data were eliminated. The "contaminated" data consisted of a total of of 6 min when the roll monitor indicated a bank angle of more than 1° or when the rms fluctuations in the 33-GHz signal were abnormally high. The remaining 21 h of observations were fitted by a least-squares method to a sum of spherical harmonics. Only the first spherical harmonic is necessary to obtain a good fit ($\chi^2 = 91$ for 80 data points). Thus the temperature in the direction $\hat{\theta}$ is given by

$$T(\hat{\theta}) = T_0 + T_1 \cos(\hat{\theta}, \hat{n}). \quad (1)$$

Here T_0 is the average blackbody temperature (not measured in this experiment), T_1 and $\hat{n}$ 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 $T_1 = 3.2 \pm 0.6$ m°K and $\hat{n} = [10.8 \pm 0.5$ h right ascension (R.A.), $5 \pm 10°$ declination (dec)]. In galactic coordinates $\hat{n} = (54° \pm 10°$ 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 1 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 side lobes, 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 $\hat{n} = (11.0 \pm 0.5$ h R.A., $6° \pm 10°$ dec).

The data, with and without corrections, are plotted in Fig. 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* $\cos(\hat{\theta}, \hat{n})$, the cosmic blackbody radiation is isotropic to 1 part in 3000.

The cosine anisotropy is most readily interpreted as being 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_0 and the fit to the corrected data, we calculate that the earth is moving at a velocity of $v = (T_1/T_0)c = 390 \pm 60$ 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 Rubin *et al.*[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

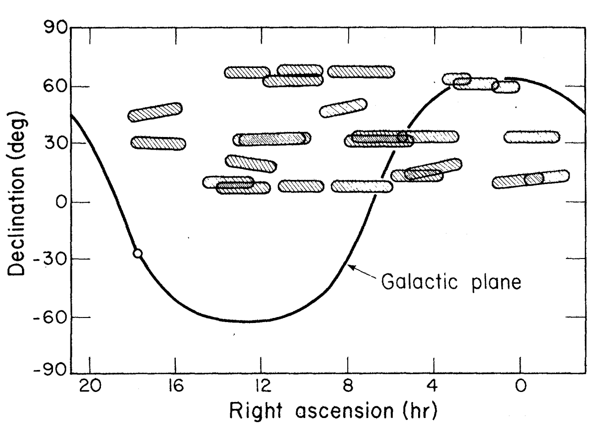

FIG. 2. Sky coverage for the eight flights is indicated by the shaded regions. Each oval region consists of several "legs" from the same flight. The width of each region was determined from the antenna pattern (7° FWHM), and the length was set by the motion of the U-2 and the rotation of the earth.

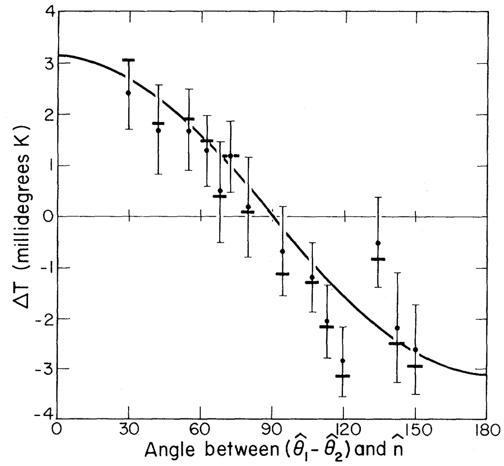

FIG. 3. Comparison of the data with the fit to Eq. (1). The temperature difference $\Delta T = T(\hat{\theta}_1) - T(\hat{\theta}_2)$ is plotted versus the angel between the vectors $(\hat{\theta}_1 - \hat{\theta}_2)$ and $\hat{n}$ $= 10.8$ h R.A., 5° dec, the direction of maximum temperature. Data from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

the net motion of the Milky Way with respect to the canonical reference frame of cosmology to be ~ 600 km/sec in the direction (10.4 h R.A., $-18°$ dec). 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. Collins and Hawking have shown[13] 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 which one can place on this rotation depends strongly on the model of the universe that is assumed. Using a semiclassical 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[14]:

$$T_2 = \frac{T_0 \omega_0^2 (1+z)^4}{8 H_2^0 (1+2q_0 z)}, \tag{2}$$

where ω is the present value for the angular velocity of the universe. If we take $H_0^{-1} = 2\times 10^{10}$ yr for the present value of Hubble's constant, $q_0 = 0.03$ for the deceleration parameter, $T_0 = 2.7$°K for the present temperature of the radiation, $z = 1500$, and $T_2 \leq 10^{-3}$ °K, we calculate that the rotation of the universe is presently less than 10^{-9} sec 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,[15] we conclude that the mass

TABLE I. Peculiar velocities (km/sec).

Reference	V (km/sec)	R.A. (h)	dec	Galactic (long.) l	Galactic (lat.) b
Motion of sun relative to cosmic blackbody radiation					
3	270 ± 70	13 ± 2	− 25° ± 20°	306°	38°
This work	390 ± 60	11 ± 0.6	6° ± 10°	248°	56°
10	≲ 350				
Motion of sun relative to nearby galaxies					
11	299 ± 45	7.3	51°	167° ± 13°	25° ± 6°
7	600 ± 125	2 ± 1	53° ± 11°	135°	− 8°
8	300 ± 25	21.2	48°	90°	0°
9	308	23.1	51°	105° ± 4°	− 7° ± 5°
12	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°

density of such radiation in the universe is $\lesssim \rho_c$, where ρ_c is the critical mass density necessary to close the universe.

In summary, we have observed anisotropy that varies as $\cos(\hat{\theta}, \hat{n})$. Excluding this component, the cosmic blackbody radiation is isotropic to 1 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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