N O T I C E

FINAL REPORT

FOR

"AETHER DRIFT" AND THE ISOTROPY OF THE UNIVERSE -

A Measurement of Anisotropies in the Primordial Black-Body

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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 $3^{o}K$ primordial black-body radiation with a sensitivity of $2 \times 10^{-4}\ ^{o}K$ and an angular resolution of about 10^{o}. 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 in both the northern and southern hemispheres. Data taking and analysis to measure the anisotropy have been successful.

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I. Introduction

The Earth is bathed in an apparently universal $3^{o}K$ 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} ^{o}K. We have detected a first order spherical anisotropy of about 3 m^{o} K which is interpreted as the motion of the Earth and solar system at 350 km/sec relative to the black body radiation. 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^{o} 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 $3^{o}K$ 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

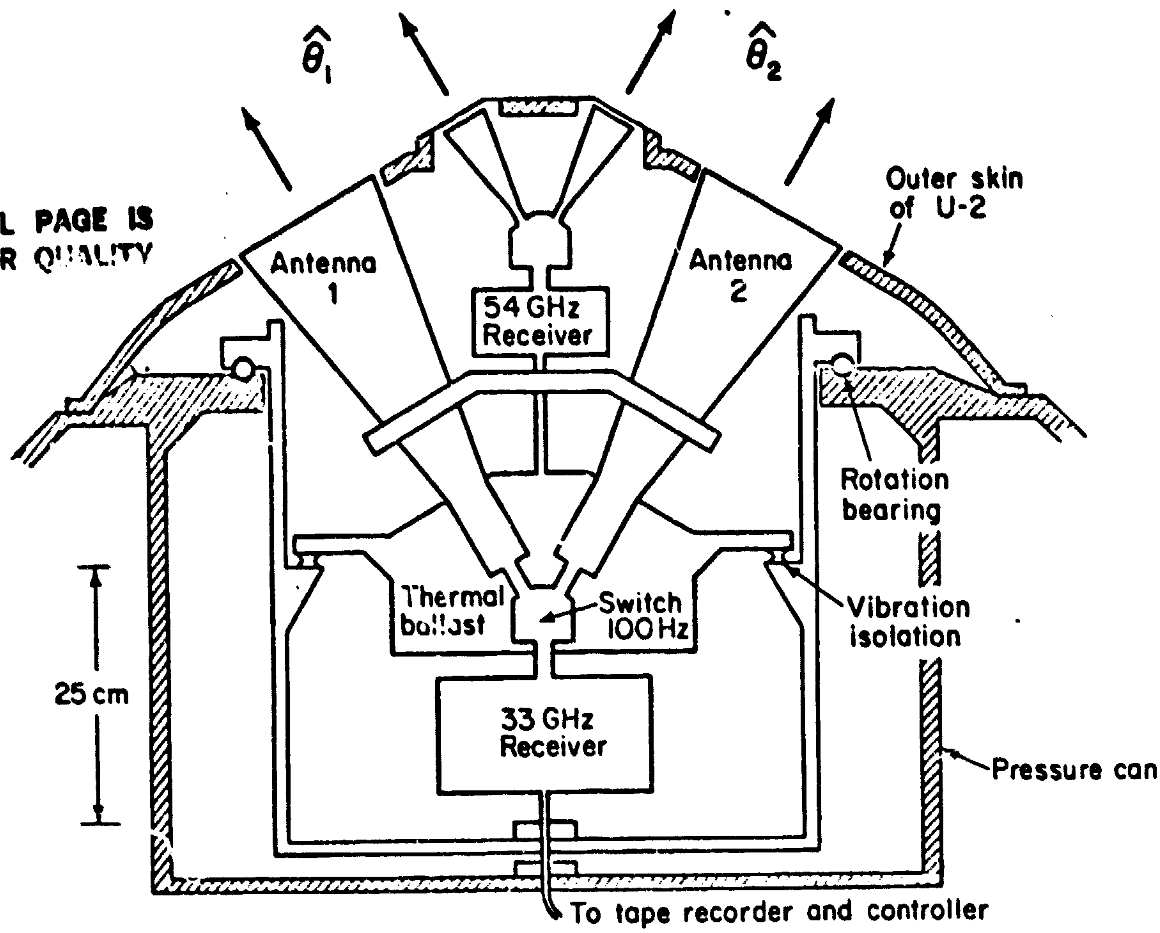

Figure 1. Schematic of Apparatus in U-2 Hatch.

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.

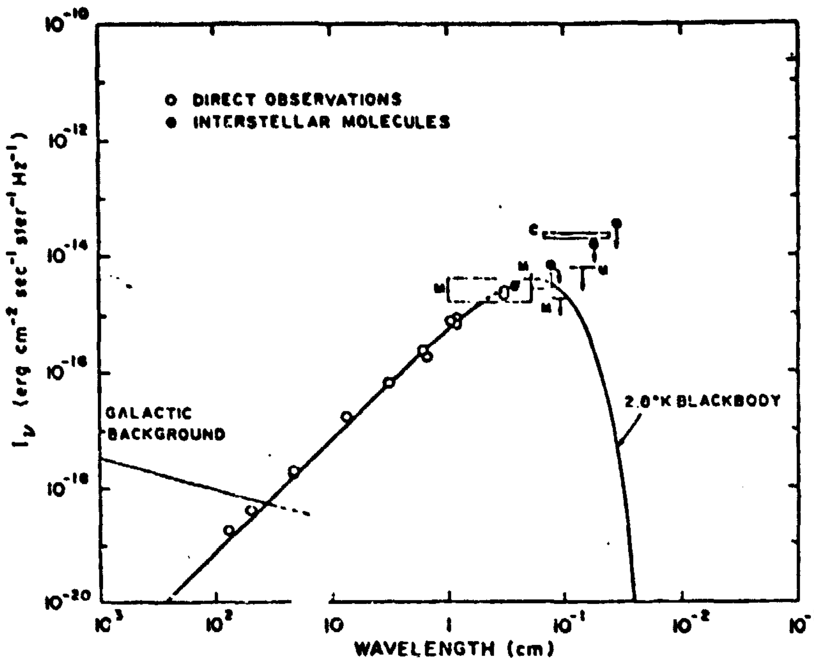

Figure 2. Measurement of the microwave background. (Taken from P. Thaddeus, Ann. Rev. Astron. and Astrophys. 10, 305 (1972)).

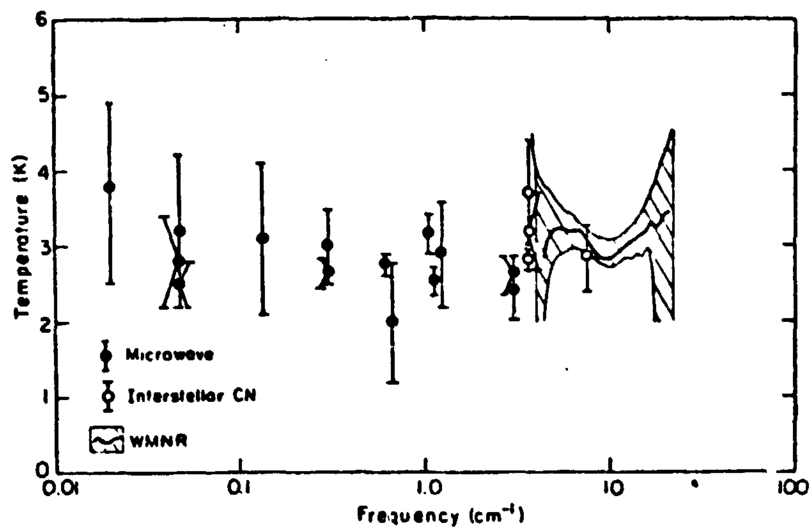

FIG. 3. The present measurement (±2σ) of the thermodynamic temperature of the cosmic background radiation compared with selected results of other experiments. The data for frequencies ≤3 cm^{-1} were obtained using ground-based microwave radiometers (see Ref. 1). The data at 3.8 and 7.6 cm^{-1} were 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 ^{o}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 ^{o}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. 174, 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 ^{o}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 $V_{\bullet} = 2 \pm 40$ 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 <u>caused</u> 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

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

III. Experiment Status and Results Prior to Southern Hemisphere Flights

The highlight of our results prior to flights in the southern hemisphere 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 as of March 1978.

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.

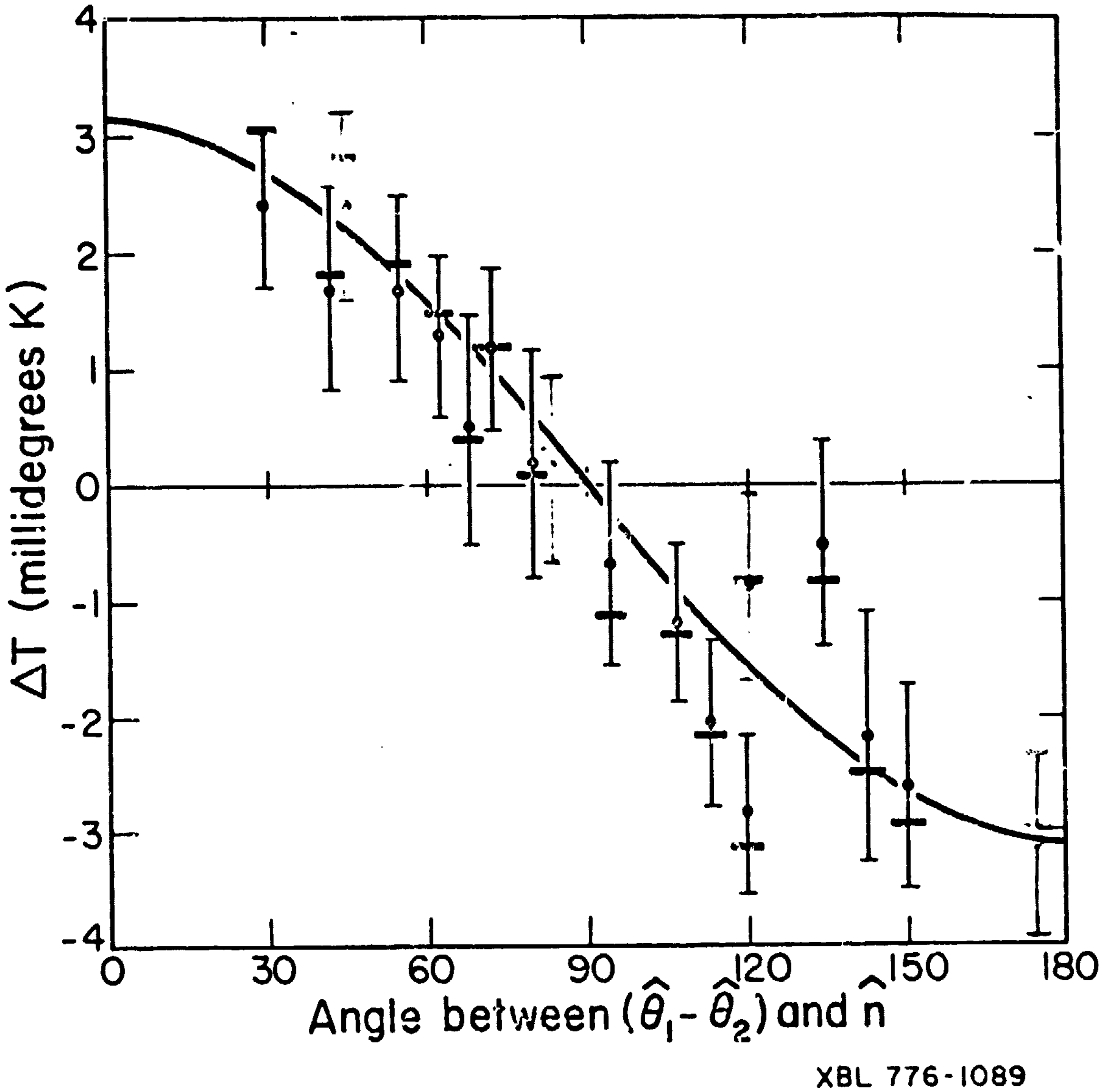

Figure 4

Fit to First Order Spherical Harmonic

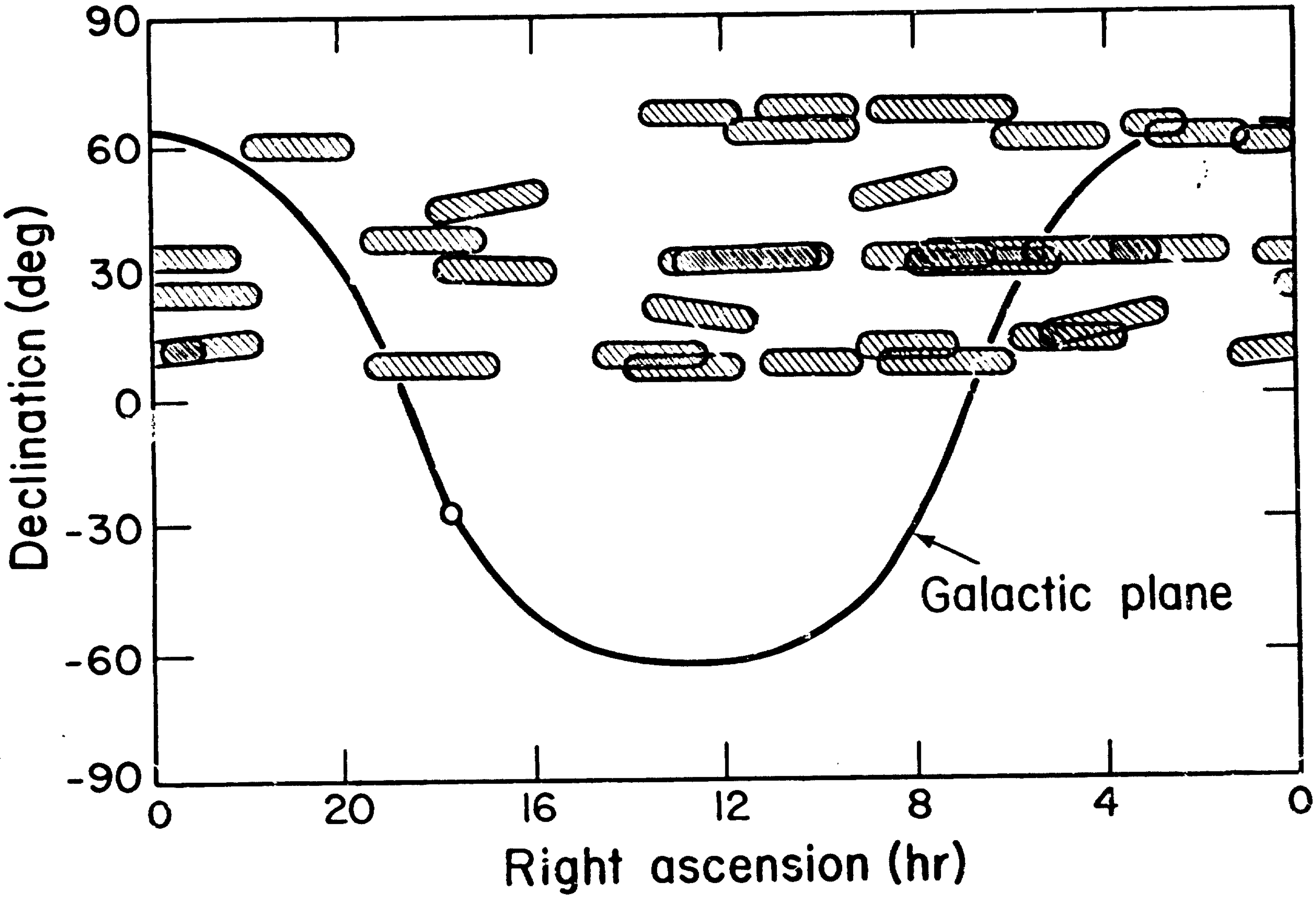

Figure 5 Sky Coverage as of March 1978

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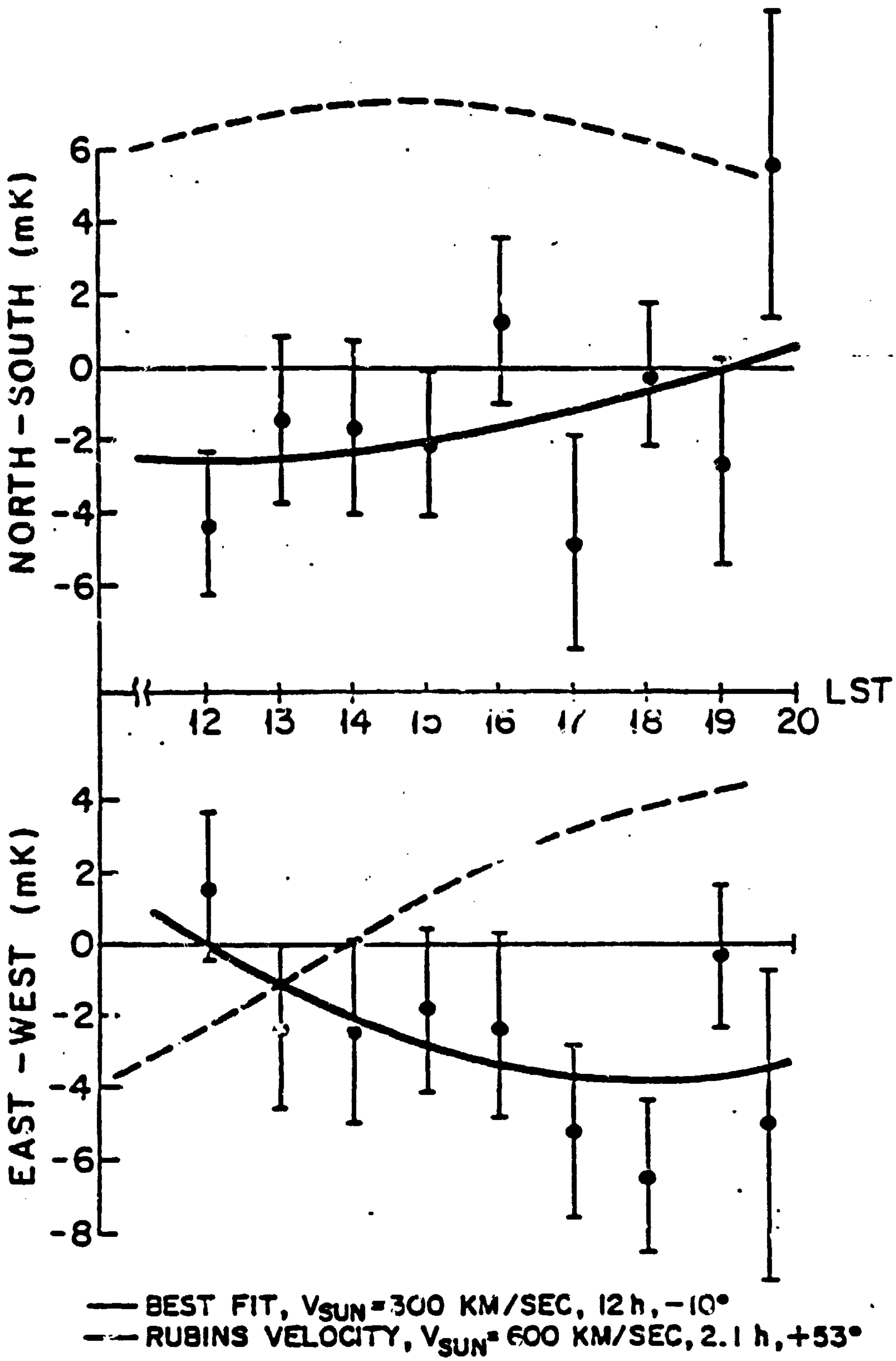

Figure 6. Balloon measurements of background isotropy at 19 GHz by Corey and Wilkinson.

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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

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

* 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 so far analyzed 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 ascension, 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. We expect our flights from Peru (at roughly the same latitude) will 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 are expected to drop below 0.5 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. SOUTHERN HEMISPHERE FLIGHTS

U2 operations were undertaken in Peru in order to provide southern sky measurements of the cosmic background radiation. Flights from Lima, Peru took place on the nights of March 2, 3, 4, 5. Supportive ground based measurements were taken from March 2 to 21. A press conference was conducted on March 2 and significant interaction with the press, public and some Peruvian officials continued through March 6.

The observation of previously unexplored regions was 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. We were hoping to improve our limit on the quadrupole and higher order anisotropies by a factor of two or one part in 6000, putting the Cosmological Principle to a strong test.

Our results conclude that we have detected a southern-hemisphere anisotropy that is consistent with the first-order anisotropy measured in the northern hemisphere. These southern sky measurements further reduce the correlation between spherical harmonics of low order.

The net anisotropy from the combined data can be described by a first-order spherical harmonic (Doppler) anisotropy of amplitude 3.1 ± 0.4 mK with a quadrupole component of less than 1 mK. Additional ground based measurements of the linear polarization yield an upper limit of mK, or one part in 3000, at a 95% confidence level for the amplitude of any spherical harmonic through third order.

V. CONTINUING WORK

We are working on several changes in instrument design to increase sensitivity of the radiometer, reduce systematic effects and improve the quality of anisotropy data.

We plan to modify the radiometer to incorporate a liquid nitrogen cooled receiver with a GaAs diode balanced mixer and GaAs FET IF amplifier. The cooled receiver should have a system temperature of about 200 K over a 500 MHz bandwidth. The radiometer will then have a sensitivity of 19 mK$(t/sec)^{-1/2}$, an improvement by a factor of 2.7 over the ambient temperature system. With the improved sensitivity, we should be able to achieve an rms error of 0.15 mK on the dipole and quadrupole anisotropy coefficients with four U2 flights.

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%. A simple in-flight calibration using the moon as a noise source is, at best, accurate to $\pm$ 5%. We have therefore installed a calibrator that utilized a 60,000 K noise diode coupled into one of the antennas to produce a signal of about 1 K. The calibrator is automatically turned on for 8 seconds every 8 and 1/2 minutes during normal in-flight operation.

We estimate that the other systematic errors are 25% of our statistical errors. We are in the process of refining our estimates of systematic backgrounds. For example, we have 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.

The addition of antenna windows constructed out of a single layer of Saran wrap prevents the airstream from entering the antenna horns during data-taking at altitude. Differential wind cooling between the antennas can cause a measurable offset in the radiometer. If the airstream is uniform, the offset can be removed by rotating the apparatus; however, changing wind patterns will introduce spurious signals. While it is still somewhat uncertain whether the windows will actually reduce the variations in differential emission along the antennas, preliminary tests indicate that the Saran wrap greatly decreases heat loss from the antennas. In-flight, the antenna apertures are approximately 40°C warmer with the windows in place, reducing thermal gradients along the horns and resulting in improved thermal stability.