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Final Report
for

"AETHER DRIFT" AND THE ISOTROPY OF THE UNIVERSE

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1 October 1977 - 30 September 1978

Principal Investigator

Richard A. Muller

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Marc V. Gorenstein
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February 23, 1979

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FINAL TECHNICAL REPORT
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"AETHER DRIFT" AND THE ISOTROPY OF THE UNIVERSE:
A measurement of anisotropies in the primordial black-body radiation

ABSTRACT:

This experiment has detected and mapped large-angular-scale anisotropies in the 3°K primordial black-body radiation with a sensitivity of 2×10^{-4} $^{\circ}$K and an angular resolution of about 10°. It has measured the motion of the Earth with respect to the distant matter of the Universe ("Aether Drift"), and has probed the homogeneity and isotropy of the Universe (the "Cosmological Principle"). The experiment uses two Dicke radiometers, one at 33 GHz to detect the cosmic anisotropy, and one at 54 GHz to detect anisotropies in the residual oxygen above the detectors. The system has been installed in the NASA-Ames Earth Survey Aircraft (U-2), and has operated successfully in a series of flights. Data taking and analysis to measure the anisotropy have been successful. We will continue these measurements and data analysis in the future, with additional coverage in a portion of the northern hemisphere not yet covered adequately and in the southern hemisphere which is completely unexplored.

CONTENTS:

I. Introduction

The Earth is bathed in an apparently universal $3^{\circ}K$ microwave radiation from space. Its existence is the strongest evidence we have in support of the Big Bang theory of the Universe, and its observed isotropy to one part in 10^{3} is the strongest evidence we have in support of the Cosmological Principle (the speculation that the Universe is isotropic and homogeneous on a large scale). Anisotropies are expected at the level of one part in a thousand or smaller. We have designed, constructed, and flown a radiometer system to detect and map these small anisotropies with a sensitivity of 2×10^{-4} °K. We have detected a first order spherical anisotropy of about 3 m° K which is interpreted as the motion of the Earth and solar system at 350 km/sec relative to the black body radiation. The PRL reprint in Appendix I describes a determination of this "Aether Drift" effect. Study of the anisotropies observable with this sensitivity will provide a unique probe of the nature of the Universe.

The experiment uses two twin-antenna Dicke radiometers, flown to an altitude of 65,000 feet in a modified upper hatch of the NASA-Ames Earth Survey Aircraft (U-2). The cosmic anisotropy is measured with a 33 GHz (1cm) radiometer, whose frequency is in the window between galactic synchrotron emission and atmospheric oxygen emission. Background anisotropies from oxygen and residual tilt to the aircraft are measured by a 54 GHz radiometer. Each radiometer has two horn antennas, pointing in opposite azimuthal directions but 30° from the zenith (see figure 1). The receiver is switched between the two antennas at 100 Hz in order to make a comparison between the two regions of the sky. This fast switching eliminates 1/f noise due to amplifier drift. The two antennas are physically interchanged every minute in order to cancel any residual anisotropies between the antennas. Every twenty minutes the airplane reverses direction, to detect and cancel anisotropies due to the aircraft. And, for the "Aether Drift" measurement, the Earth changes its direction of revolution around the sun every six months, a reversal shift that our instrument may be sensitive enough to detect.

II. Theory of the $3^{\circ}K$ radiation and expected anisotropies

In 1965, Penzias and Wilson found an unexpectedly large background in their 7 cm microwave receiver. Many workers have since confirmed the existence of this background, covering a range in wavelength from several

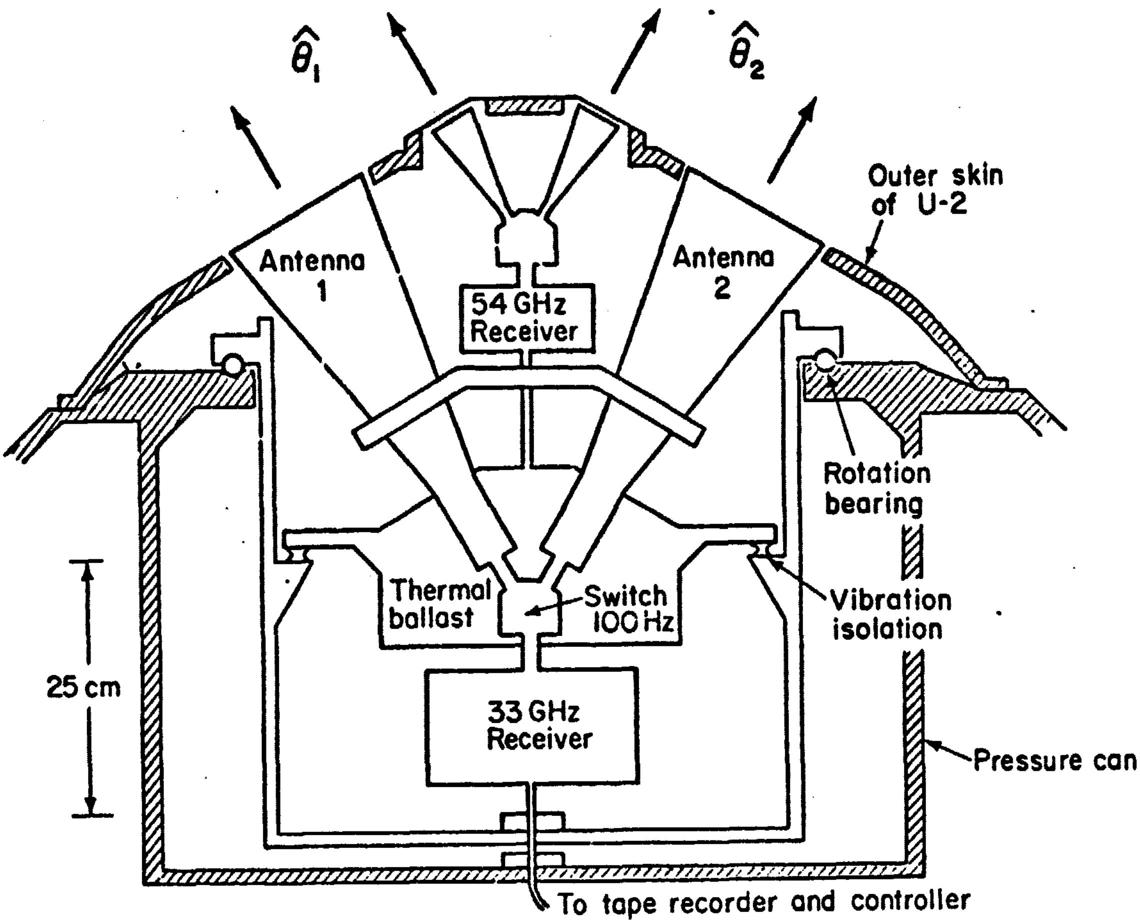

Figure 1. Schematic of Apparatus in U-2 Hatch.

millimeters to many centimeters. Figure 2 shows the measurements, together with a 2.7°K black-body Planck distribution. Also shown in the figure are intensities indirectly deduced from measurements of the absorption spectra of cyanogen molecules around nearby stars, covering short wavelengths absorbed by the Earth's atmosphere.

The best data in the millimeter region as of 1973 (Muehlner and Weiss, Phys. Rev. C, 7 (1973)) marked with the letter M, clearly shows the expected turnover. More recent measurements at Berkeley (D. Woody, J. Mather, N. Nishioka, P. Richards, Phys. Rev. Lett. 34, 1036 (1975)), shown in Figure 3, have verified this turnover in detail. The measurements are all consistent with a black-body shape for the radiation. A number of measurements have also been made of the directionality of this radiation. All experiments prior to ours have been consistent with a finding of no significant departure from isotropy greater than one tenth of one percent.

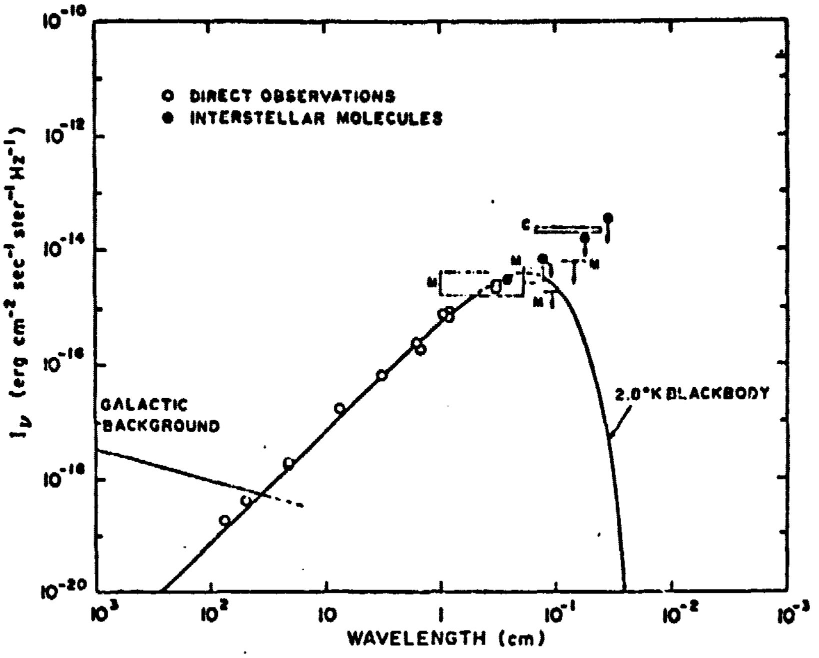

Figure 2. Measurement of the microwave background. (Taken from P. Thaddeus, Ann. Rev. Astron. and Astrophys. 10, 305 (1972)).

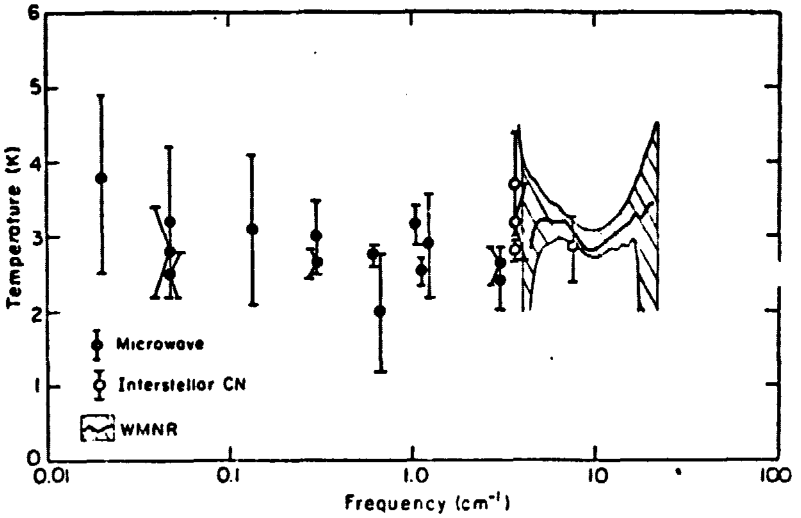

FIG. 3. The present measurement ($\pm 2\sigma$) of the thermodynamic temperature of the cosmic background radiation compared with selected results of other experiments. The data for frequencies ≤ 3 cm^{-1} were obtained using ground-based microwave radiometers (see Ref. 1). The data at 3.8 and 7.6 cm^{-1} were obtained from optical measurements of cyanogen (see Refs. 2 and 12).

(Taken from Woody, et al.)

Most cosmologists take this radiation to be a relic from past epochs when our universe was much hotter and denser than it is now. Indeed, the presence of the black-body radiation provides the strongest evidence to date for such a "Big Bang" origin of the Universe. In these early epochs the high temperature and densities kept almost all matter in an ionized state. Free electrons provided the thermal coupling between radiation and matter. When the expanding Universe had cooled to approximately 4000 °K, these electrons became bound into atoms. At this point the radiation decoupled from the matter, and the Universe became essentially transparent to the thermal radiation. The expansion of the Universe has red-shifted the radiation down to its present-day termperature of 2.7 °K without altering its black-body shape.

The black-body radiation we observe now was originally emitted from a sphere of matter whose present radius is 2×10^{10} light years. Unless neutrino astronomy becomes practical, these black-body photons provide our deepest probe into the past history of our Universe. At the time the radiation decoupled from matter, atoms and molecules were just beginning to form. Condensation into stars and galaxies had presumably not yet begun. The isotropy of the black-body radiation is the strongest experimental evidence that the early Universe was isotropic and homogeneous when viewed on a large scale (the "Cosmological Principle").

The angular size of any anisotropy in the black-body radiation is characteristic of the mechanism which generated it. Motion of the Earth relative to the "rest frame" defined billions of years ago by the last-scattering of the black-body photons is one mechanism that could produce an anisotropy. This modern "Aether Drift" experiment measures the vector sum of all the various motions of the Earth listed in Table I. According to Special Relativity (Peebles and Wilkinson, Phys. Rev. <u>174</u>, 2168 (1968)), motion of an observer relative to the uniform black-body radiation leaves the spectral shape of the radiation the same, but alters the observed black-body temperature to

$$T(\theta) = \frac{T_o\sqrt{1 - \beta^2}}{1 - \beta\cos\theta} \simeq T_o\,(1 + \beta\cos\theta)$$

where $T_o = 2.7$ °K, β is the velocity of the observer relative to the black-body rest frame, and θ is the angle between the observer's viewing direction and β. It is clear from Table I that Earth rotation is negligible and that motion of the solar system in the galaxy dominates. Small as it is, the annual orbit of the Earth around the sun should be separately detectable by our experiment by taking data throughout a year, thus providing an extremely powerful cross-check of the entire procedure. At present our best limit gives $V_\oplus = 2 \pm 40$ km/sec. Since we have detected an anisotropy, our flight plans have been designed to look roughly perpendicular to the Earth's rotation around the sun. If the flight plans had been optimised to measure the Earth's annual velocity, the error would be reduced by approximately a factor of two.

TABLE I: MOTIONS OF THE EARTH RELATIVE TO "REST" FRAME

	Source of Motion	Expected Velocity(a) (km/sec)	Anisotropy (°K)
1.	Earth Rotation	.46	0.1×10^{-4}
2.	Orbit around Sun	29.8	5.3×10^{-4}
3.	Solar System in Galaxy	270 ± 40	$(49 \pm 7) \times 10^{-4}$
4.	Galaxy around Local Group	80 ± 20	$(14 \pm 4) \times 10^{-4}$
5.	Total Solar System around Local Group	315 ± 15	$(57 \pm 3) \times 10^{-4}$
6.	Motion of Sun relative to Black-Body	350 ± 50	$(63 \pm 5) \times 10^{-4}$ (measured)
7.	Local Cluster relative to Black-Body	600	120×10^{-4} (inferred)

(a) Our source for velocities 3 to 5 is D. W. Sciama, "Astrophysical Cosmology," pages 183-236, Proceedings of the Enrico Fermi International School of Physics, Course XLVII, Academic Press, New York, 1971.

(b) Calculated according to the formula $\Delta T = T_{max} - T_{min} = 2T_o\beta$ where β = velocity/veocity of light and $T_o = 2.7°K$.
This formula gives the peak-to-peak amplitude of the anisotropy.
This experiment can measure a maximum amplitude of $\Delta T_A = T_o\beta \times 0.97$.

Other features of the Universe which generate anisotropy in the black body radiation yield more complicated angular dependencies. For example, consider the possible rotation of the Universe as a whole. If the Universe rotates with an angular velocity ω, then objects a distance R from us, and at an angle θ to the axis of rotation, will have a velocity $v_\theta = \omega R \sin\theta$, which, when added to its Hubble recessional velocity, yields a second order Doppler shift (due to time dilation) that depends on θ. The variation should be axially symmetric, and its first order term (proportional to $\cos(2\theta)$) would be easily distinguishable from the Aether Drift. It would be cool in the plane of rotation and warm at the two poles of the axis. A detailed analysis by Collins and Hawking (Monthly Notices of the Royal Astronomical Society, 162, 307 (1973)) shows that if the Universe rotated at a rate of once per 10^{14} years, an anisotropy of 10×10^{-4} °K would result.

Detection of an overall rotation of the Universe would be of great philosphical and cosmological importance. According to Mach's Principle, the existence of local frames is caused by the mass of the distant galaxies, implying that the apparent rotation of the universe is zero. A discovery of non-zero rotation (which is allowed by General Relativity) would cast the entire Machian philosophy of matter and space-time into doubt.

Inhomogeneities in the matter distribution or in the expansion of the Universe should likewise lead to an anisotropy of the black body radiation. Although these might in principle give a second spherical harmonic (quadrupole) term which could be confused with rotation, it is likely that they would also yield higher order terms. If the Universe is closed or nearly closed one could expect the dominant portion of a shear anisotropy to be quadrupole; if the universe is open it would be mostly of higher order. Most cosmologists believe that an experiment an order of magnitude more sensitive than previous experiments is bound to detect such an inhomogeneity. Such inhomogeneities have been related, in certain theories, to the existence of the observed super-clusters of galaxies.

In some of these theories the Universe was initially completely inhomogeneous. The approximate homogeneity we now observe came about by the transport of energy and momentum that occurred early in the Big Bang. There are limits on the angular scale size of regions which could have been isotropized this way: a given region of space could not have received any homogenizing signal from further away than the distance light could travel between the time of the Big Bang and the time of the decoupling of radiation and matter.

Weinberg has calculated the angular size of isotropized regions in the sky which could have been generated this way ("Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity", Wiley, New York, 1972, page 525). He reports that isotropy larger than just a few degrees of angle in the sky requires a primordial homogeneity.* A good sky map, with the temperature of the black-body

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* For the case of an ionized intergalactic medium providing the mass to close the universe gravitationally, this size grows to perhaps 1/10 of the sky, since the uncoupling of matter and radiation then took place at a much later time.

radiation measured with fractional millidegree temperature accuracy in 15° angular bins might in fact show such residual anisotropies, thereby disclosing information about the size of the density homogeneity in the early universe, even before matter and radiation were uncoupled.

Most other sources of anisotropy should occur on angular scales too small for us to observe with this experiment (resolution of about 10°), but might conceivably occur on scales larger than expected. Such small-scale anisotropies could be due to inhomogeneities in the promordial plasma, or nascent galaxies, or they might be the first indication of discrete sources. Such emission anisotropies would appear as bright spots in the sky. Dark spots could also occur due to absorption of some black-body radiation by large objects along the line of sight. A high density of energetic electrons in galactic clusters might attenuate the black-body radiation, by scattering it to higher frequencies. Such a cloud of electrons and their associated protons could help provide the mass needed for gravitational binding of galactic clusters.

The following table summarizes the possible causes of an inhomogeneity in the black-body radiation, and states the features of its angular distribution which would help distinguish it.

TABLE II: SOURCES OF ANISOTROPY AND THEIR ANGULAR DISTRIBUTIONS

Aether Drift - motion around sun	0.3 m^oK $\cos\theta$, direction varies during a year
Aether Drift - motion of sun around galaxy and galaxy relative to relic radiation	3.2 m^oK $\cos\theta$
Spin of Universe	cos (2θ), although higher order terms possible
Anisotropic Expansion of Universe	cos (2θ), although higher order terms possible
Primordial Inhomogeneities	cos (nθ), n probably large
Other Inhomogeneities	correlated position in sky with suspected source

III. Experiment Status and Results

The instrument hardware now exists and has already been used to take data. Appendix II (preprint of RSI article) describes the apparatus, tests, and calibrations. Appendix I, a reprint of the PRL article, contains the first results of the data analysis. The highlight of these results was the detection of an anisotropy best described by a first order spherical harmonic (dipole). The dipole component is about 3 m°K while any quadrupole and higher order component is less than 1 m°K. Figure 4 shows the fit of the data to a first order spherical harmonic. A quadrupole term alone gives a significantly worse fit to the data than a dipole alone. A combined dipole and quadrupole fit does not give a significantly better fit. Figure 5 shows the sky coverage to date.

This first order anisotropy is most readily interpreted as being due to the motion of the solar system relative to the cosmic black-body radiation. The relative motion produces a Doppler shift of the observed radiation. An anisotropy of magnitude 3 m°K corresponds to a solar peculiar velocity of about 350 km/sec. This velocity is comparable to the motion of the solar system around the galaxy. However, its direction is not consistent with that given by the rotation of the galaxy. In fact, when the rotation of the galaxy is taken into account, this measurement implies a galactic peculiar velocity of about 600 km/sec relative to the cosmic black-body radiation. This is a disturbingly large velocity. In addition this velocity disagrees with that found by several astronomers looking at the motion of the sun with respect to nearby sets of galaxies. Our results, however, are in agreement with the anisotropy in the background radiation measured by Corey and Wilkinson at Princeton. (See Figure 6).

The apparent fact that the measurements of the background radiation agree with each other but are not consistent with the astronomers' findings raises the question of whether the anisotropy is produced by the solar peculiar velocity of is intrinsic to the black-body radiation itself. Only two homogeneous models of the Universe produce dipole anisotropies in the background radiation.

One model (discussed by Collins and Hawking, MNRAS 162), involving a closed universe, allows all the matter in the Universe to have a net peculiar velocity relative to the comoving expansion frame of reference.

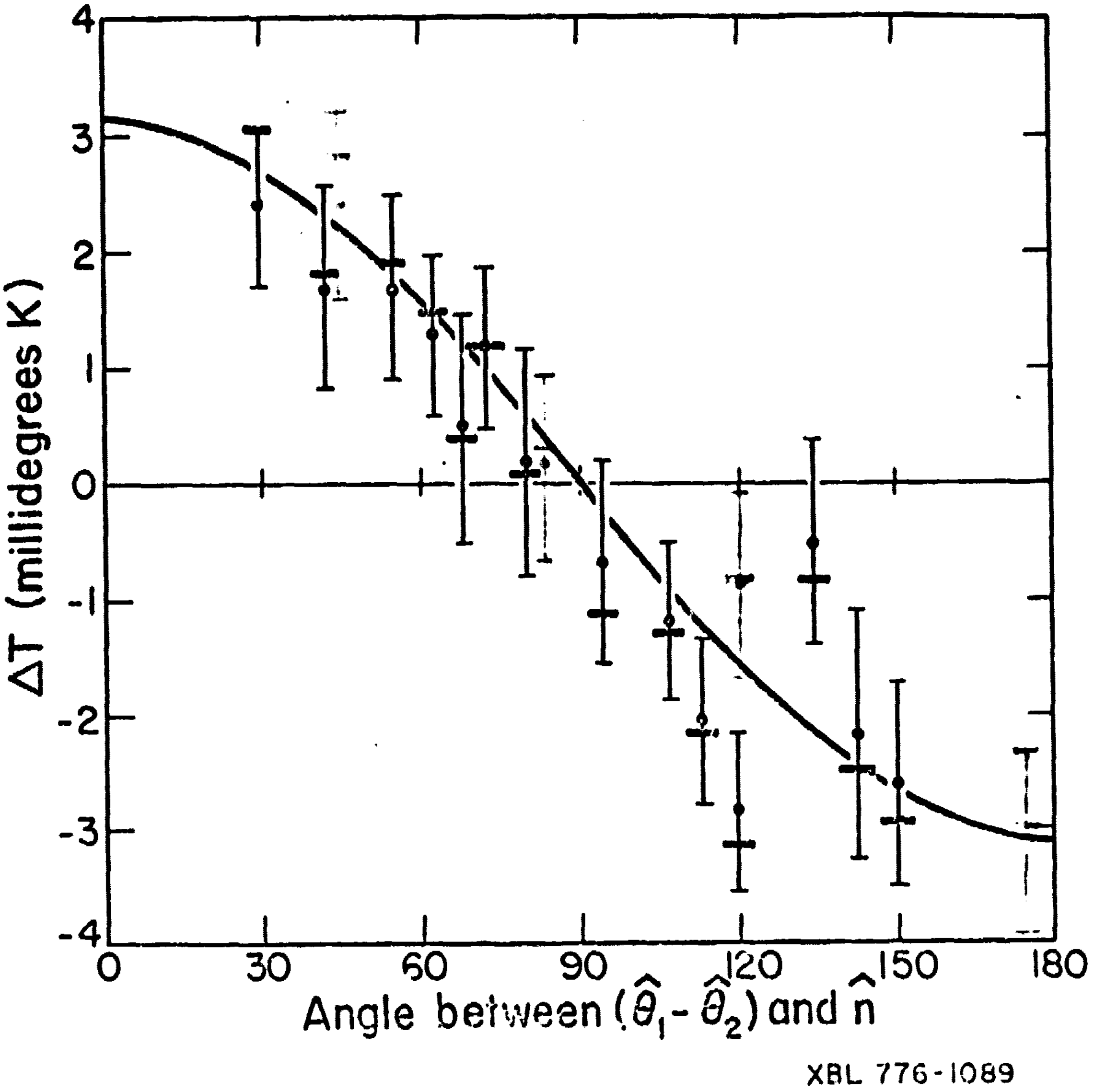

Figure 4

Fit to First Order Spherical Harmonic

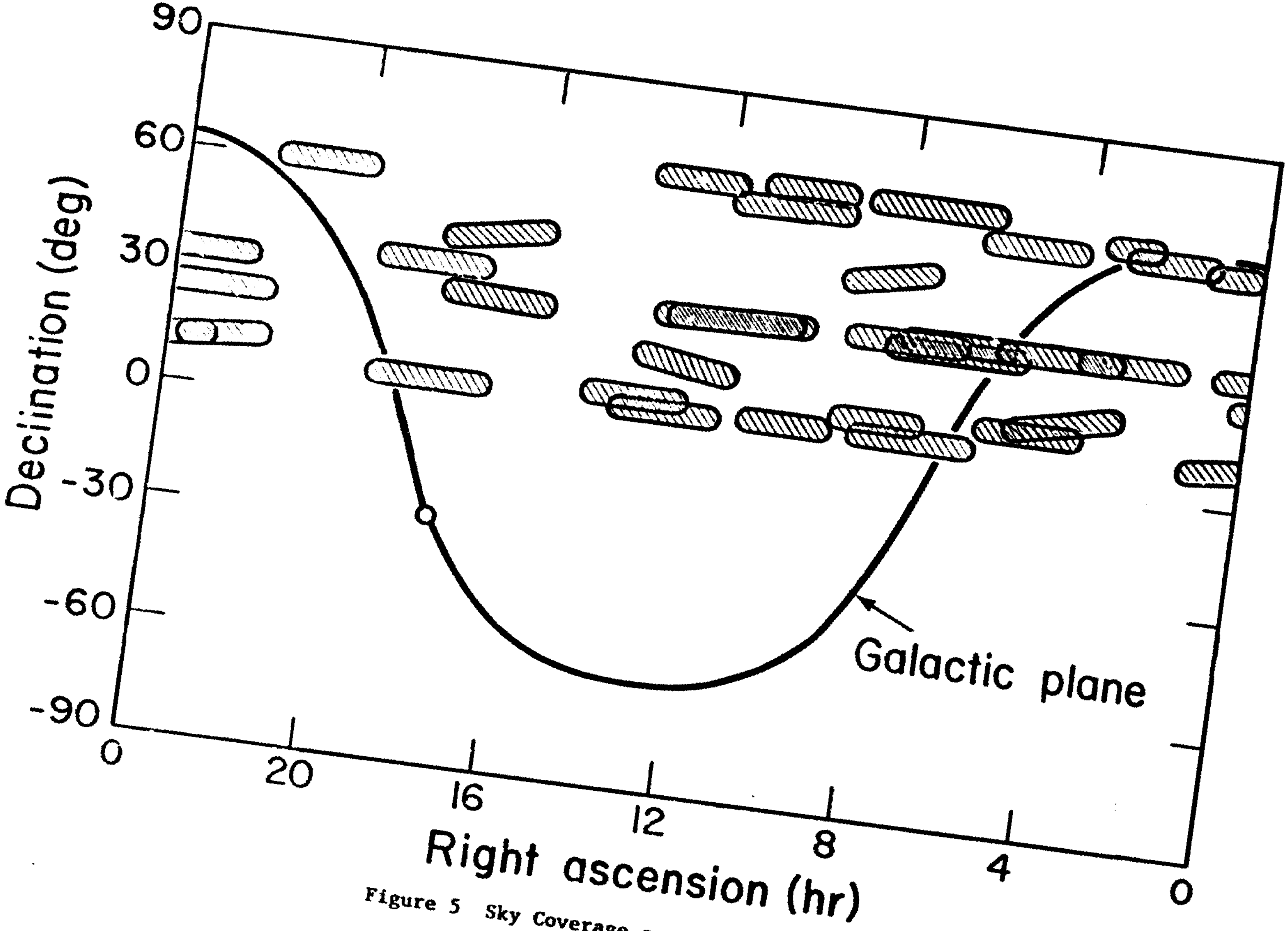

Figure 5 Sky Coverage as of March 1978

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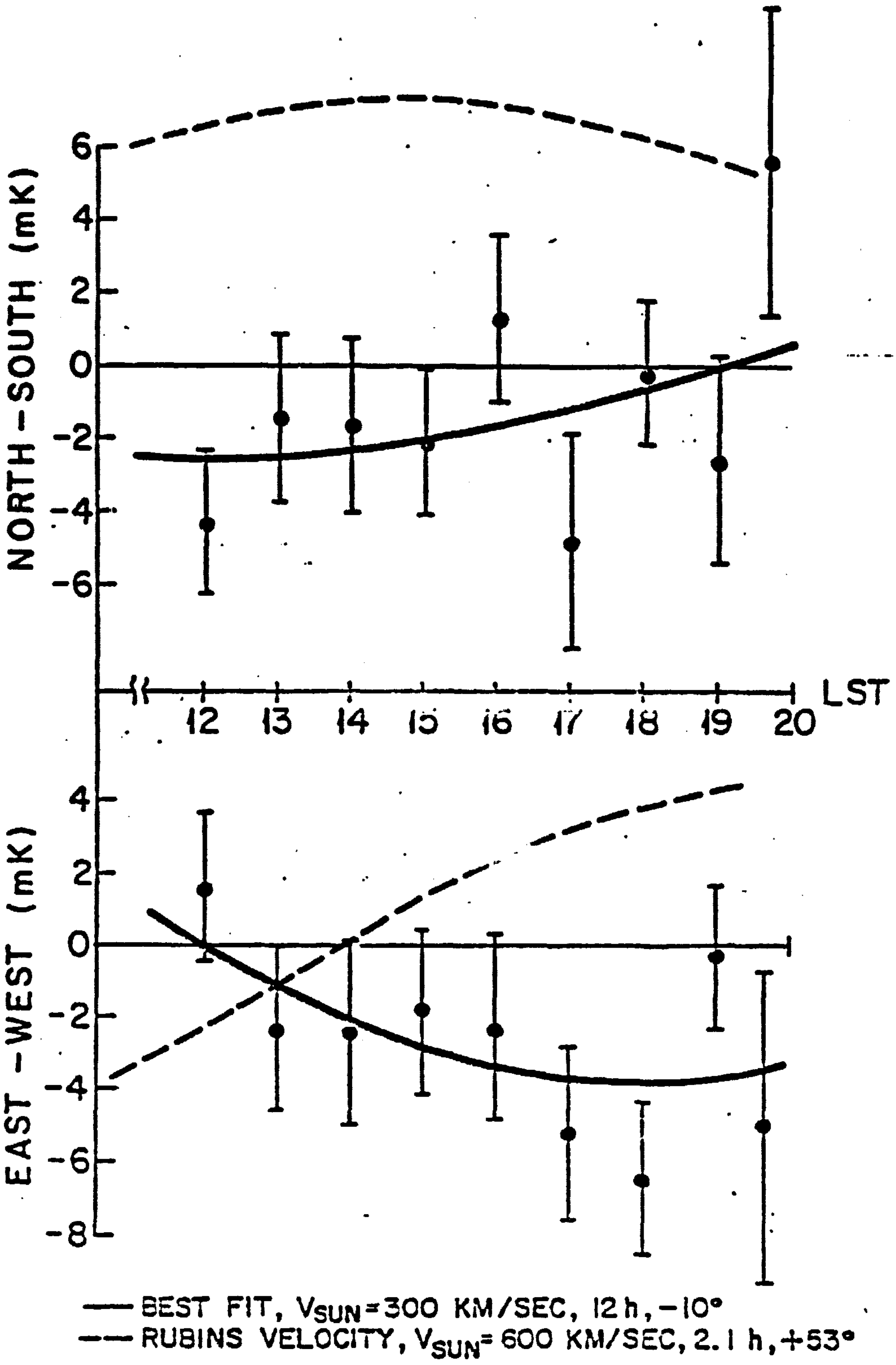

Figure 6. Balloon measurements of background isotropy at 19 GHz by Corey and Wilkinson.

In this case, we have measured that peculiar velocity to be about 600 km/sec at the time of last scattering. This velocity could presently be between about 1 and 80 km/sec depending upon the time of last scattering. This model is not particularly pleasing insofar as it postulates that all the matter in the Universe had a peculiar velocity near the speed of light shortly after the Big Bang, which damped down to 600 km/sec at the last scattering, and then down to a few km/sec at the present.

The other model is discussed by Doroshkevich, Lukash, and Novikov (Sov. Astron., Vol. 18 No. 5). An open universe which expands at a different rate along one axis than the other two will have an intrinsic quadrupole anisotropy. If the Universe is open, its changing hyperbolic geometry distorts the appearance of the quadrupole anisotropy into a roughly dipole character over a large fraction of the sky. The bulk of the quadrupole anisotropy would be squeezed into a relatively small portion of the sky. The characteristic angular size of the distorted region would be about 23° if the density of the Universe is 10% of the critical density. For our measured anisotropy, we predict this section of the sky would be roughly centered on RA = 11 hrs, and $\delta = -20°$. Measurements in the region should distinguish this distortion from a true dipole.

The present data is well fit by a dipole anisotropy and has symmetrical errors. Table III below gives correlation matrix* and the data and errors vectors.

TABLE III: CORRELATION MATRIX AND SIGNAL AND ERROR VECTORS

	Correlation Matrix					
Direction	$\hat{X}$	$\hat{Y}$	$\hat{Z}$	Signal	± Error	(m°K)
$\hat{X}$ = 0 hrs	1.00	-0.08	-0.41	$\Delta T_x = -3.07$	0.31	
$\hat{Y}$ = 6 hrs	-0.08	1.00	0.08	$\Delta T_y = 0.68$	0.32	
$\hat{Z}$ = 90° dec	-0.41	0.08	1.00	$\Delta T_z = 0.43$	0.36	

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* The correlation matrix is a measure of how independently each component is measured.

There is a correlation (-0.41) between the X and Z (polar) axis components because our present sky coverage is not uniform - most of the coverage is between 3 and 15 hours of right ascension and for the first flights the equipment had about twice its eventual noise, thus less effective coverage by the data from 22 to 3 hours of right ascension. Without this correlation the errors would be 0.28, 0.32, and 0.31 m°K respectively. The polar component has a larger error even with nearly twice the observing time of the other two components because all flights have been in the northern hemisphere and from Ames; no more than about 60° in declination has been covered, while the full right ascension has been swept out. This effect is even more pronounced in a combined dipole and quadrupole fit. For the combined fit the errors are substantially enlarged, being 0.51, 0.50, 40.3 m°K for the dipole. The larger error in the polar dipole and quadrupole components is due to a correlation in their errors. Over the range from 6° to 66° in declination it is difficult to tell the difference between $\sin\theta$ and $\sin^2\theta$. This coupled with the correlation of sky coverage in declination and right ascention, results in a strong correlation between the polar dipole component and the quadrupole components. Linear combinations of these give the same anisotropy to about 0.5 m°K over the regions we have measured, but grossly different results for regions far from where we have measured. For example, one or two flights from Argentina, Australia or any other place at roughly the same latitude would reduce the errors to 0.34, 0.46, 0.56 m°K and 0.32, 0.38, 0.40 m°K respectively. Similarly all errors on the quadrupole would drop below 0.5 m°K. For a pair of flights from the Panama Canal Zone, from which the U-2 usually flies every year, errors for the polar dipole and all quadrupole components would be reduced to 1 m°K.

At this point the data can be used to measure and limit either the dipole or quadrupole alone; however, for a combined limit we must make a statistical argument, stating the probability that the dipole and quadrupole components would happen to cancel over the 1/3 of the sky currently measured. Using this reasoning, we have measured the dipole discussed above and set a limit on the amount of power in the quadrupole as no more than 1 m°K with a 70% probability. This limit on the quadrupole anisotropy provides stringent limits on any possible rotation of the universe, anisotropic Hubble expansion, or long wavelength gravity waves.

The actual value of the limit depends on cosmological parameters such as the ratio of the actual density to the critical density and the time of last scattering. Assuming the last scattering was at the time of decoupling, the present rate of anisotropic Hubble expansion is limited to less than one part in 10^5. The limit on density homogeneities for the part of the sky observed is about one part in a thousand, while the energy density of long wavelength gravity waves is limited to approximately the critical density. We have also tested the Cosmological Principle to one part in 3000, assuming that the anisotropy that we see is due to our peculiar velocity.

IV. FUTURE WORK TO BE PERFORMED

We will continue our work on the measurement and mapping of the anisotropies in the cosmic blackbody radiation, including data analysis, supporting ground measurements, additional flights from Ames and flights from a southern latitude.

We believe that a well chosen pair of flights from a single trip to the southern hemisphere will provide: (1) good verification of dipole anisotropy, (2) absolute and significantly improved limits on any quadrupole component, and (3) observations of a previously unexplored hemisphere. The four new data points (two from each flight) shown in figure 4 demonstrate how two flights could verify the cosine curve. With reasonable planning the two flights could be conducted within a couple of days of each other; one early and the other late at night. The discussion in the data analysis section describes how data from a southern latitude will decrease the errors and thus the limit on the quadrupole terms. Briefly, upon changing hemispheres: a dipole component will change sign while a quadrupole moment will keep the same sign; thus a single good measurement below the equator will readily distinguish between the two and will quickly limit the maximum possible value of either. These flights will take place in February and March 1979. We will be flying over Peru at a latitude of 33° south.

The observation of previously unexplored regions is probably the strongest motivation for a southern hemisphere flight. Data from the southern skies tests for departures from the dipole anisotropy and unusual new features. One possible reason that the optical astronomers have found a velocity different from our measurement is that there are many more intermediate distance galaxies in the northern hemisphere than in the southern. This is indicative of two things, a possible systematic bias and the fact that in the past the southern hemisphere has proven different from the northern.

We will continue the analysis of the existing data and conduct some related ground-based measurements. At present the data from a flight can be processed, have first order corrections (amounting to typically $\lesssim$ 0.5 m°K) applied, and then be fitted to dipole and quadrupole components. This stage of data analysis has progressed past the quick look level. We are now in the process of a more thorough and complete data analysis program. In this process we are doing the usual data handling cross-checking, and studying the statistical properties of the data, and the interpreting of the results. We are also evaluating the effects of possible systematic errors both through calculation and ground based measurements.

The absolute calibration of our system introduces the largest uncertainty to our results aside from statistics by a scale factor which could vary by about 7%. We plan to reduce this uncertainty by a more careful analysis of existing data and additional calibration of the equipment.

We estimate that the other systematic errors are $\lesssim$ 25% of our statistical errors. We are in the process of refining our estimates of systematic backgrounds. For example, we have recently measured the 33 GHz emissions from Orion A - a typical H-II region using a larger ground based antenna but with the same receiver system used in our flights. We are also re-estimating and cross-checking the galactic synchrotron emission and the other systematic errors.

Through this future work, we expect to understand our experiment to the point where we will have measured the dipole anisotropy to an accuracy of about 2×10^{-4} °K and have improved our limit on the quadrupole and higher order anisotropies a factor of two to one part in 6000. This will represent a very significant limit and strong test of the Cosmological Principle, and is about a factor of 6 improvement over other experiments.

Sensitivity of Apparatus

1) Measure of the Noise Equivalent Flux Density (NEFD) at the antenna input

$$\text{NEFD} = 3 \times 10^{4} \text{ flux units} / \sqrt{\text{Hz}}$$

The moon shows up at $T_A = 0.70 \pm 0.04$ °K for one second of observation.

2) A measure of the raw detector sensitivity as the Noise Equivalent Power (NEP) in the standard operating environment is

$$\text{NEP} = 2.5 \times 10^{-16} \text{ watts} / \sqrt{\text{Hz}}$$

Since the purpose of the experiment has been to measure the intensity of the cosmic background radiation, it is important to have a low NEP but a relatively high NEFD so that galactic backgrounds are minimized. In practice though, these are relatively unimportant; systematic errors are the main limitations. This apparatus is used to observe a signal which is roughly 1/40 of the rms noise.

Detection of Anisotropy in the Cosmic Blackbody Radiation

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(Received 6 July 1977)

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 $(3.5\pm0.6)\times10^{-3}$ °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 $0.044\,°\mathrm{K/Hz}^{1/2}$. 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

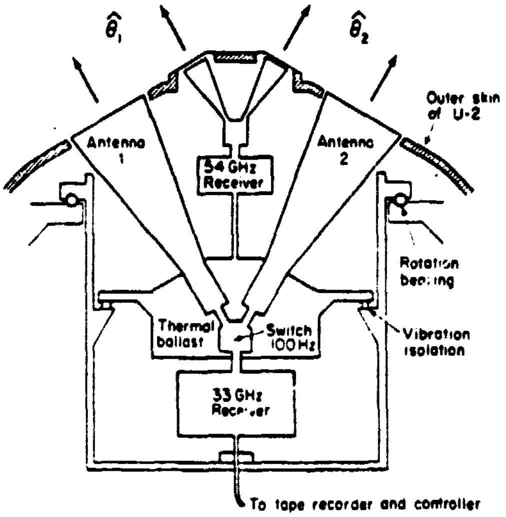

FIG. 1. Schematic view of the apparatus mounted in the U-2 aircraft. The anisotropy reported in this Letter was detected with the 33-GHz radiometer; the 54-GHz radiometer monitored the oxygen anisotropy above the aircraft.

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

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

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.).

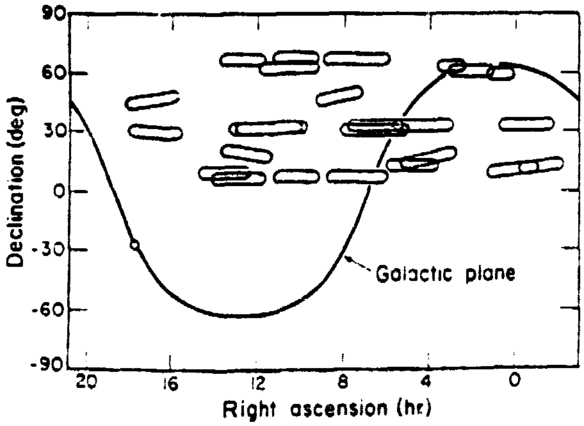

FIG. 2. Sky coverage for the eight flights is indicated by the shaded regions. Each oval region consists of several "legs" from the same flight. The width of each region was determined from the antenna pattern (7° FWHM), and the length was set by the motion of the U-2 and the rotation of the earth.

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 $\leq 10^{-3}$ °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

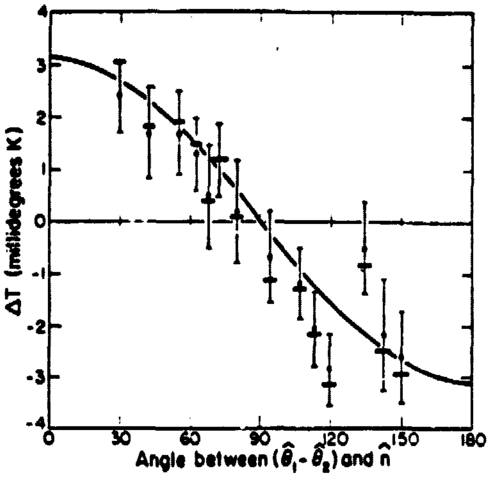

FIG. 3. Comparison of the data with the fit to Eq. (1). The temperature difference $\Delta T = T(\hat{\theta}_1) - T(\hat{\theta}_2)$ is plotted versus the angel between the vectors $(\hat{\theta}_1 - \hat{\theta}_2)$ and $\hat{n}$ $= 10.8$ h R.A., 5° dec, the direction of maximum temperature. Data from 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]:

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

where ω is the present value for the angular velocity of the universe. If we take $H_0^{-1} = 2\times10^{10}$ 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 $T_2 \leqslant 10^{-3}$ °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	(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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Radiometer system to map the cosmic background radiation

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We have developed a 33-GHz airborne radiometer system to map large angular scale variations in the temperature of the 3 K cosmic background radiation. A ferrite circulator switches a room-temperature mixer between two antennas pointing 60° apart in the sky. In 40 min of observing, the radiometer can measure the anisotropy of the microwave background with an accuracy of ±1 mK rms, or about 1 part in 3000 of 3 K. The apparatus is flown in a U-2 jet to 20 km altitude where 33-GHz thermal microwave emission from the atmosphere is at a low level. A second radiometer, tuned to 54 GHz near oxygen emission lines, monitors spurious signals from residual atmospheric radiation. The antennas, which have an extremely low side-lobe response of less than -65 dB past 60°, reject anisotropic radiation from the earth's surface. Periodic interchange of the antenna positions and reversal of the aircraft's flight direction cancel equipment-based imbalances. The system has been operated successfully in U-2 aircraft flown from NASA-Ames at Moffett Field, CA.

INTRODUCTION

We have developed and tested an airborne radiometer to detect and map anisotropy of the 3-K cosmic blackbody radiation on a large angular scale. This radiometer represents a state-of-the-art improvement of the basic twin-antenna Dicke radiometer used by several groups[1-4] to set previous limits on the anisotropy.

Anisotropy in the background radiation of a few millikelvins (mK) should result from the motion of the solar system with respect to the 3-K cosmic blackbody radiation.[5] In addition, the motion of the earth around the sun produces an annually varying anisotropy of 0.3 mK. Anisotropies would also be expected from asymmetric expansion of the universe, large scale irregularities in the distribution of matter or energy, or various other dynamical effects important in the evolution of the universe.

Our radiometric system is designed to detect anisotropic radiation in the cosmic background with a sensitivity of a few tenths of a millikelvin. The design incorporates several new features that reveal or cancel systematic effects. In this section we shall briefly describe the system operation. In the balance of the paper we expand on this description, detail the design criteria, and document the system's performance.

Two antennas that point 30° from the zenith and oppositely in azimuth collect the 33-GHz radiation (see Figs. 1–3). Thus the sky provides both the source and the reference for differential detection of anisotropy. The 33-GHz frequency is in a "window" where the sum of atmospheric and galactic microwave backgrounds is minimal. The antennas are dual-mode corrugated horns that reject side-lobe illumination from the direction of the earth by more than −65 dB and thereby reduce signals due to anisotropic terrestrial radiation below the 0.2 mK level.

A switching ferrite circulator, alternating between the antennas at 100 Hz, directs the radiation to a room-temperature mixer. Rapid switching between antennas reduces $1/f$ noise from the receiver. Two 1000-MHz bandwidth i.f. gain stages amplify the signal, and a lock-in amplifier analyzes the detected output for a component synchronous with the switching. Thus the radiometer detects *only* the difference in sky temperature, not its absolute intensity. The 33-GHz receiver rms sensitivity is 44 mK/Hz$^{1/2}$.

The equipment is carried on board a U-2 jet to 20 km altitude where atmospheric microwave emission is greatly reduced. Pointing the antennas at the same zenith angle cancels most of the remaining thermal emission from the residual atmosphere. Slight departures from level flight are the primary cause of the remaining imbalance in atmospheric radiation received by the antennas. A second radiometer, functionally identical to the primary 33-GHz radiometer measures these im-

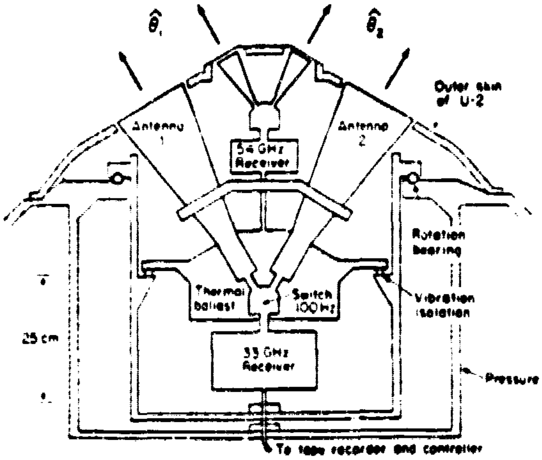

FIG. 1. Schematic layout of the radiometer apparatus in the U-2 equipment bay. The main electronics and mechanical components of the system are illustrated. The antennas are shown in the data taking position, with the direction of flight perpendicular to the plane of the drawing. Interchange of the antennas is accomplished by a periodic (once per 64 s) rotation of the equipment 180° about the vertical center-line.

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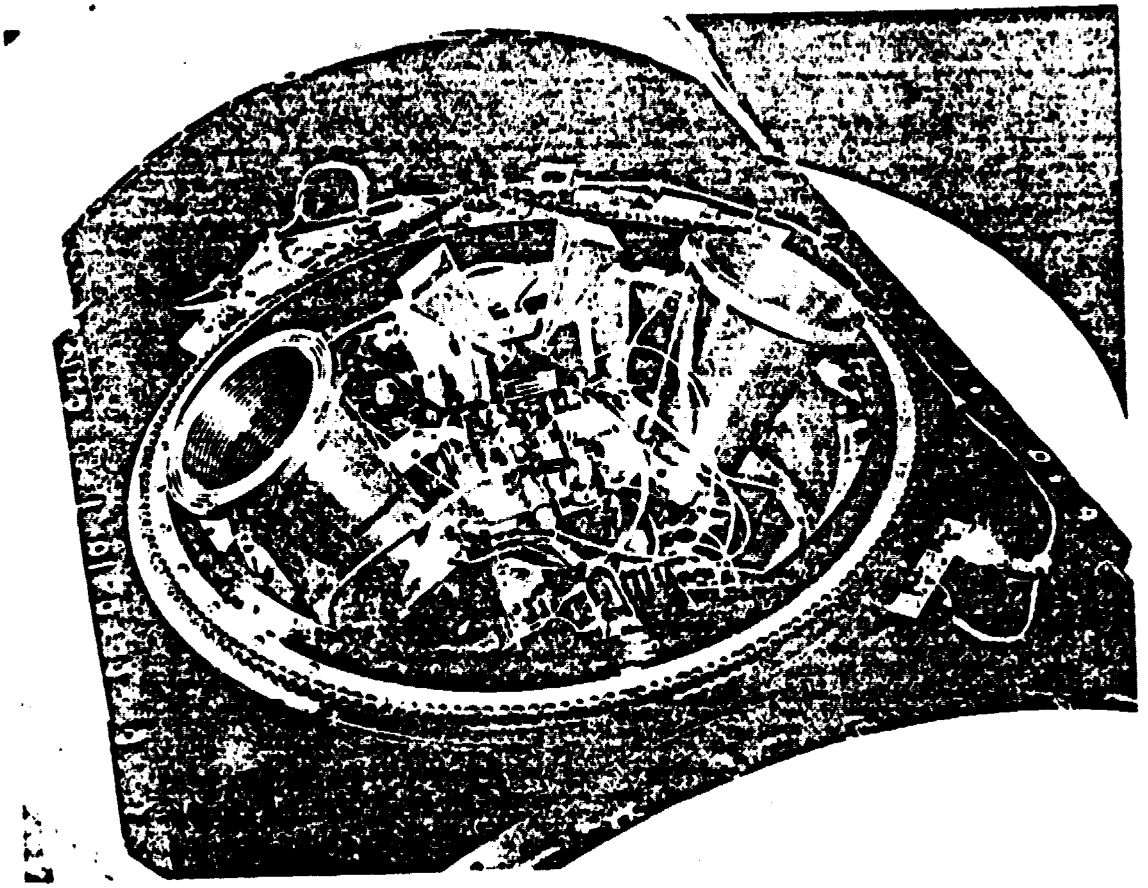

FIG. 2. The 33- and 54-GHz radiometers in the modified upper hatch of a U-2 jet. The rf shields and protective air cover have been removed to expose the horn antennas of the radiometer systems, the monitoring and demodulating electronics packages, and the outer bearing clamp and chain drive of the rotation system.

balances. This "roll monitor" is tuned to 54 GHz, in a region near strong oxygen emission lines.

Two switching techniques cancel and detect equipment-based imbalances. Periodic interchange of the antennas cancels insertion loss differences between the radiometer arms. The system is mounted in a bearing that rotates the radiometers 180° every 64 s. Periodic reversal of the aircraft flight path (about once per 20 min)

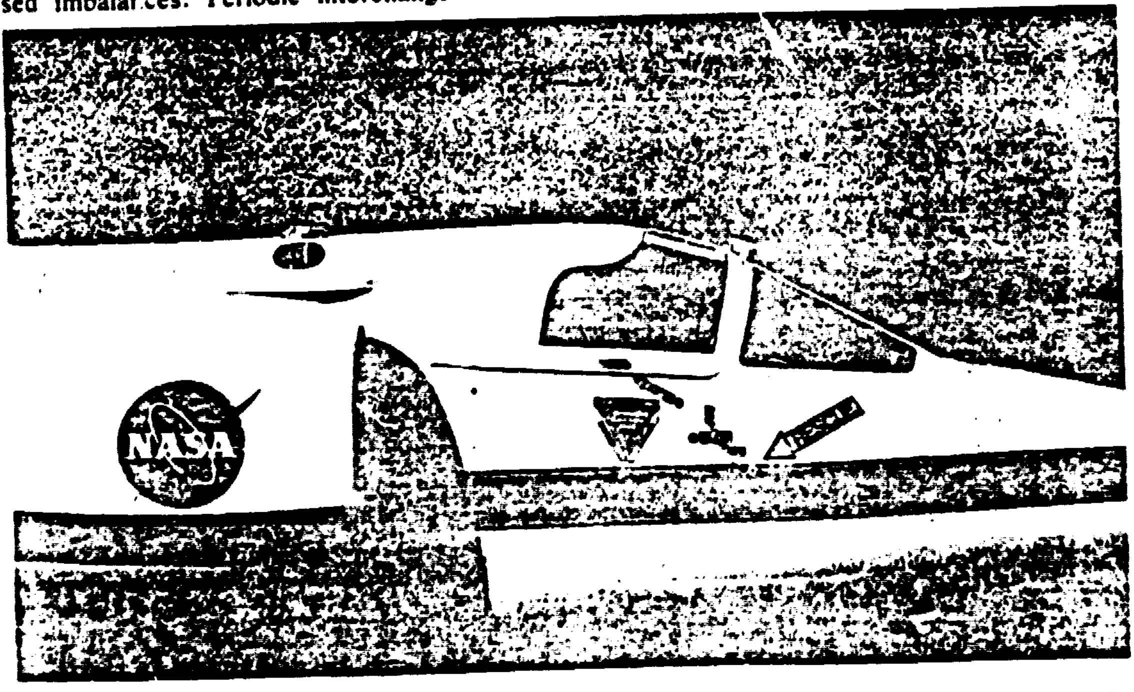

FIG. 3. The forward section of U-2 jet with a 33-GHz antenna mouth and a 54-GHz Teflon window visible. The modified upper hatch, situated just aft of the pilot's canopy, is easily removed from the U-2 equipment bay with the equipment installed, for checkout and testing. The top surfaces of the airscoops are 72° from the 33-GHz antenna beam axis.

detects asymmetries in the equipment correlated with rotation state.

The system incorporates thermal controls that regulate and monitor the temperatures of crucial components. All anisotropy, roll, and housekeeping data are recorded in flight on a magnetic tape cassette for later processing. The data collection is fully automated. Except for turning the equipment on, and initiating the rotation sequence at altitude, the pilot's primary responsibility is to orient the airplane according to the flight plan.

I. CHOICE OF FREQUENCY AND OBSERVING PLATFORM

In choosing a receiver frequency one must consider astrophysical backgrounds, emission from the atmosphere, and receiver sensitivity. Synchrotron radiation from the Milky-Way Galaxy places a fundamental limit on the sensitivity of any experiment which measures the anisotropy of the cosmic background radiation. At about 1 GHz the intensities of galactic synchrotron emission and the cosmic background are comparable. Fortunately, compared to the cosmic background, galactic synchrotron radiation falls off rapidly with frequency.

The antenna temperature[6] of typical galactic synchrotron emission is plotted as a function of frequency in Fig. 4. This plot shows that by 20 GHz the magnitude of the extrapolated galactic background falls below 1 mK. The thermal spectra of ionized hydrogen (H II) regions and dust clouds, which are mainly localized near the galactic plane, are also shown.

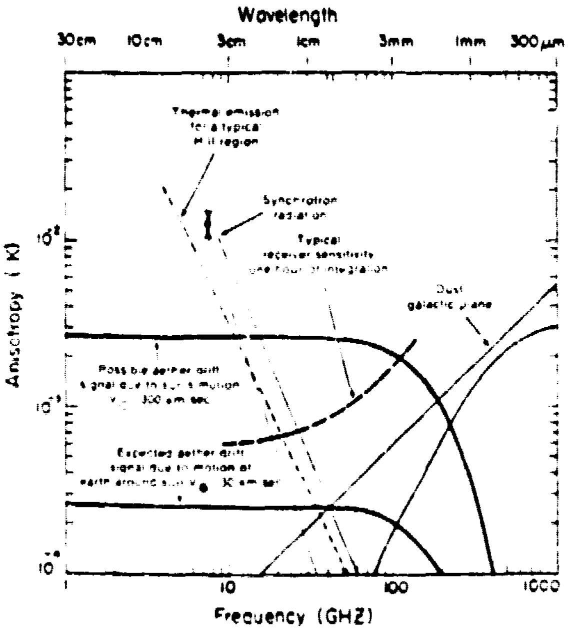

FIG. 4. Estimates of galactic radiation backgrounds as a function of frequency compared to a possible "Aether Drift" signal. The large scale anisotropy of galactic microwave radiation is comparable to the absolute intensity of the sources. The dust and HII regions are concentrated in the galactic plane and tend to be greatest near the galactic center. An estimate of receiver sensitivity for 1 h of integration is included.

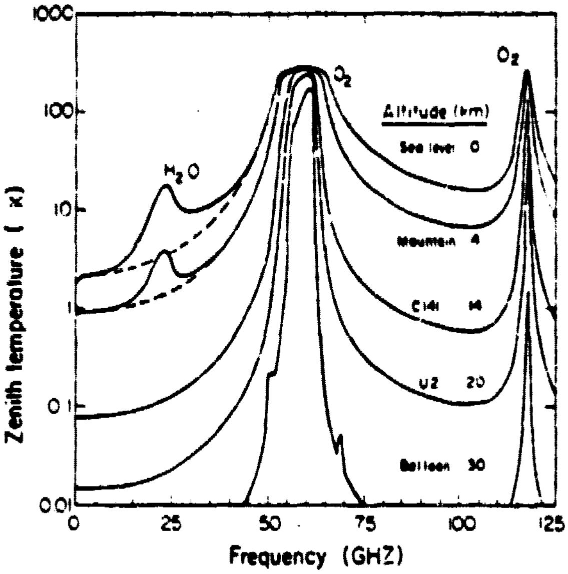

FIG. 5. An estimate of the zenith temperature due to atmospheric emission as a function of frequency and altitude, computed from the formulae of Meeks and Lilley.[7] We used these calculations in conjunction with other considerations described in the text to choose the 33-GHz observation frequency. Atmospheric emission at 54 GHz gives sufficient signal strength to monitor rolls at the U-2 altitude, but is sufficiently unsaturated on the ground to permit verification of the predicted emission.

Also plotted in Fig. 4 is our estimate of state-of-the-art room-temperature receiver sensitivity as a function of frequency for 1 h of integration. The need to detect anisotropies on limited time scales constrains the choice of receiver frequency to frequencies where the expected anisotropy is on the order of a millikelvin or more.

Thermal microwave emission from the earth's atmosphere is an important background. Figure 5 is a plot of the expected zenith temperature due to atmospheric emission as a function of frequency and altitude. The oxygen spectrum is calculated using a standard model of the earth's atmosphere together with formulae that describe the microwave spectrum of O_2 as a function of temperature and pressure.[7] This plot shows that there are preferred windows—below 20 GHz, around 35 GHz, and around 90 Ghz—in which atmospheric effects are greatly reduced relative to the peaks. The choice of the 33-GHz receiver frequency was based on the above considerations. This is a frequency where the effects of galactic background and atmospheric emission are minimized, and where receiver performance and signal strength are adequate.

A high-altitude platform is required for this measurement because fluctuations of precipitable water vapor do not allow a sensitive experiment to be done on the ground. Even at mountain-top altitude fluctuations of 20 mK are common.[8] The experiment must be conducted at altitudes above 14 km, where all significant water vapor has been frozen out.[9] Pointing the antennas at nearly the same zenith angle can cancel the residual thermal radiation from the oxygen above this altitude.

There are several vehicles which could be used for altitudes of 14 km and above: satellites, balloons,

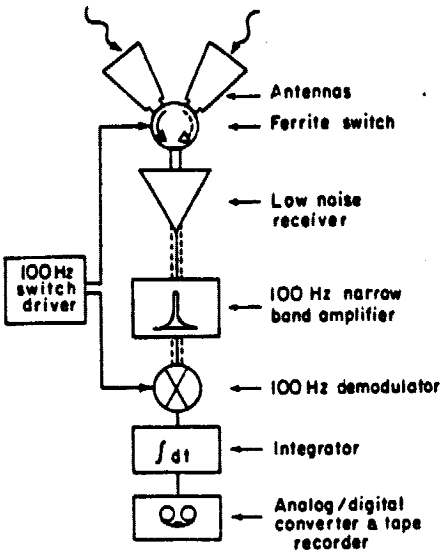

Fig. 6. Components of the 33- and 54-GHz radiometers. The individual components making up the receiver section are shown in Fig. 8.

and aircraft. Although a satellite experiment is potentially the most sensitive, having no atmospheric background and long integration times, it is also the most expensive. Such an experiment (the Cosmic Background Explorer) is now being planned, but it will not be flown for several years. The results from an airplane experiment will aid in the design and planning of the satellite experiment. Other anisotropy experiments sensitive to the millikelvin range are currently being flown,[4,10] and use balloons to reach the necessary altitudes. The U-2 is a particularly good vehicle for this experiment because of its high-altitude (20 km), excellent roll stability, and quiet electrical and mechanical environment. The U-2 has the advantage over balloons of being piloted and less at the mercy of weather. Recovery of the instrument after a flight is straighforward.

II. RADIOMETER

Figure 6 shows a schematic drawing of the 33- and 54-GHz radiometers. Rapid switching between a source and a reference load is a standard technique used to reduce the effect of receiver gain fluctuations (1/*f* noise) in a microwave radiometer. We use a dual antenna configuration where the sky is both the source and the reference. Thus difficulties in monitoring the temperature of a reference load within a few tenths of a millikelvin are eliminated. Radiation from the atmosphere is canceled by pointing the antennas at the same zenith angle. The primary components of the radiometers are the antennas, the ferrite ("Dicke") switch, the receiver, and the downstream electronics. A discussion of each of these components for the 33-GHz radiometer follows.

A. Antennas

The anisotropy in the blackbody radiation is minute compared to anisotropies in the radiation from the earth and aircraft. Thus a first requirement of the antenna system is that its side-lobe response reduce the differential emission from the earth and aircraft below the design sensitivity, about 0.2 mK. Thus the integrated 300-K signal from the earth must be reduced by a factor of about 10^{-6} compared to the main beam. Secondly, this performance must be achieved with a compact design. Mechanical and aerodynamic considerations make installation of antennas with large apertures or ground shields impractical in the U-2. Thirdly a beam width of more than 1° is needed. A small beamwidth would make the measurement susceptible to spurious signals from pointlike astrophysical sources of radiation. Finally to eliminate potential systematic errors, the insertion loss of the antennas must be small, or comparable to losses of other components upstream of the receiver.

These criteria were met by corrugated horn antennas based on the work of Simmons and Kay.[11] A matched pair of antennas with a beam width of 7° FWHM were built by TRG Division of Alpha Industries for this experiment. Each antenna is an aluminum cone with concentric grooves machined down the full length of the inside surface. The grooves force the electric field at the edges to zero, effectively apodizing the aperture. This effect is enhanced by the excitation of two modes in the antenna throat phased to cancel at the mouth of the antenna. At the throat end of the antenna a transition is made from circular to rectangular waveguide.

A sensitive measurement of the antenna beam patterns was made at the JPL–NASA test range of the Jet Propulsion Laboratory in Pasadena, CA. Figure 7 shows the results of the experimental measurement along with the theoretical predictions of antenna patterns.[12] These re-

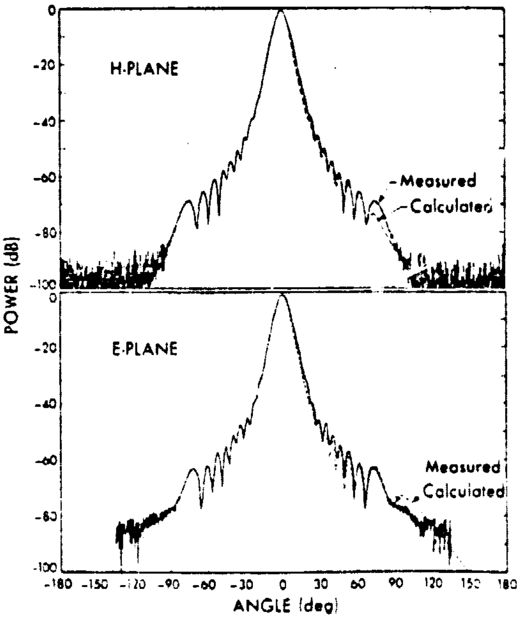

Fig. 7. The *E* and *H* plane one-way power pattern of the 33-GHz corrugated horn antennas used in this experiment, as measured at the JPL test range. Low side-lobes are necessary to reduce anisotropic radiation from the earth and aircraft. The integrated power received from the earth is reduced by over 10^{-5} compared to the main beam.

sults imply that the earth should contribute a total antenna temperature of no more than 2 mK, and the airplane no more than 2.1 mK into either antenna during level flight. Radiation from terrestrial surface features with different emissivity illuminating the side-lobes should result in differential reception between the two antennas of no more than 0.2 mK.

The aircraft made 20° banks over the California coast to check the calculations. During the banks, terrestrial radiation illuminated the side-lobes of the lowered antenna to within 40° of the central beam axis. Systematic differences of <4 mK out of the 22-mK bank signal were observed as the lowered antenna swept over terrain of varying emissivity. This limit is in agreement with the predicted value calculated from convolving the antenna beam pattern with the varying thermal emission from the earth at 33 GHz.

B. Ferrite switch

A latching ferrite circulator switches the input of the receiver between the two antennas at 100 Hz. The switch was manufactured by Electromagnetic Sciences Corporation of Atlanta, GA. The input ports are canted at ±30° so the antennas connect directly to the switch without any intervening waveguide. Small adjustable attenuation stubs in each port reduce the insertion loss imbalances between switch states to less than 50 mK.

The switching is accomplished by reversing the magnetic field of a ferrite embedded in the circulator. If an interaction between the earth's magnetic field and the switch has a significant orientation dependence, then a signal synchronous with the antenna rotation may result: thus the earth's field is a potential background. To avoid this background we had the manufacturer shield the switch with μ-metal and we enclosed the switch in additional magnetic shielding. We tested the shielding by immersing the entire hatch in a periodically reversing 10-G field. Based on these tests, we conclude that an interaction of the earth's field with the switch results in a spurious signal of less than 0.1 mK.

C. Receiver

A primary limitation in the measurement of differential signals of a few tenths of a millikelvin is the noise added to the signal by the receiver. The sensitivity of a radiometric system is defined as the root-mean-square (rms) noise fluctuation in the power output of the receiver (referenced to the input port) and is given by the formula[13]

$$\Delta T_{\rm rms} = K \frac{(T_R + T_A)}{\sqrt{B\tau}} .$$

T_R is the receiver noise temperature in kelvins, T_A is the antenna temperature for this measurement, B is the i.f. bandwidth, τ is the integration time, and K is a constant depending on radiometer design (1 for a total power radiometer, 2.2 for this configuration).

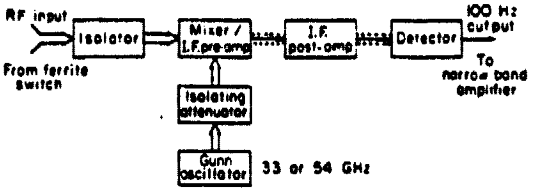

FIG. 8. The component layout for the 33- and 54-GHz receivers. In this standard superheterodyne receiver a nonlinear element, excited by a local oscillator, down-converts the signal to an intermediate frequency for further amplification. These receivers feature low-noise and wide-bandwidth operation at room temperature.

Our design goal was a system that would have an rms sensitivity of less than 1 mK in 1 h of integration time, and would operate at room temperature, while being rugged enough to perform satisfactorily in an aircraft environment.[14] These goals were met by a receiver based on a balanced mixer built by SpaceKom in Santa Barbara, CA. The combination of a balanced mixer and i.f. preamplifier yielded an rms sensitivity of 35 mK in 1 s of integration or 0.8 mK in ½ h. The device has a 26-dB rf to i.f. power gain with an i.f. bandwidth B of 1000 MHz, and a double-sideband noise temperature of 500 K. Figure 8 illustrates the components of this receiver. Including 0.7-dB insertion loss from the upstream switch, isolator, and antennas, the system noise performance $\Delta T_{\rm rms}$ at altitude is 44 mK for 1 s of integration time, (T_R = 630 K) in agreement with measurements made in the laboratory.

D. Downstream electronics

The 33- and 54-GHz radiometers use similar demodulation, integration, and recording electronics. A narrow-band amplifier tuned to 100 Hz filters the detected output of the radiometer. A lock-in amplifier demodulates the sine-wave component in phase with the 100-Hz switching between the antennas. The resulting difference signal is integrated for 2 s in an "ideal" integrator, then sampled, digitized, and recorded on magnetic tape for processing after the flight.

As a diagnostic of equipment performance the phase of the square wave that demodulates the 100-Hz component is switched by 180° every 12 s. The difference of the signals between the phase states provides a monitor of the radiometer imbalance which is observed to be about 50 mK for the 33-GHz radiometer. The average of the two signals is used to verify that the dc level of the system after demodulation is constant.

III. MONITOR FOR ATMOSPHERIC ANISOTROPY

Atmospheric microwave emission at 33 GHz can yield a spurious signal if the U-2 aircraft files at a bank. A second twin antenna radiometer, of the standard Dicke design, operating at 54 GHz monitors this potential source of background. Its antenna beam widths are matched to those of the 33-GHz antennas. Figures 1 and 2 show the position of the radiometer in the airplane hatch. The 54-GHz radiometer has a double-sideband noise temperature of 1000 K, and 500-MHz i.f. band-

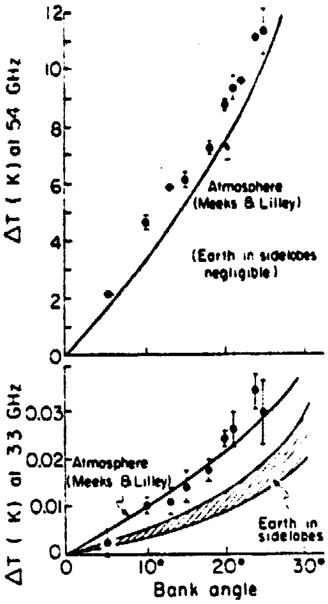

FIG. 9. The measured atmospheric signal at 33- and 54-GHz as a function of aircraft bank angle. Data taken during banks of the aircraft show the magnitude of the atmospheric signals to be in reasonable agreement with predictions based on the work of Meeks and Lilley.[7] Both sets of data can be empirically fit to a secant θ law with zenith temperatures of (38 ± 2) mK at 33 GHz and (16.1 ± 0.2) K at 54 GHz. The 33-GHz data are expected to include a contribution to the bank signal from differential earthshine in the back antenna lobes as indicated.

width, yielding an rms sensitivity of 100 mK for 1 s of integration time. The choice of 54 GHz satisfies the requirements that the oxygen signal due to aircraft rolls be strong and easily monitored at the 20-km altitude, yet not be saturated on the ground, facilitating check out.

In several flights the U-2 performed a series of banks from 5° to 25° during which the 33- and 54-GHz radiometers measured the differential atmospheric emission. The results of these runs are shown in Fig. 9 along with the predictions based on our calculations of atmospheric zenith temperature (Fig. 5). Due to the small optical depth, atmospheric emission at this altitude varies approximately as the secant of the zenith angle. A 0.25° bank results in a differential signal of 0.2 ± 0.03 mK at 33 GHz and 95 ± 5 mK at 54 GHz, a ratio of 1 to 420. Thus in 1 s of integration the 54-GHz radiometer can measure the atmospheric contribution to the 33-GHz signal to ±0.2 mK rms.

In level flight the 54-GHz roll monitor indicates that the U-2 autopilot, a Lear 201 automatic flight control system, maintains the aircraft at constant average bank angles of less than 0.25° for periods up to an hour. For departures from level flight of a few degrees or less, the average roll monitor signal is proportional to the average atmospheric signal at 33 GHz. Since a 0.25° roll yields a signal of only 0.2 mK at 33 GHz, the subsequent corrections to the anisotropy data during post-flight analysis are small. As with the 33-GHz signal, the 54-GHz signal is integrated and recorded every 2 s. On this time scale the rms fluctuations about the mean bank in level flight are less than 1° in roll angle. The output of the roll monitor is displayed to the pilot, but the average bank is so small that there has been no need to make corrections to the attitude of the aircraft in flight.

IV. U-2 AIRCRAFT AND ENVIRONMENT

The NASA–Ames Earth Survey Aircraft (U-2) is a single-seat aircraft designed as a high-altitude (20 km), long-range (2500 km), reconnaissance jet by Clarence "Kelly" Johnson of Lockheed Aircraft Company of California. In appearance the U-2 is like a glider with a single powerful jet engine. Our apparatus fits in a modified upper hatch replacing the standard access hatch above the equipment bay. It is located just aft of the cockpit and foward of the wings, Fig. 3. The two radiometers and most of the accompanying electronics are sealed off from below by a pressure can which maintains the equipment bay atmosphere at 0.28 kg cm^{-2}.

Twenty-eight volts dc supplied by the aircraft powers the equipment. The voltage is filtered against rf interference and regulated at 24 V. All data are recorded on board; no telemetry is used. The pilot flies the aircraft on a predetermined path. Normally there is no communication to the ground during data taking.

The equipment is operated in a carefully regulated thermal environment. Due to the finite emissivity of the horn antennas, a 0.05 °C physical temperature difference between the 33-GHz antennas would produce a 1 mK signal. However there is considerable variation in the loss per unit length along the horn. In flared smooth-walled antennas each transverse section radiates power approximately in inverse proportion to its diameter. But in the dual-mode corrugated design, the greatly reduced fields at the surface of the antenna mouth result in correspondingly lower loss per unit length. In the 33-GHz antennas the power per unit length contributed by the mouths is only 1/300 that of the throats.

A 20-kg aluminum block thermally shorts the throats together, and an aluminum bar shorts the midpoints of the antennas together. The temperature of the block, containing the antenna throats and the ferrite switch, is regulated at 26 °C by embedded resistive heaters. The antenna mouths cool in the air-stream where they reach −35 °C during the flight.

Silicon diodes used as temperature sensors monitor the absolute and differential temperatures of the antenna mouths and midpoints. Measurements made during the flight show the differential temperatures to be less than 0.05 °C. Additional heaters maintain the 54-GHz ferrite switch at 35 °C and regulate the digitizing and sequencing electronics at 25 °C. Total heat dissipation through the antennas is about 70 W from the electronics and 50 W from the heaters. The equipment cools for 20 min after the rotation sequence is initiated at altitude, allowing the system to reach thermal stability. The aluminum block gradually cools an additional 1.6 °C during the remainder of the flight.

Teflon windows protect the mouths of the 54-GHz antennas. The windows are 1.9 mm thick, or ½ wavelength at 54 GHz, thereby minimizing reflections of an incoming signal. The emissivity of the windows is less than 1%. A physical temperature difference between the windows of a few kelvins results in a thermal signal of a few hundredths of a kelvin. This is negligible compared to the 85-mK signal generated at 54 GHz by the minimal roll to be detected, 0.2°. In contrast, at 33 GHz, windows with sufficient mechanical strength to withstand aerodynamic stress cannot be used. Differences in physical temperature of a few kelvins would produce spurious signals large compared to a few tenths of a millikelvin to be detected with this radiometer.

The entire assemblage is mounted on three vibration dampers that reduce potential microphonics due to aircraft vibration. The electronic components are packaged in modules that are shielded against radio-frequency interference and a double-shielded container encloses the entire assembly except for the actual antenna mouths.

A. Rotation system

As with previous anisotropy experiments, it is essential that the position of the antennas be periodically interchanged to cancel anisotropy inherent in the instrument. The main portion of the equipment is suspended on a 56-cm-diam bearing mounted in the U-2 hatch. A motor drives the bearing through a worm gear, a clutch, and a stainless steel chain. This system rotates the instrument 180° every 64 s to the alternate observing position.

A rotation takes 5 to 6 s during which the instrument is accelerated through a 90° turn and then deaccelerated until it coasts to rest against a positioning stop. The motor is shut off with a sensing microswitch. The design of the system insures proper alignment of the antennas in the observing positions to within 0.1°. A ten-turn potentiometer and four microswitches measure the rotation angle to within 0.5°. Their outputs are recorded, and the analog rotation angle signal is displayed on the pilot's instrument panel.

During ascent and descent the equipment is rotated 90° away from the observing positions to protect the 33-GHz antennas from the external environment. In this 'stored' position, the 33-GHz antennas are positioned inside the hatch, and plugs, lined by brushes, seal the open ports.

B. Aircraft reversals

A spurious anisotropy signal would appear if the output depended on rotation state or if the apparatus were not located symmetrically in the U-2 aircraft. We detect and cancel any such signal by taking data in pairs of "legs" flown in opposite directions with respect to the ground and sky. During each leg the pilot flies the aircraft straight and level for 20 min. Six pairs of legs are flown in a typical flight. The final three pairs are usually flown in directions perpendicular to the first three.

TABLE I. Data recorded: The 28 analog and 4 digital words sampled in an 8-s data cycle. The 33- and 54-GHz integrated signals are sampled and recorded once every 2 s during each cycle. The other signals, primarily monitors of equipment performance and environmental conditions, are sampled less frequently.

Analog	Number of times sampled in 8 s
1. 33-GHz radiometer signal	4
2. 33-GHz noise monitor	2
3. Atmospheric (54-GHz) monitor signal	4
4. Atmospheric noise monitor	2
5. Heater circuit current	2
6. Antenna orientation	2
7. Absolute temperature, antenna mouth	1
8. Differential temperature between antenna mouths	1
9. Absolute temperature at middle of antenna	1
10. Differential temperature across middle of antennas	1
11. Temperature of 35-GHz ferrite switch	1
12. Five temperatures of 33- and 54-GHz radiometers	5 × 1
13. Accelerometer output	1
14. Power supply voltage	1
Digital	
Universal time	2
Antenna position, status bits	2
	32 words

V. DATA RECORDING AND ANALYSIS SYSTEM

The experiment is run in an automated mode. Controlling electronics, activated by the pilot at take-off, provide the necessary timing and sequencing signals to the equipment. A Datel LPS-16 data logger, a lightweight low-power incremental tape recorder, digitizes and records four words of data per second on a magnetic tape cassette. Table I lists the quantities measured and recorded in an 8-s data cycle.

During post-flight analysis we use computer programs to display, edit, and average the measurements. The bulk of the editing consists of deleting data taken during banks and antenna rotations. The scatter of the edited data is generally consistent with a gaussian distribution, as expected for signals from a noise-limited radiometer. On two occasions during data-taking flights transients occurred that were inconsistent with statistical fluctuations about the mean. These points were removed, resulting in a loss of 20 s of data. Data taken during course corrections made by the pilot are deleted if the 54-GHz roll monitor indicates a bank of more than 1°. The cuts due to rolls and transients amount to less than 6 min out of 32 h of data taken over nine flights.

The remaining data are grouped by "legs" and averaged. The anisotropy is found in each leg by subtracting the averages of data taken in one antenna orientation from the average of data taken in the other orientation. Corrections are applied to these averages for astrophysical, local, and equipment-based backgrounds. Table II lists these corrections, and tabulates the 90 percentile limits on the magnitudes of the corrections that are ap-

TABLE II. Residual systematic effects: The 90 percentile limits on the magnitude of the corrections applied to data averaged over a leg. Most systematic corrections applied to the data are small compared to the integrated sensitivity of a flight, about 0.5 mK.

Effect	90% of the corrections in each category result in change of less than: (mK)
Galactic backgrounds	
Synchrotron radiation	0.32
Ionized hydrogen (H II regions)	0.01
Radio sources	0.06
Dust	0.01
Atmospheric anisotropy (Banks)	0.15
Antenna side-lobes	0.20
Antenna temperature difference	0.27
Motion of Earth around Sun	0.23
Jupiter	0.01
Combined	0.56

plied to each leg. The 90 percentile limits for the combined corrections applied to each leg is 0.56 mK.

VI. RESULTS OF ENGINEERING AND DATA FLIGHTS

Three engineering flights were used to study the thermal environment of the equipment in the U-2 by monitoring the external temperatures and the heat flow through the antennas. During these flights the effect on the equipment of radio transmissions from the plane and engine restart were checked and found not to cause significant interference.

The statistical and systematic properties of the 33-GHz signals in nine subsequent data flights were studied by a variety of methods. The data were auto-correlated, and signal-averaged at the rotation period. In the initial three data flights correlations were seen with time periods of 40 to 120 s, and amplitudes that varied from 10 to 45 mK. After these flights were made a number of changes and improvements including the following: A parametric amplifier[14] was replaced with the SpaceKom mixer, and regulation of the temperatures of the aluminum block and the controlling electronics was improved. In the final six data flights no correlations were observed, nor anomalous effects in the signal-averaged plots, down to sensitivities limited by statistics. Figure 10 shows a segment of data taken with the 33- and 54-GHz radiometers from the fifth data flight.

A spurious signal of about 2 mK, of yet unexplained origin, is associated with the rotation state of the system. Reversing the heading of the aircraft measures this effect, and shows it is constant during a flight. This offset is subtracted from the data for later analysis. It may be inherent in the system, or due to an asymmetry in the way the equipment is mounted in the plane. This problem is being investigated.

Microwave absorbers maintained at room temperature and at liquid nitrogen temperature are used in the laboratory as the primary calibrators of the 33- and 54-GHz radiometers. The equipment was also calibrated during pre- and post-flight checkout with a secondary calibrator. In several flights the moon provided a check of the calibration. The U-2 flew the equipment over a predetermined location at the proper time and heading so that one of the antennas pointed at the moon to within 0.5°. The observed signals of (675 ± 25) mK imply a surface temperature of (228 ± 12) K consistent with measurements made on the ground by us and others[15] at similar wavelengths.

During the flights the anticipated thermal, terrestrial, and atmospheric backgrounds were at the expected level. Data were accumulated for directions distributed over the northern hemisphere. Anisotropy in the cosmic background radiation has been detected in these data with an overall sensitivity of ±0.6 mK. Details are published elsewhere.[16]

ACKNOWLEDGMENTS

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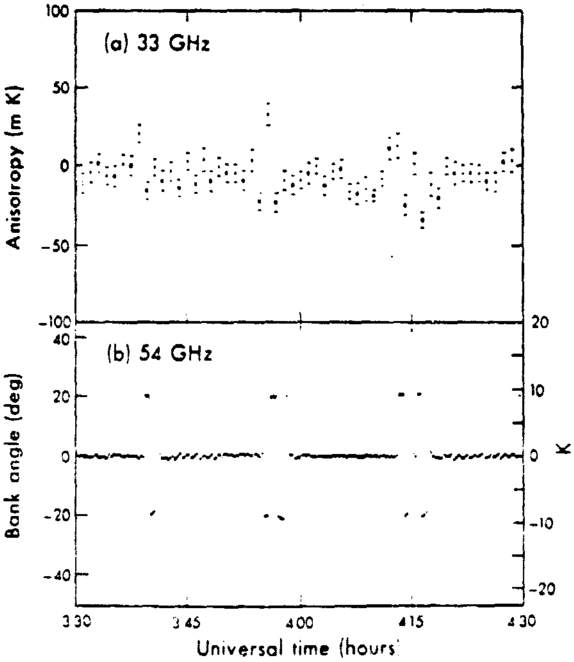

FIG. 10. The 33- and 54-GHz data from the fifth data flight. (a)—Each point is the measured anisotropy at 33 GHz averaged for 56 s during successive antenna orientations. The data are combined from both phase states of the 100-Hz demodulating wave form. The error bars are the computed rms fluctuations of the 2 s data divided by the square root of the number of measurements. (b)—The corresponding 54-GHz data, where no averaging has been done, show the scatter for 2 s of integration, and the roll signal during 20° banks of aircraft. There is more oscillation about the mean in legs flown north (e.g., 3:41 to 3:55) than in alternate legs flown south. This effect is produced by an interaction between the aircraft's magnetic heading sensor and the autopilot. Averaging the data shows that only the amplitude, not the mean, of the roll oscillation is affected.

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3008
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The Cosmic Background Radiation and the New Aether Drift

by Richard A. Muller

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The Cosmic Background Radiation and the New Aether Drift

Sensitive instruments have found slight departures from uniformity in the radiation left by the primordial "big bang." The experiment reveals the earth's motion with respect to the universe as a whole

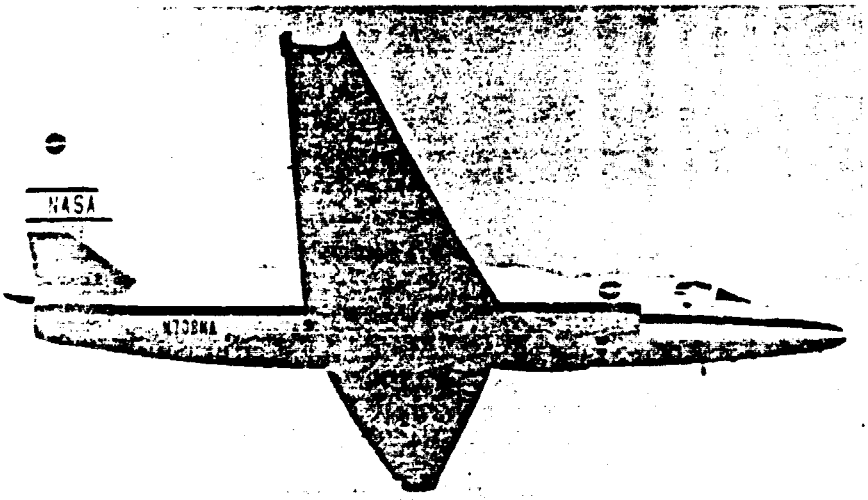
by Richard A. Muller

A curious radiation that bathes the earth almost uniformly from every direction has turned out to be a unique source of information about the nature and history of the universe. The faint radiation was identified 13 years ago during a search for noise sources capable of interfering with satellite communications systems. The "noise" proved to be of cosmic origin and soon became known as the three-degree cosmic black-body radiation because it has the spectral characteristics of a black body, or perfect emitter of radiation, whose temperature is about three degrees Kelvin (three degrees Celsius above absolute zero). Most astrophysicists now believe this microwave radiation was emitted shortly after the "big bang," the cataclysmic explosion in which the universe was created some 15 billion years ago. Not only is it the most ancient signal ever detected; it is also the most distant, coming from well beyond the quasars, the most remote luminous sources known. The three-degree radiation is a background in front of which all astrophysical objects lie.

The observation of the cosmic background radiation is the closest we have come to a direct study of the primordial explosion itself. The very existence of the radiation is the strongest evidence in favor of the big-bang theory. The isotropy of the radiation, that is, the uniformity of the radiation from different directions in space, tells us that the big bang, although it was unimaginably violent, also went quite smoothly. The slight departure from isotropy that has recently been discovered indicates that our galaxy is hurtling through the universe with the surprisingly high velocity of 600 kilometers per second. It is this cosmological velocity that has been called "the new aether drift," in reference to the "aether drift" that A. A. Michelson and E. W. Morley sought unsuccessfully to discover nearly a century ago by measuring the velocity of light over paths rotated at different angles with respect to the earth's motion in space. The three-degree cosmic background radiation provides an all-pervasive radiation "aether" for performing an analogous experiment.

The cosmic background radiation was discovered in 1965 by Arno A. Penzias and Robert W. Wilson of Bell Laboratories; its significance was immediately recognized by Robert H. Dicke and his group at Princeton University. Since then much has been learned about the spectrum of the radiation. Its intensity has now been studied at wavelengths ranging from 30 centimeters down to half a millimeter, confirming the initial conjecture that its spectral curve conforms to that of a black body at a temperature of three degrees K.

One of the most important observations reported by Penzias and Wilson was the constancy of the temperature of the radiation from different directions in space. Their measurements indicated that the temperature varies by less than 10 percent in any direction. Subsequent experiments set even lower limits on the departure from isotropy. Two independent groups have recently carried out measurements sensitive enough to show, however, that the temperature of the radiation is not precisely the same in all directions. One set of experiments was performed at Princeton by David T. Wilkinson and Brian E. Corey, the other set at the Lawrence Berkeley Laboratory of the University of California by a group that included George F. Smoot, Marc V. Gorenstein and me. It is now known that the temperature of the three-degree back-



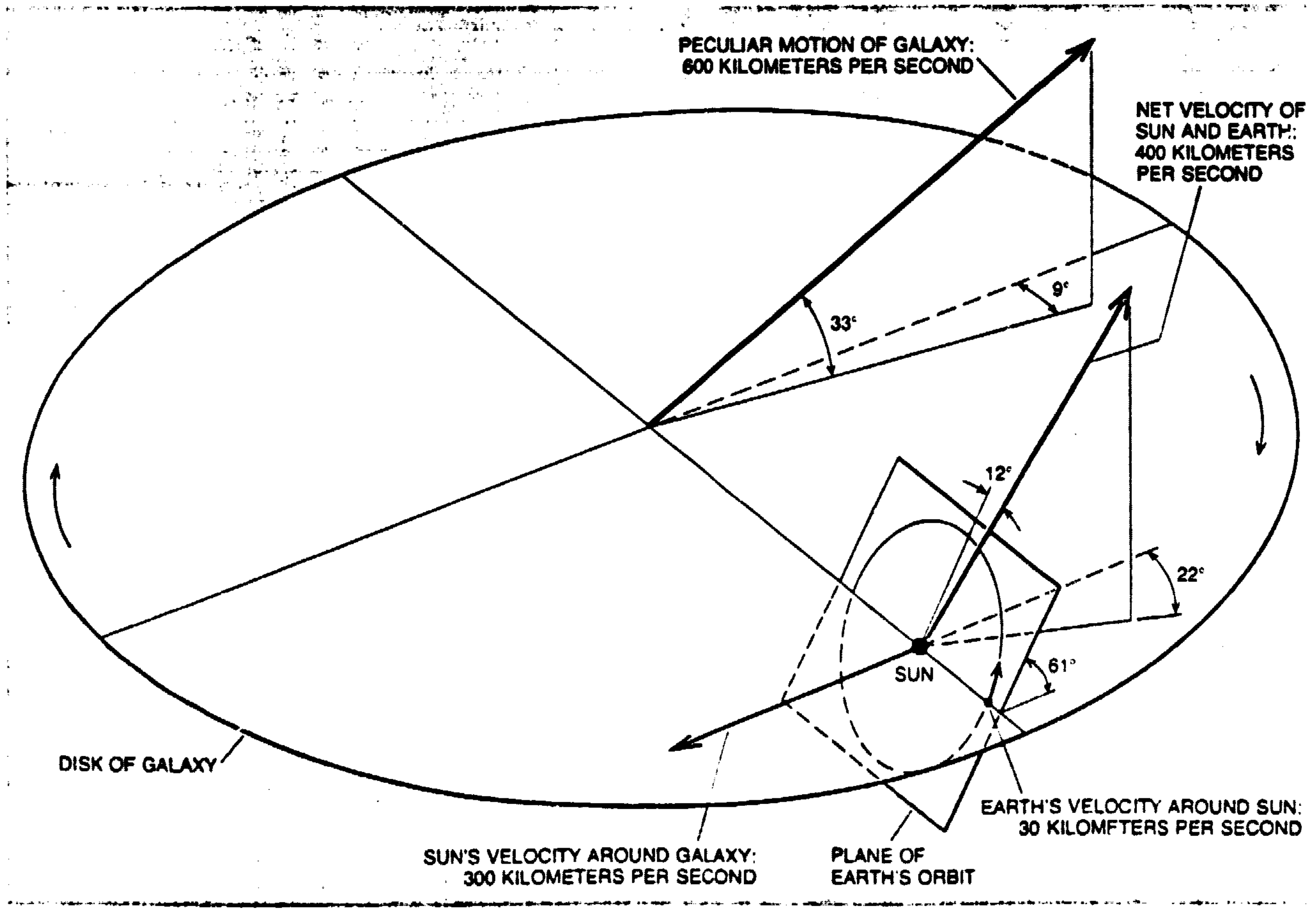
INSTRUMENT PLATFORM in the new aether-drift experiment was a U-2 aircraft operated by the National Aeronautics and Space Administration. Like the original aether-drift experiment performed nearly a century ago by A. A. Michelson and E. W. Morley, the new experiment was designed to measure the earth's motion with respect to a universal frame of reference, in this case the cosmic background radiation. That radiation, which is equivalent to the radiation emitted by a black body (a perfect radiator) with a temperature of about three degrees Kelvin (three degrees Celsius above absolute zero), is radiation left over from the fireball in which universe was created 15 billion years ago. U-2 has made 10 flights carrying an ultrasensitive microwave receiver designed by the author, George F. Smoot and Marc V. Gorenstein.

ground radiation varies by about a tenth of a percent across the sky, with the hottest region being in the direction of the constellation Leo and the coolest in the direction of Aquarius. The temperature varies smoothly between these two regions, following a simple cosine curve. This distinctive pattern ("the great cosine in the sky") leads us to identify the velocity of the solar system as the cause of the anisotropy. In order to explain how this conclusion has been drawn and what its significance is it is necessary to review the big-bang theory, the origin of the cosmic background radiation and just what it is that has been learned from the existence of the anisotropy.

The big bang was not simply an explosion of a clump of matter into an otherwise vast and empty space. Although such a picture would account for Hubble's law (the observation that distant galaxies are receding from us at a velocity proportional to their distance), it seems incapable of accounting for the uniformity with which matter and radiation fill space. The known universe appears to be so uniformly populated that astronomers accept the "cosmological principle": the belief that the universe is essentially the same everywhere. In addition, the idea of an exploding clump of matter sitting somewhere in space offers no natural way to account for the existence of the cosmic background radiation. Any radiation emitted at the time of the explosion would have left the vicinity of the original mass even faster than the matter would have left it, and the radiation would no longer be around to be observed.

In the big-bang theory there is no primordial clump of matter and no center to the explosion. Space is uniformly occupied: there is no outer edge to the distribution of matter. The big bang was not an explosion of matter within space but an explosion of space itself. According to Einstein's general theory of relativity, the "amount" of space between objects is not fixed, even if the objects retain their respective coordinate positions. In the calculations done in the big-bang theory the galaxies are usually assumed to be at rest as the amount of space between them increases. Any motion that leads to a change in a galaxy's coordinate position in this theory is referred to as a peculiar velocity, not because it is strange but because it is peculiar to the individual galaxy and is not part of an overall cosmic motion.

The rate of the expansion of space is reduced by the presence of matter and energy. If the average mass density of the universe is less than a critical value (about 10^{-29} gram per cubic centimeter), the expansion will go on forever. If the average mass density is more than the critical value, the expansion will slow to a stop and turn into an implosion. The mass density also determines the large-scale geometry of the universe. If the mass density is greater than the critical value, the volume of the universe is finite: otherwise the volume is infinite. So far the mass density of the universe has not been established accurately enough to say for sure whether the universe is finite or infinite. Fortunately for most of the calculations of the big-bang theory the issue is not critical. We shall assume that the average mass



ABSOLUTE MOTION OF THE EARTH through space has been determined by measuring slight differences in the temperature of the three-degree cosmic background radiation reaching the earth from various directions. The earth travels in its orbit around the sun at 30 kilometers per second and, as the sun's gravitational captive, is being swept around the center of the galaxy at 300 kilometers per second. The new aether-drift experiment shows that the earth's net motion in space is about 400 kilometers per second. The vector of the earth's net motion lies in the same plane as its orbit around the sun and at an angle tilted sharply upward (northward) from the plane of the galaxy. In this diagram the vector of the earth's net motion is depicted as a colored arrow centered on the sun, since the two bodies travel together. Both are being carried along by the galaxy's own "peculiar" motion through space (the motion peculiar to the galaxy and not a part of the overall cosmic motion). In order to account for the earth's motion with respect to the three-degree radiation the galaxy must be traveling at about 600 kilometers per second, or more than 1.3 million miles per hour, in the direction shown by the heavy black arrow.

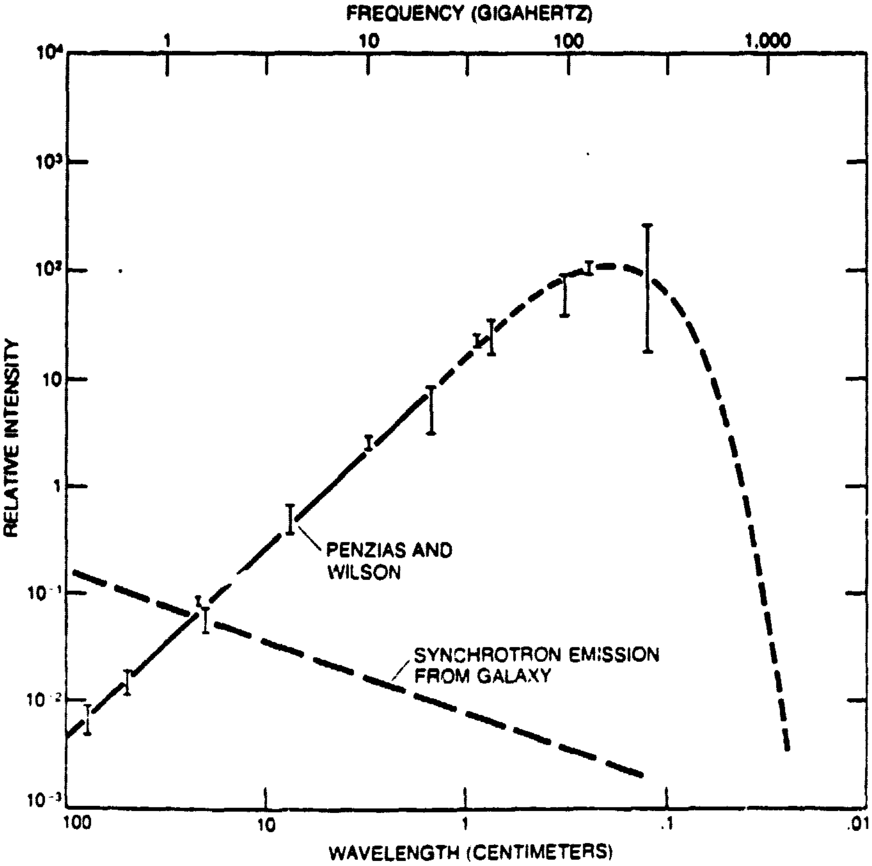
density is equal to the critical value, which has the added advantage of implying that the average curvature of space is zero. Therefore we can work with the familiar Euclidean geometry.

The concept that the distance between two objects can change without the objects themselves moving seems strange because it is completely foreign to our everyday experience. It is hardly stranger, however, than the curvature of space itself. Fairy tales and much science fiction describe events in which space is flexible. What distinguishes the general theory of relativity from mere flights of fancy are specific equations that relate the geometry and volume of space to its previous history and to its mass-energy content.

Hubble's law fits naturally into the big-bang theory. The relation follows from two facts: not only is space uniformly occupied by matter but also space is being created at a uniform rate. Thus the greater the distance separating two galaxies, the greater the amount of space created between them. Hubble's observation that all galaxies are moving away from our own does not mean that our galaxy is at the center of the universe: a similar observation would be made from every other galaxy.

The uniform expansion of space applies only to distances on an intergalactic scale. It does not hold, for example, in the vicinity of massive objects such as the sun, where the geometry of space can be quite different. It also does not hold at the distances between the atoms in a molecule or the electrons in an atom. Such distances are determined by electromagnetic forces rather than gravitational ones. Even if the expansion of space tended to move the constituents of atoms and molecules apart, their internal electric fields would draw the constituents back. If this were not the case, human observers and their meter sticks would grow at the same rate as the universe, making the expansion of space unobservable.

The great initial success of the big-bang model came when George Gamow, Ralph A. Alpher and Robert Herman extrapolated the expansion back to a period when the universe was more than 10^{30} times denser than it is now. They postulated that the early universe would be extremely hot and that the combination of high temperature and density would initiate thermonuclear reactions, converting the plasma of protons, electrons and neutrons into deuterons and helium nuclei. Within only a few minutes the expansion of the plasma would reduce the temperature and density below the level needed to sustain further reactions. The conversion would be incomplete and just sufficient to account for the present ratio of helium to hydrogen in the universe.



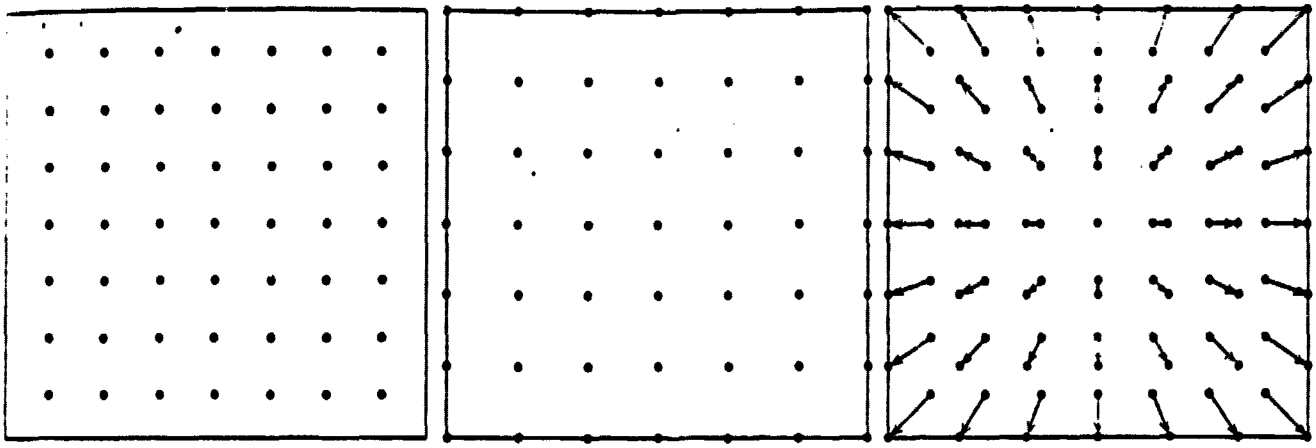
INTENSITY OF COSMIC BACKGROUND RADIATION follows the energy spectrum of a black body with a temperature of three degrees K. The first measurement of the radiation was made in 1965 by Arno A. Penzias and Robert W. Wilson, working with a microwave receiver tuned to a wavelength of 7.35 centimeters (corresponding to a frequency of four gigahertz). Most of the subsequent measurements were also done at single wavelengths, indicated by the vertical bars. Recently, however, Paul L. Richards and his co-workers at the University of California at Berkeley have measured the higher-frequency portion of the curve with a wide-band technique, obtaining the results indicated by the colored area. The broken line represents synchrotron radiation from our galaxy: radiation emitted by electrons as they spiral around lines of magnetic force. At frequencies below 10 gigahertz the anisotropy, or the directional nonuniformity, of the synchrotron emission masks the anisotropy in the background radiation.

Another consequence of the Gamow-Alpher-Herman model, which went virtually unnoticed at the time, was that the hot plasma would emit and absorb electromagnetic radiation, just as the hot plasma at the surface of the sun emits light. The radiation would be scattered and rescattered by the free electrons until roughly half a million years after the big bang. At that time the density and temperature of the matter would have dropped to the point where its constituent ions (mostly protons and electrons) would unite to form electrically neutral atoms. This period (which actually lasted for several thousand years) is usually called the "moment of decoupling," since there is little interaction between the radiation and matter from that time on. The previously opaque universe suddenly becomes clear, allowing the electromagnetic radiation to travel unscattered through space and preserving an image of the plasma from which the photons were last scattered.

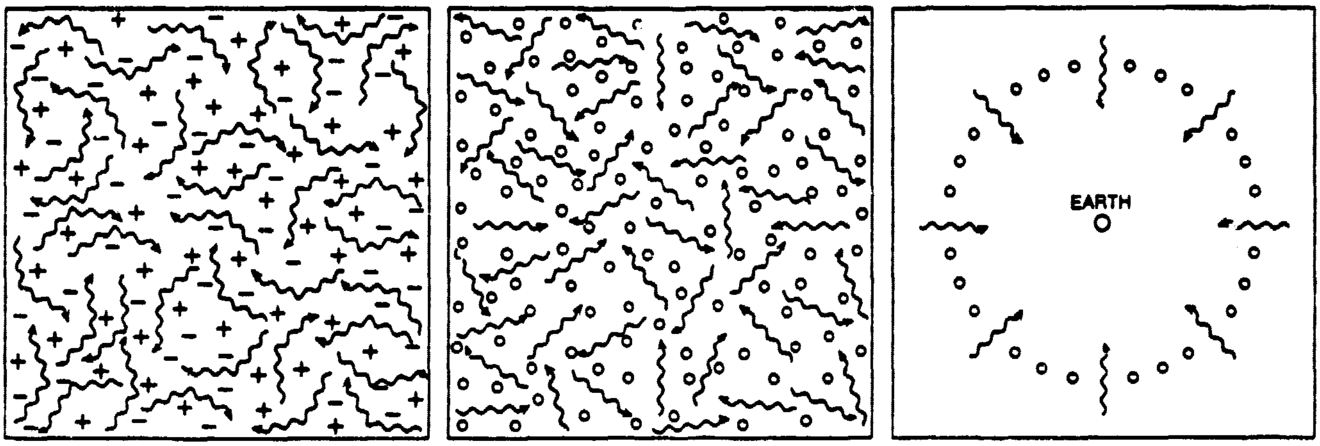
It is this radiation we now observe as the cosmic background. The radiation reaching us today was last scattered from a shell of plasma that completely surrounded our present position in space. If some of the matter in that plasma has formed into a galaxy far removed from our own, one can imagine it supports intelligent beings who are now observing the radiation that was last scattered in our region of space 15 billion years ago.

Originally emitted as visible and infrared radiation with a peak wavelength of about .7 micron, the cosmic background radiation has been red-shifted by a factor of 1,500, so that we now observe its peak wavelength to be at about a millimeter. The red shift is due to the tremendously high velocity of the expanding shell of radiation, or more properly the high rate at which space between us and the shell is increasing. The radiation itself has not changed its wavelength. Rather, we are observing it in a frame of reference that is "moving" at 99.9 percent the speed of light with respect to the matter that emitted it 15 billion years ago.

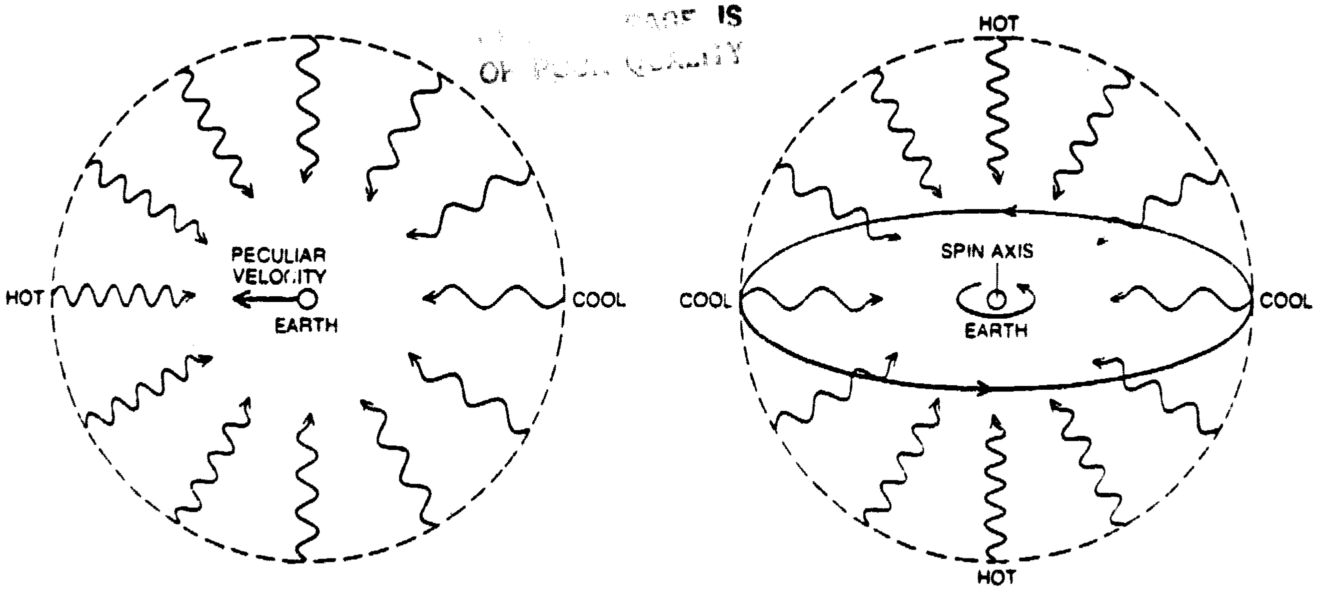
A remarkable feature of a black-body spectrum is that when it is viewed in a frame of reference moving with respect



UNIFORM EXPANSION OF SPACE accounts for the "law" discovered by Edwin P. Hubble of the Mount Wilson Observatory 50 years ago when he observed that distant galaxies are receding at a velocity proportional to their distance. Here the expansion of space is represented by the change in the spacing of galaxies (*dots*) in the arrays at the left and in the middle. In the diagram at the right the two arrays are superposed. Connecting arrows show the distance traveled by each galaxy as viewed from the central galaxy. The same pattern would be observed from every other galaxy. Although the space between the galaxies expands, the size of each galaxy remains the same.



ACCORDING TO BIG-BANG THEORY (*left*), the early universe is filled by protons (*plus signs*) and electrons (*minus signs*) that absorb and reemit photons (*color*). After 500,000 years (*middle*) the universe has expanded and cooled enough for the protons and electrons to combine into hydrogen atoms (*circles*), after which most photons are no longer scattered. Those photons (*redrawn at right*) last scattered from a shell surrounding the position at which the earth will form constitute the cosmic background radiation reaching us today.



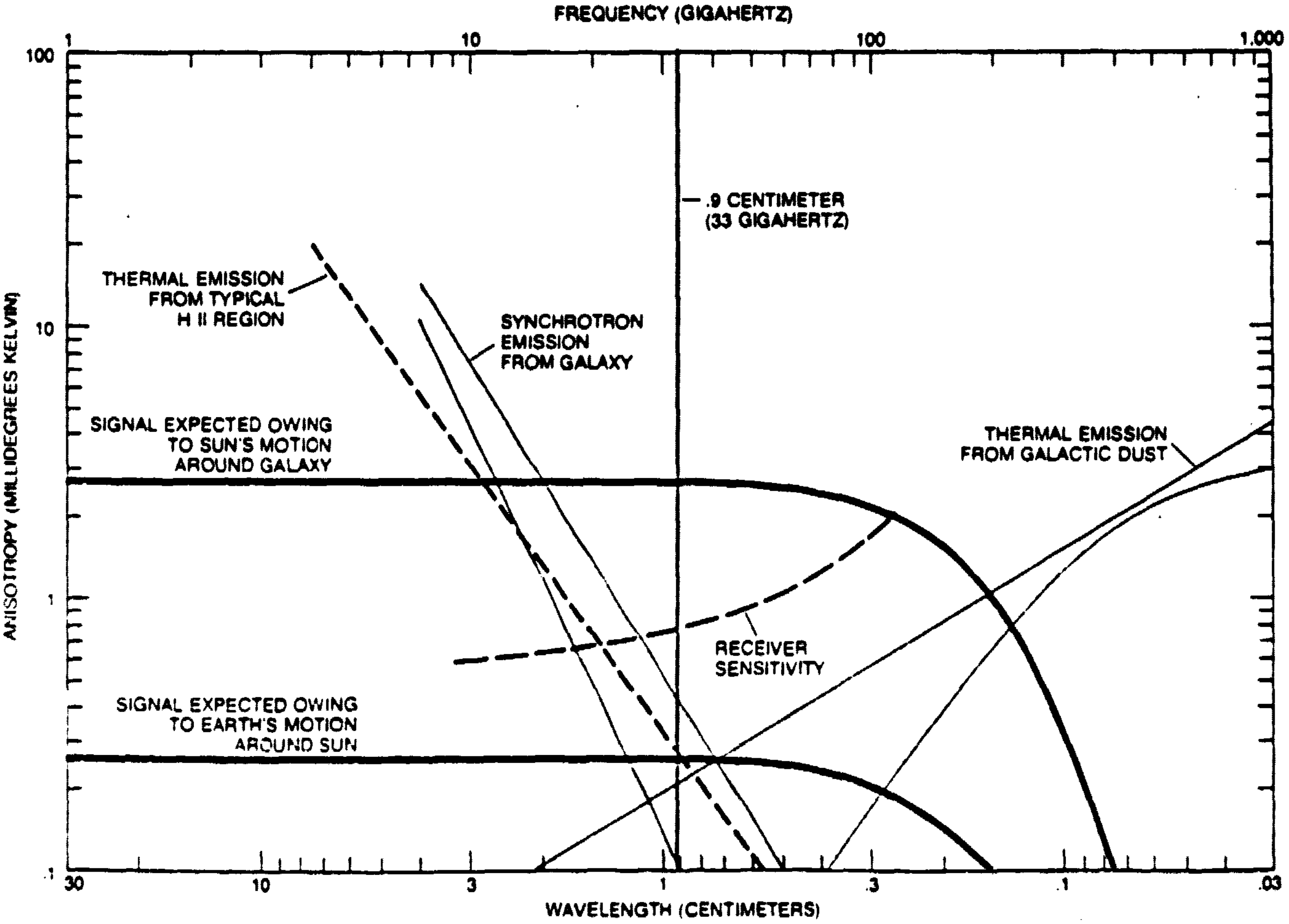
STUDY OF BACKGROUND RADIATION can provide clues to the large-scale structure of the universe. If the earth has a peculiar velocity (*left*), the radiation is slightly "bluer" (hotter) in the direction of motion and "redder" (cooler) in the opposite direction. If the shell of matter that last scattered the radiation was spinning with respect to our local inertial frame, the photons emitted at the shell's equator are slowed by their additional velocity (in accordance with the general theory of relativity) and hence appear redder than photons emitted toward its poles. The two possibilities can be distinguished by differences in the pattern of the observed temperatures. The temperature of the radiation will vary in the first instance as the cosine of the angle in the sky and in the second instance as the square of the cosine.

to the emitter, it retains the characteristic black-body shape, altered only in temperature. In a frame of reference moving with the plasma the characteristic temperature of the radiation is about 4,500 degrees K.: in our frame of reference it is three degrees. As time passes we shall continue to intercept the cosmic background radiation, but the signal we shall then observe will have come from even more distant regions in space. Since those more distant regions are moving away at still higher velocities, the radiation will be observed in our frame of reference to have a temperature lower than three degrees. In another 15 billion years the radiation reaching our present position in space should have a temperature of about 1.5 degrees. It will also be radiation emitted at the decoupling time, but from a region far more distant in space than the radiation we are observing today.

When one observes the cosmic background radiation, one is studying the structure of the shell of matter that scattered it half a million years after the big bang. If the universe were totally homogeneous and isotropic, the cosmic background signal would be totally featureless. Clearly the present universe is quite lumpy, containing as it does planets, stars, galaxies and clusters of galaxies. If large-scale clumping had begun before the moment of decoupling, the background radiation should exhibit bright and dark spots corresponding to the clumps. If such features were to be observed, one would obtain a fascinating glimpse of the early evolution of the universe. On the other hand, the absence of such features would indicate that large-scale structures, such as the clumping necessary to account for clusters of galaxies, had not yet appeared at the moment of decoupling.

The background radiation also provides an opportunity for testing some of the more speculative theories of the universe. For example, the universe may be spinning, a possibility allowed by the general theory of relativity. S. W. Hawking of the University of Cambridge was the first to point out that the spin would show up clearly as a particular departure from isotropy in the cosmic background radiation. If the shell of the last scattering were rotating with respect to our local inertial frame of reference, the plasma at the equator of the shell would have a transverse velocity not shared by the plasma at the poles of the shell. According to the time-dilation effect of special relativity, clocks and other oscillators along the equator of the plasma shell would run slow, with the result that light emitted from the equatorial region would have a small red shift over and above the recessional red shift. The additional red shift would result in a slightly lower temperature for the radiation coming from the equatorial region.

Although a spinning universe would be detectable according to the general theory of relativity, it would not be detectable according to a principle stated by Ernst Mach. Mach postulated that the very existence of local inertial frames of reference depended on the distant matter of the universe. Thus a local inertial frame would be inextricably linked to the distant matter, and it would be rotating if the universe as a



DETERMINING ANISOTROPY in the background radiation is complicated by the microwave emission from various sources that are themselves anisotropic. H II regions, for example, are concentrations of gas and dust heated by young stars. For the new aether-drift experiment it was necessary to select a frequency at which the expected anisotropy of the background radiation would predominate. A frequency of 33 gigahertz was considered to be optimum. The two curves representing the signals expected from the earth's motion around the sun (30 kilometers per second) and the sun's motion around the center of the galaxy (300 kilometers per second) are computed on the assumption of zero velocity for the galaxy. The experiment reveals that the galaxy's velocity is 600 kilometers per second.

whole were rotating. If analysis of the background radiation were to reveal the universe to be spinning, Mach's principle would be disproved.

If gravity waves of very long wavelength were generated during the early moments of the big bang, they too should give rise to a distinctive pattern in the cosmic background radiation. (Since the moment of decoupling for gravity waves is only a fraction of a second after the big bang, their direct detection would provide an even earlier glimpse into the history of the universe than the one provided by the cosmic background radiation.) One might also discover anisotropies revealing that the universe has not expanded uniformly in strict accordance with Hubble's law. Such phenomena would tend to form different patterns in the sky, making it possible to distinguish them from one another. Perhaps the most distinctive pattern to look for, however, is the anisotropy caused by the motion of the solar system with respect to the shell of plasma that emitted the radiation.

There can be only one inertial frame in any region of space where the background radiation is completely isotropic. In any other frame an observer's motion will reveal itself as a variation in the temperature of the radiation proportional to the velocity of the observer and to the cosine of the angle between his direction of motion and the direction of observation. P. J. E. Peebles, one of the physicists in Dicke's group who correctly identified the origin of the radiation, coined the term "the new aether drift" to describe the expected motion. Although it is not motion with respect to some frame of reference fixed in space, it is motion with respect to the most natural frame of reference in cosmology: the expanding coordinate system in which the galaxies are nearly at rest.

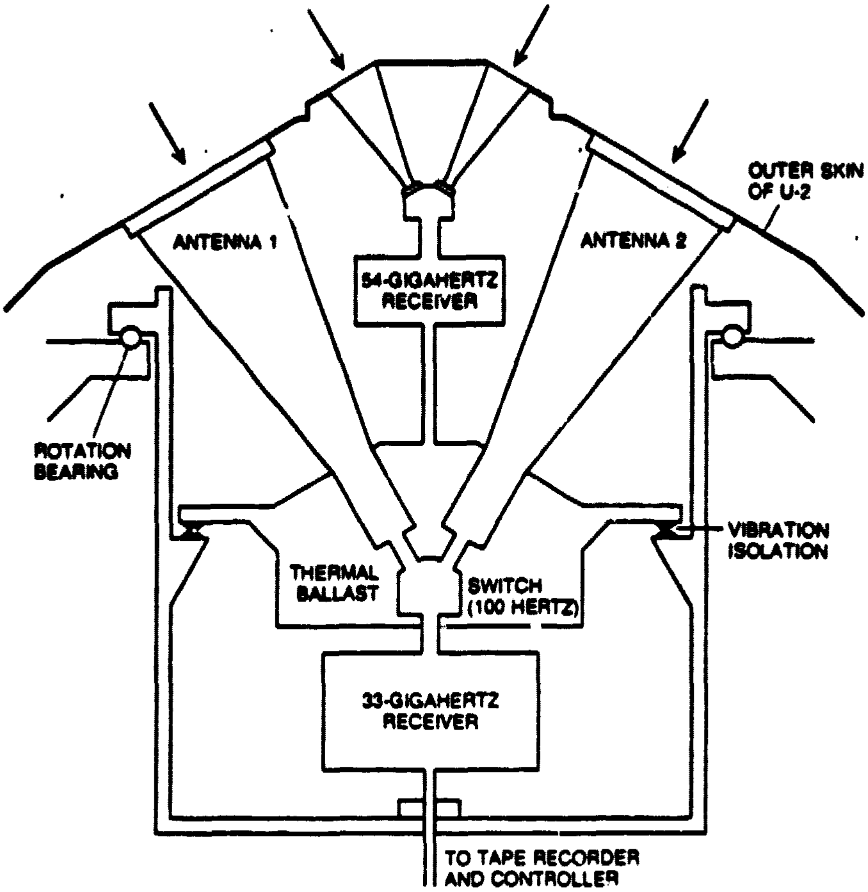
It was the realization that it might be possible to detect the new aether drift that inspired my colleagues and me to design an experiment that would improve significantly on previous measurements. We expected to discover that the motion of the earth was primarily due to the motion of the solar system around the center of our galaxy at about 300 kilometers per second, modified by a small factor to allow for the motion of the galaxy toward the Andromeda galaxy. (The relative motion of our galaxy and the Andromeda galaxy had been measured earlier by the Doppler shift of spectral emission lines as being 80 kilometers per second.) Only a small part of the expected aether drift would be due to the earth's motion around the sun at 30 kilometers per second.

Why were we excited about measuring such a well-known quantity? Our main interest was in the other possible effects: the spin of the universe, early signs of the formation of clusters of galaxies, gravity waves and an anisotropic Hubble expansion. In beginning a difficult experiment, however, it is reassuring to know that one will come out with a nonzero value of some kind. Although the other phenomena are interesting, and even a null result on them would be significant, it is frustrating to make precise measurements of zero.

When we began the experiment, the cosmic background radiation was known to be isotropic to a few millidegrees, or to better than one part in 500, owing largely to the careful measurements of Wilkinson and Robert B. Partridge of Princeton and Edward K. Conklin of Stanford University. Another Princeton experimenter, Paul Henry, had detected a small departure from isotropy, but his data did not fit a simple curve and the direction of maximum temperature was not accurately determined.

For our measurements we planned to use an instrument of the same general design as the one used in the preceding studies: a Dicke radiometer. With this device one measures not the absolute temperature of the cosmic radiation but differences in temperature between one direction in the sky and another. Although one might try to measure such differences by comparing the outputs from two receivers pointed in different directions, thermal noise in the two receivers and uncontrollable variations in their gain ("flicker noise") would swamp the minute differences expected. In the Dicke design the problem is avoided by switching the same receiver back and forth between two horn-shaped antennas pointed in different directions. If the experiment is carried out at the earth's surface, one tries to cancel the intense microwave emission from the oxygen in the atmosphere by pointing the two horns at the same zenith angle so that both "see" the same amount of oxygen.

To nullify small differences in the collecting power and emission of the two horns, or a possible asymmetry in the microwave switch connecting the horns to the receiver, the entire apparatus is rotated, interchanging the positions of the horns once a minute. With these precautions any asymmetry in the background radiation should show up as a



INSTRUMENT FOR MEASURING ANISOTROPY of the cosmic background radiation built by the author and his colleagues is shown schematically in cross section. The two large horn antennas are designed to collect cosmic background radiation in a narrow cone at a frequency of 33 gigahertz. The two smaller horns and their associated receiver monitor the emissions from atmospheric oxygen at 54 gigahertz. The apparatus is designed to measure not the absolute temperature of the cosmic background radiation but rather the difference in the temperature of the signals collected by the two large horns when they are switched alternately into a common receiver 100 times a second. To compensate for possible asymmetries in design and construction the apparatus is rotated 180 degrees every 64 seconds during collection of data.

fluctuation in the receiver output that coincides with the horn-switching rate.

In order to achieve a substantial improvement in sensitivity over earlier experiments we had to understand exactly what had limited the sensitivity of earlier measurements and to anticipate as best we could the problems that would be introduced by a new experimental design. The results of earlier experimenters had been limited in sensitivity primarily by the "synchrotron radiation" emitted by electrons accelerated in the magnetic fields of our galaxy. Although the intensity of the synchrotron radiation roughly follows the visible features of the Milky Way, its precise pattern in the microwave region of the spectrum is not known. The best one can do is to subtract an estimate of the synchrotron anisotropy from the total observed anisotropy and hope that what is left represents the anisotropy in the cosmic background radiation and not just an error in the estimate.

There is a straightforward way to reduce the interference introduced by synchrotron radiation, which is to move to wavelengths shorter than three centimeters. For example, between three centimeters and one centimeter the intensity of the synchrotron radiation falls by roughly a factor of three. Equally important, in the same wavelength interval the cosmic background radiation, following the black-body curve, becomes about 10 times stronger. The obstacle to operation at shorter wavelengths is the increased atmospheric emission: water vapor and oxygen make ground-based observations impossible at wavelengths shorter than about two centimeters. Water vapor is particularly troublesome because it can exist in patches that are not canceled by aiming a pair of antennas at the same zenith angle.

The obvious solution is to conduct the experiment at an altitude well above 50,000 feet, where the water vapor is almost totally frozen out. Mountaintop altitude is not enough. It is necessary to use either a balloon, an airplane or a spacecraft. Although we knew that a spacecraft experiment was potentially the most sensitive, an experiment in an airplane or a balloon is much less expensive and should certainly be done first. In discussing these problems with Hans M. Mark, who was then director of the Ames Research Center of the National Aeronautics and Space Administration, and Luis W. Alvarez of the Lawrence Berkeley Laboratory, we decided that the U-2 aircraft being operated by NASA for the study of earth resources would be an ideal platform for our experiment. At about the same time (mid-1973) Corey and Wilkinson at Princeton elected to use the gondola of a balloon as a platform for their anisotropy measurements. I shall not describe their experiment but instead concentrate on the problems that had to be solved for our U-2 undertaking.

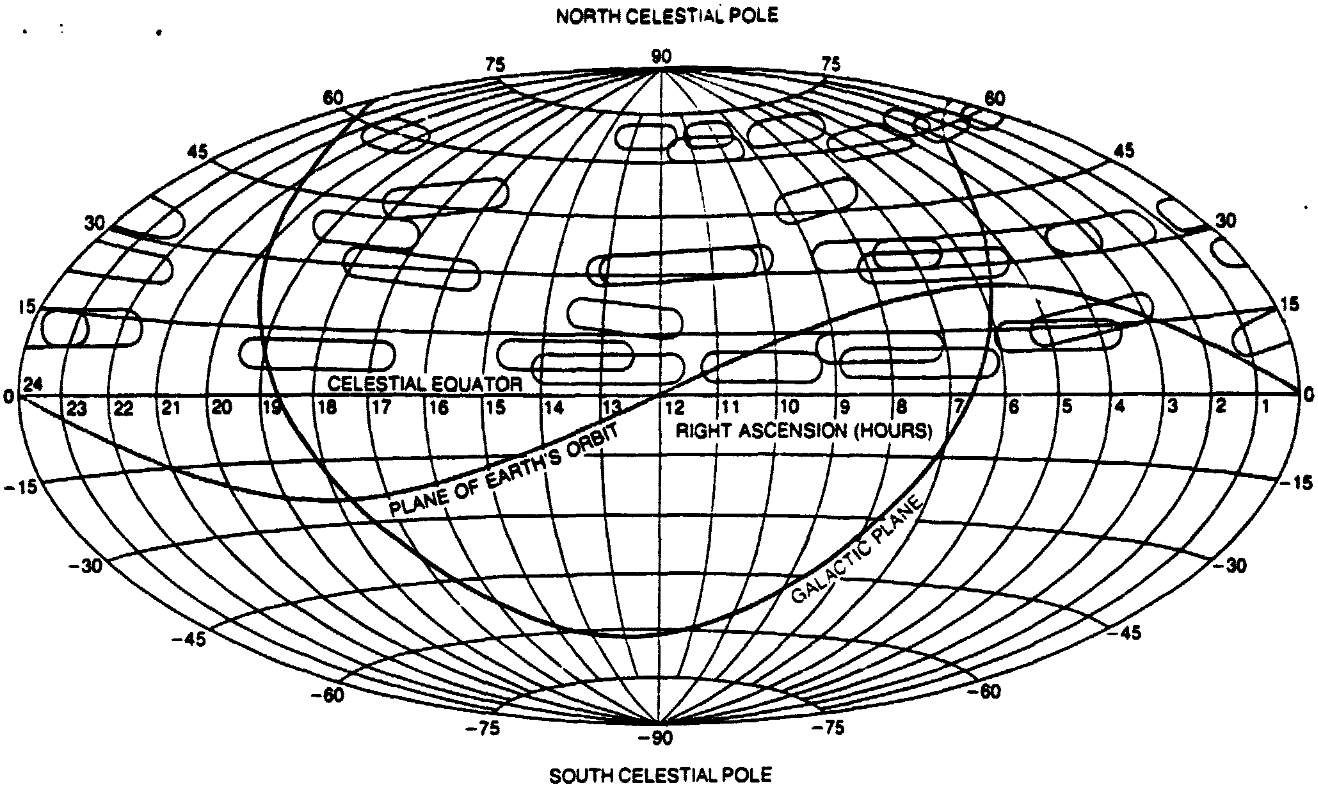
For an airborne experiment the time available is sharply limited, which meant that our receiver had to be as sensitive as possible. (In an experiment that can be conducted from the ground data can be averaged over many observations and provide sensitive results even without a low-noise receiver.) Unfortunately microwave receivers become progressively less sensitive at wavelengths below three centimeters. The constraints presented by receiver technology, the need to avoid troublesome interference from synchrotron emission at wavelengths much longer than 1.5 centimeters and strong atmospheric emission lines at wavelengths of several millimeters led us finally to choose a wavelength of .9 centimeter (a frequency of 33 gigahertz, or 33 billion cycles per second) as being optimum for the experiment. At that wavelength we thought our apparatus would be sensitive enough to detect an anisotropy of less than a thousandth of a degree, which would be more than adequate to determine the velocity at which the solar system is being swept around the galactic disk.

A major problem in an airborne experiment is the instability of the platform, which makes it difficult to ensure that both antenna horns are pointing at the same zenith angle and hence seeing the same volume of oxygen. We solved the problem by monitoring the zenith angle with a second radiometer tuned to a wavelength of .55 centimeter (a frequency of 54 gigahertz), a wavelength particularly sensitive to emission from atmospheric oxygen. With this arrangement we would be able to detect any asymmetry of the oxygen signal, whether it was due to a tilted airplane or to a tilted atmosphere. Since the earth is not a sphere but a quasi ellipsoid, the atmosphere is indeed often tilted with respect to the ground; the atmosphere is also tilted by weather fronts. If the tilt were large, the pilot would be asked to bank the plane in compensation. (The maneuver turned out not to be necessary.)

The size of our apparatus was severely limited by the space available within the rear hatch of the U-2, which made the design of the antennas particularly difficult. Since the earth is an intense emitter of microwave radiation, we had

PROBLEM	REMEDY
Synchrotron emission from galaxy	Make measurements at frequency above 10 gigahertz
Emission from galactic dust	Make measurements below 100 gigahertz
Emission from atmospheric water vapor	Collect data at altitude above 15 kilometers (with U-2)
Emission from atmospheric oxygen	Use twin horn antennas at high altitude and monitor oxygen emission at 54 gigahertz
Emission from sun	Fly at night
Emission from earth	Use dual-mode corrugated horns with narrow field of view
Emission from horn antennas	Symmetrize emission by careful temperature control
Thermal noise in receiver	Integrate signal for 20 minutes
Receiver flicker noise (∝ 1/frequency)	Switch between two horn antennas 100 times per second
Asymmetry of airplane	Reverse flight path every 20 minutes
Asymmetry in experimental apparatus	Rotate equipment itself every 64 seconds
Bias from earth's magnetic field	Carefully shield microwave switches
Radio emission from U-2	Place metallic shields around sensitive parts and minimize communications to U-2
Geometric distortion of atmosphere due to nonsphericity of earth	Determine "zenith" from oxygen signal rather than from earth's horizon or flight instruments

PRINCIPAL PROBLEMS associated with measuring the anisotropy of the background radiation are listed with the remedies adopted by the investigators. They and their associates spent three years planning the experiment and building the equipment before the first test flight.



REGIONS OF SKY SURVEYED by the new aether-drift experiment are plotted on an equal-area projection of the celestial sphere. All the flights were made at night (in order to avoid the microwave emission from the sun) and were spread out over a period of roughly a year (in order to scan as much of the sky as can be observed from a base in northern California). Flights in the Southern Hemisphere, which are proposed for the current year, will help to verify the pattern of the detected anisotropy in temperature. Typical flights lasted four hours and surveyed four different regions of the sky. Each of the horn antennas was sensitive to a region of the sky about seven degrees across. The length of each scan was determined primarily by rotation of the earth rather than by the 400-knot speed of the airplane.

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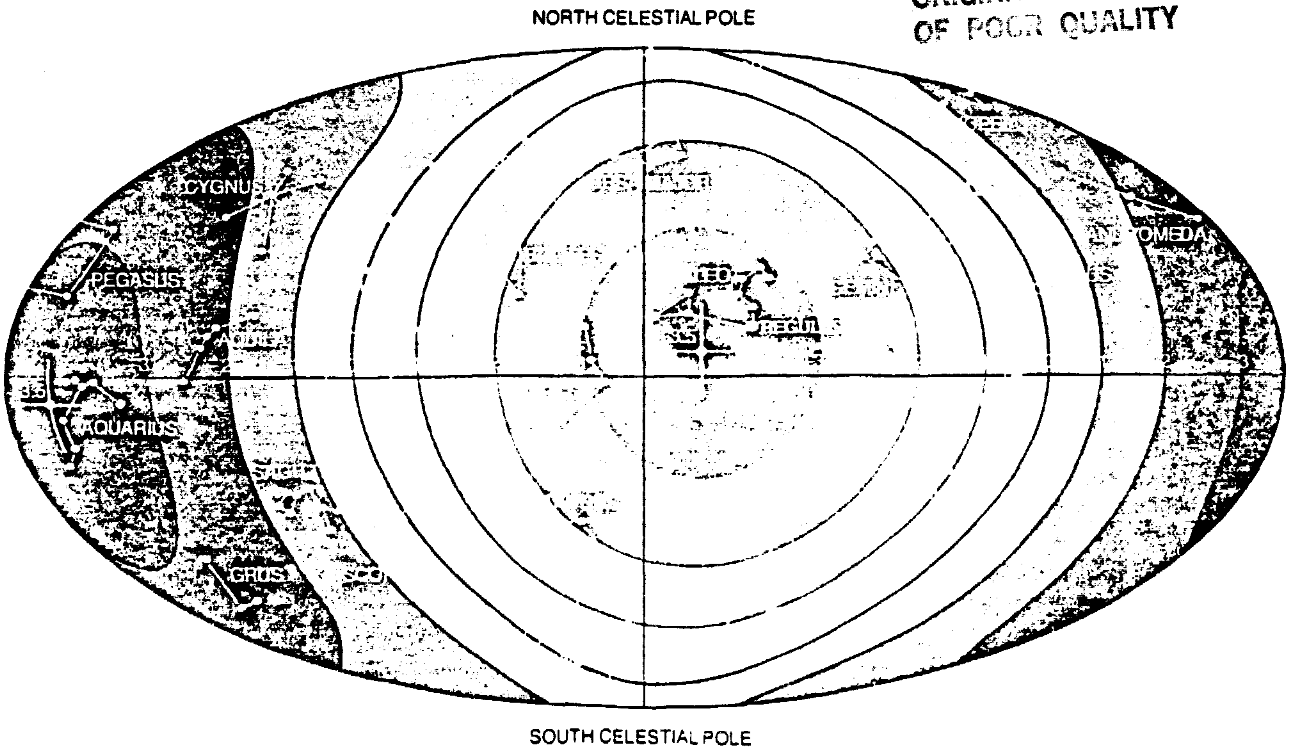
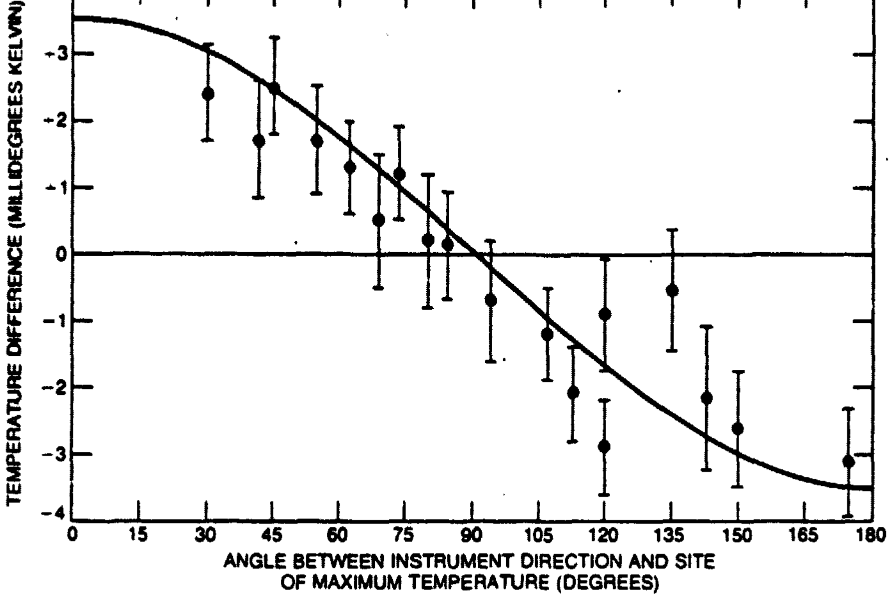
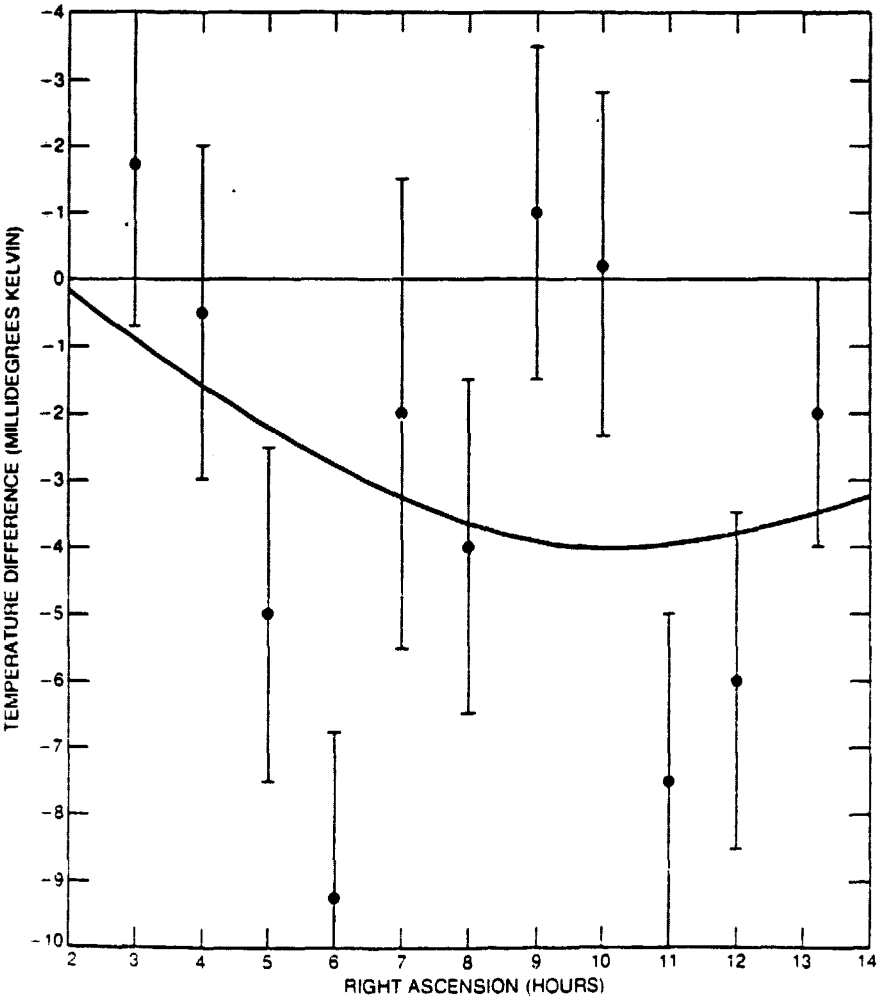


ANISOTROPY OF THE BACKGROUND RADIATION, as deduced from the U-2 survey, is plotted on the celestial sphere in contours of one millidegree K. The "hottest" spot, indicating the direction of the earth's maximum relative motion toward the background radiation, lies in the constellation Leo at right ascension 11 hours (±.5 hour) and latitude six degrees (±10 degrees). The "coldest" spot, the direction in which the radiation is most "reddened" by the earth's relative motion away from the incoming photons, lies 180 degrees away in Aquarius. If the temperature difference between hottest and coldest points is plotted against distance, the result is a cosine curve.



COSINE CURVE provides the best fit for the data (averaged into 18 points) taken by the author and his colleagues in the new aether-drift experiment. The horizontal axis represents the angle made by a line connecting the two horn antennas and the direction of maximum temperature in Leo. The cosine curve is temperature distribution to be expected in the cosmic background radiation if the solar system's peculiar velocity toward Leo is 400 kilometers per second.



FIRST SIGNIFICANT DEVIATION FROM ISOTROPY in the cosmic background radiation was detected by Paul Henry of Princeton University with an instrument that was carried aloft by a balloon. The anisotropy in the radiation shows up in the preponderance of data points lying below the zero line. The scatter in the points, however, made it impossible to establish distribution of anisotropy or to determine precisely direction of maximum temperature.

to find a way to shield our antennas. Ground-based experiments had solved the problem with large metallic reflectors that intercepted and reflected the earthshine. Our solution was a special horn antenna designed to have an extremely small pickup from directions more than 60 degrees from the horn axis. The small space available in the U-2 also required that the apparatus be fully automatic, since there was no room in the airplane for a scientist passenger. Another nontrivial problem was that the U-2 is designed to carry cameras that look down, and we wanted to look up. One does not cut a hole in the top of a skin-stressed airplane such as the U-2 without considerable planning, but the modification was achieved with the help of the NASA staff at the Ames Research Center and engineers of the Lockheed Aircraft Corporation, which was responsible for the maintenance of the aircraft.

These were just a few of the problems we had to address in the experiment. Part of the challenge of a novel experiment is trying to anticipate new problems and deal with them. Much credit belongs to my collaborators Smoot and Gorenstein, who had the chief responsibility for transforming a theoretical plan into a successful experiment.

After three years of planning, construction and testing we mounted the apparatus in the U-2 in July, 1976. We made various modifications after a series of test flights and continued to make others during the data-taking period, which began in December of that year. All the data-taking flights were made at night, since even our special horn antennas picked up microwave signals from the sun. There was also no practical way to shield our apparatus from uneven solar heating. Microwave emission from the moon, when it was at the correct angle for it, provided a handy way to calibrate the receiver gain in flight.

The data collected from the first few flights revealed an unmistakable departure from isotropy in the cosmic background radiation. To get a clear picture of the anisotropy, however, we had to have flights spread out over a full year so that the antennas could scan as large a fraction as possible of the celestial sphere visible from northern California. By the end of last year the data from 10 flights plotted into the distinct cosine curve one would expect if the solar system were moving with a high cosmological velocity. A similar anisotropy was detected at a wavelength of 1.6 centimeters by the 19-gigahertz radiometer flown in the gondola of a balloon by Corey and Wilkinson. In both the Berkeley and the Princeton experiments the magnitude of the anisotropy was consistent with that first reported by Henry.

Our data indicate that the temperature of the cosmic background radiation reaches a maximum of .0035 degree (3.5 millidegrees) above the average value in a direction defined, in the usual celestial coordinates, as 11 hours right ascension and six degrees north latitude, or about 15 degrees east-southeast of Regulus, the brightest star in the constellation Leo. The velocity of the solar system in that direction can be computed by dividing the maximum temperature difference, .0035 degree, by the average temperature of the cosmic background radiation, 2.7 degrees (the best current value), and multiplying the result by the velocity of light. The answer is a velocity of 390 kilometers per second.

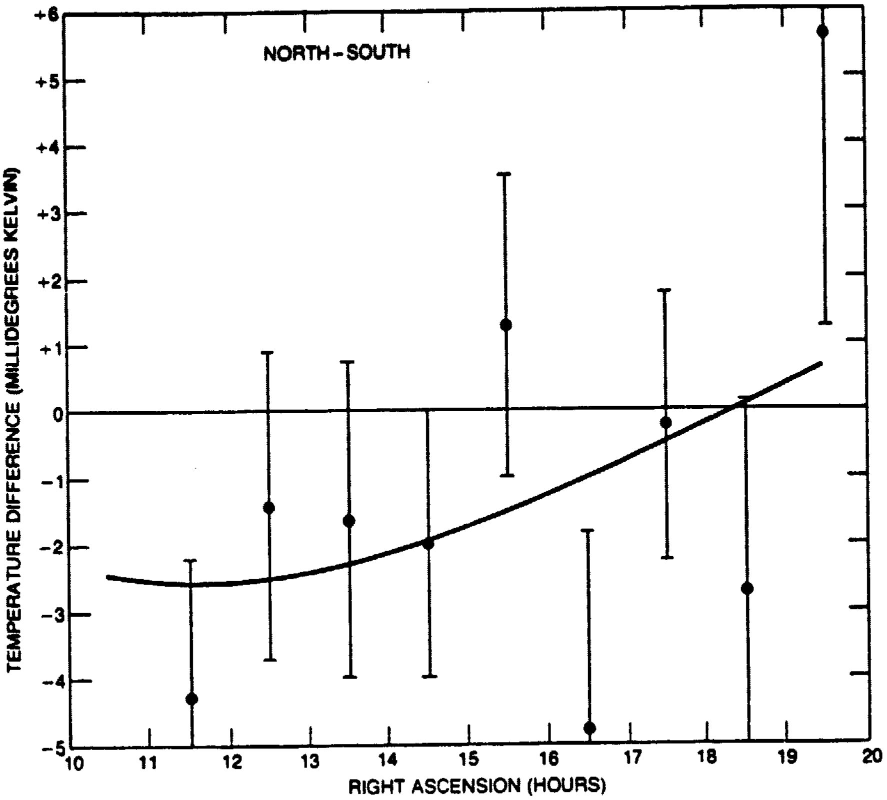
Although this velocity is not much greater than that of 300 kilometers per second expected from the solar system's motion around the center of the galaxy, it is in a different direction. Since the velocity of the solar system is the sum of the velocity due to the rotation of the galaxy plus any peculiar velocity of the galaxy, we could take our measured number and by properly handling the vectors calculate the peculiar velocity of the galaxy. When we did this, we found that the galaxy must be moving at about 600 kilometers per second with respect to the cosmic background radiation.

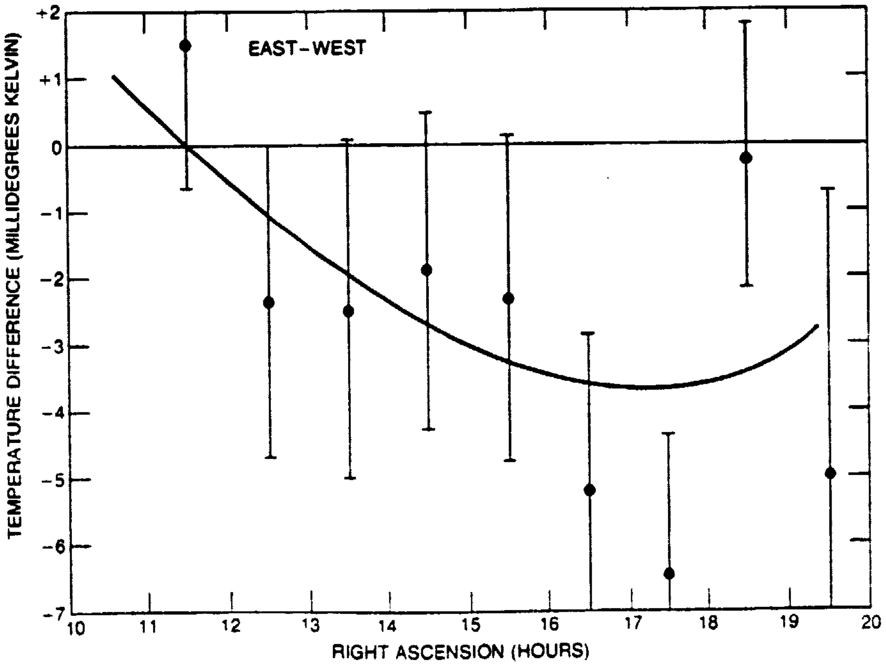
Except for the cosine variation in temperature the background radiation was found to be isotropic to better than one part in 3,000, placing strict limits on several of the phenomena I have mentioned. If the universe is rotating, its rate of rotation must be less than 10^{-9} second of arc per century. If large-scale gravity waves exist, they do not have sufficient energy to close the universe or to reverse the Hubble expansion into an implosion. The expansion itself must be isotropic to one part in 3,000. There is also no evidence of the early formation of clusters of galaxies, indicating that very-large-scale clustering did not exist at the moment of decoupling.

Perhaps the most fascinating and unexpected result of the experiment is the size of the implied cosmological velocity of the galaxy. Since the motion of our galaxy relative to the Andromeda galaxy is small (80 kilometers per second), the Andromeda galaxy must share this high velocity through space. Moreover, it is known that the peculiar (non-Hubble) motion of our local group of galaxies relative to the nearest large cluster of galaxies, the Virgo cluster, is small; thus the entire Virgo cluster must have a cosmological velocity similar to ours. The picture that emerges is of a vast volume of space, tens of millions of light-years in radius, moving with a velocity of roughly 600 kilometers per second with respect to the distant universe.

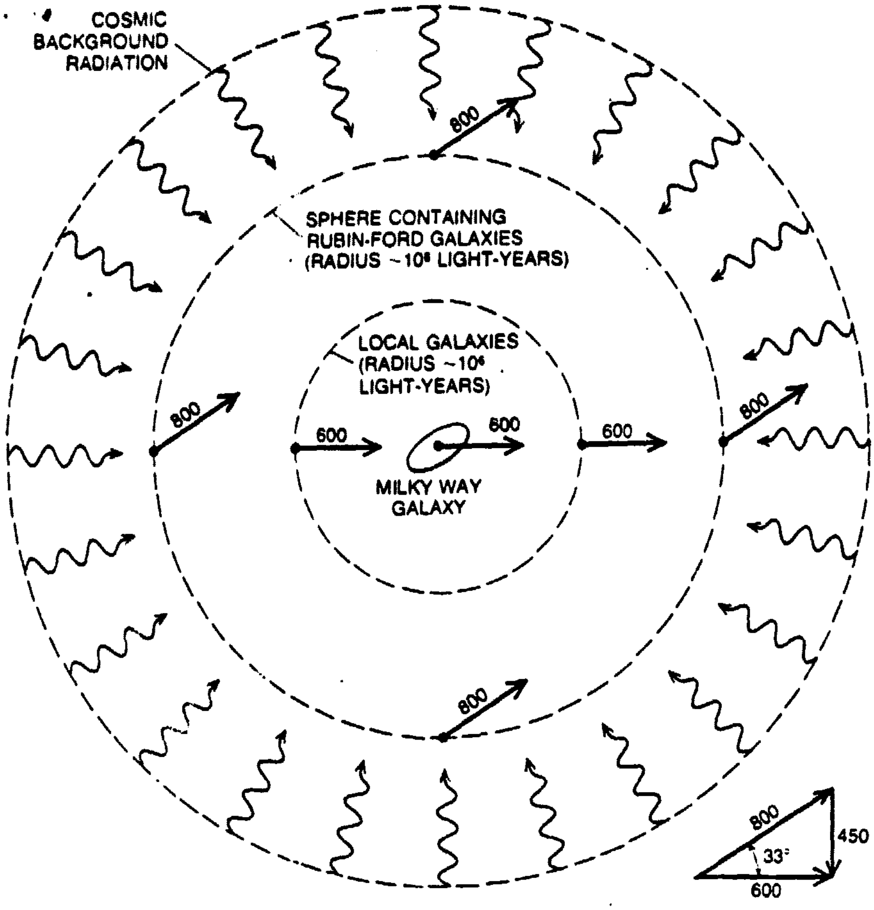
The picture becomes more complicated when we look farther out into the local regions of space. Prior to our work Vera C. Rubin and W. Kent Ford, Jr., of the Carnegie Institution of Washington's Department of Terrestrial Magnetism had with their colleagues analyzed the motion of our galaxy relative to an all-sky sample of spiral galaxies some 100 million light-years away. They concluded that relative to the sample the solar system has a net velocity of 600 kilometers per second. After allowing for the fraction of the velocity of the solar system that is due to galactic rotation, they calculated that our galaxy is moving relative to the sphere of reference galaxies at a velocity of about 450 kilometers per second.

Our measurement of our galaxy's peculiar velocity, as determined from the

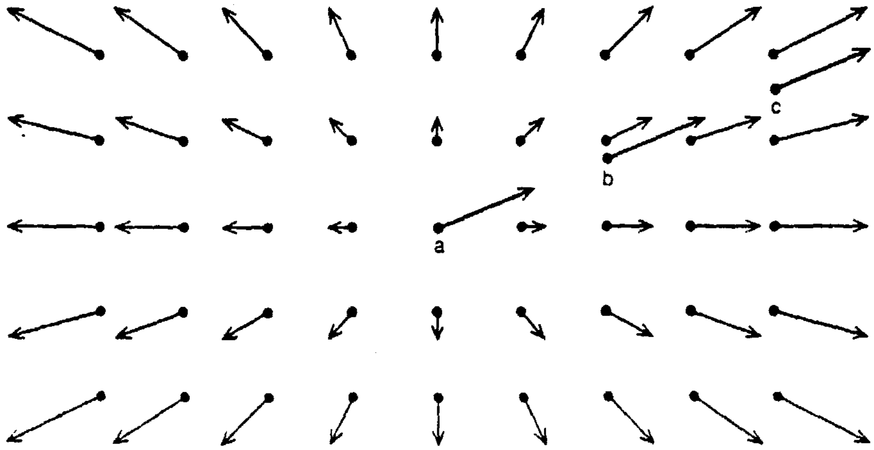




SECOND PRINCETON EXPERIMENT, conducted by David T. Wilkinson and Brian E. Corey with a balloon-borne instrument operating at a frequency of 19 gigahertz, supports the Berkeley U-2 measurements. Because the Princeton workers plot their data differently (with a north-south projection and an east-west projection) the similarity between their results and the Berkeley ones is not readily apparent. It is clear, however, that the Princeton data define cosine curves. Princeton group concluded that the earth is moving at 300 (±70) kilometers per second toward right ascension 12 (±2) hours and latitude −10 (±20) degrees in the celestial sphere.



FANTASTIC VELOCITY PICTURE emerges when the peculiar velocity of our galaxy, evidently shared by all the members of the local cluster of galaxies, is plotted in relation to a sample of galaxies 10^8 light-years away whose velocities were analyzed spectrographically by Vera C. Rubin and W. Kent Ford, Jr., of the Carnegie Institution of Washington's Department of Terrestrial Magnetism. Their results imply that our galaxy is moving at 450 kilometers per second with respect to those in the reference sample. The diagram shows how the Rubin-Ford velocity can be reconciled with the peculiar velocity of 600 kilometers per second determined for our galaxy by the anisotropy in the cosmic background radiation. The Rubin-Ford sphere of galaxies would require a peculiar velocity of 800 kilometers per second displaced roughly 33 degrees from the direction in which our galaxy is moving. Diagram at right shows how our galaxy would then be carried toward the Rubin-Ford galaxies at 450 kilometers per second. In view of uncertainties in measurements the velocities are rounded to 50 kilometers per second.



CONVERSION OF PECULIAR VELOCITY into Hubble velocity, the cosmic velocity of expansion, can be expected to take place in time. The vector arrow *a* represents the current peculiar velocity of our galaxy, shown embedded in a space that is expanding uniformly. As our galaxy moves outward it will overtake other galaxies (*b*) until it reaches a region (*c*) where its velocity matches that of neighboring objects. Our galaxy will then no longer exhibit a peculiar velocity; its motion with respect to nearby matter will tend toward zero. A similar argument shows that in the past our galaxy's peculiar velocity must have been greater than it is today. This line of reasoning is invalidated, of course, if the peculiar velocity arises from a local effect, such as the rotation of a cluster of galaxies, in which case the peculiar velocity would oscillate.

cosmic background radiation, not only is a third greater than the Rubin-Ford velocity but also differs in direction from theirs by more than 100 degrees. The two sets of velocity measurements can be reconciled by assuming that the Rubin-Ford sphere of galaxies is moving with a cosmological velocity of about 800 kilometers per second in a direction offset by approximately 33 degrees from the direction in which we are drifting at 600 kilometers per second through the radiation "aether" left by the big bang.

This remarkable picture is even more surprising when one realizes that a high peculiar velocity today may imply a still higher one in the past. As a galaxy moves through space with a high peculiar velocity it eventually catches up with other galaxies whose recessional velocity corresponds to the average Hubble expansion. Hence a high peculiar velocity is gradually transformed into a typical Hubble velocity, with the net result that peculiar velocities must decrease with time. Extrapolating backward, one finds that at the moment of decoupling the peculiar velocity of the stuff of which our galaxy was made must have been close to the speed of light. On the other hand, if the peculiar velocity were due to local turbulence or to orbital motion around a distant point, such an extrapolation might not be correct. The velocity of our local group of galaxies with respect to the nearby (on a cosmic scale) Rubin-Ford galaxies does in fact suggest there is considerable turbulence in the universe.

Before one accepts this turbulent picture of the large-scale structure of the universe, one should recall that our observation of the cosmic background radiation shows that except for the cosine component the radiation is uniform to at least one part in 3,000. It is not obvious how to reconcile the featureless nature of the background radiation with a high degree of local turbulence. To be sure, the local peculiar velocities are characteristics of the present universe, whereas the background radiation is a snapshot of the universe taken 15 billion years ago. Conceivably the universe possesses some large-scale structure, such as the rotation of a supercluster of galaxies, that will reconcile the apparently contradictory results.

Perhaps the most perceptive criticism of the homogeneous isotropic big-bang model is that it is far too simple to represent reality. One is easily tempted to assume that the unknown is simple. It is possible, indeed likely, that there are large-scale structures that play an essential role in determining the nature of the universe. With recent measurements of the large-scale clustering of galaxies and the anisotropy of the cosmic background radiation we may be just beginning to detect that structure.

The Author

RICHARD A. MULLER is associate research physicist at the Space Sciences Laboratory of the University of California at Berkeley and at the Lawrence Berkeley Laboratory of the University of California. He was educated at Columbia University and at Berkeley, where he earned his Ph.D. in elementary-particle physics in 1969. Since then his diverse research interests have included (in addition to the measurements of the cosmic background radiation described in his article) the development of a telescope mirror that compensates automatically for atmospheric distortion, the search for quarks with unit charge and the development of a new technique for radioactive-isotope dating. Recently Muller, his wife and his sister opened a gourmet restaurant in Berkeley. "Whenever I get totally frustrated with experimental physics," he writes, "I switch gears and work on the wine list for the restaurant."

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