3 mm **Measurements of Anisotropy in the Cosmic Background Radiation.**

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1. – Introduction.

The large-scale anisotropy in the cosmic background radiation is one of the best probes available for studying the large-scale structure of the Universe. Since the first measurements were begun in the late sixties by David WILKINSON and associates at Princeton, the promise of finding an intrinsic anisotropy and hence an imprint of the structure of the Universe itself has lured many experimenters. It soon became evident that any intrinsic variation would be at a very low level and emphasis shifted toward the near certain goal of detecting the dipole anisotropy due to our motion. The effect was expected at the 0.1% level since typical galactic velocities were on the order of 0.1% of the speed of light. This proved to be a difficult task which took nearly ten years. By 1977, after several earlier tentative indications of detection, the Princeton and Berkeley groups using high-altitude platforms finally had firm evidence for a dipole anisotropy of amplitude about 3 mK [1, 2], at least near 1 cm wavelength.

Papers in 1980 by FABBRI *et al.* [3] of Florence and in 1981 by BOUGHN, CHENG and WILKINSON [4] of Princeton claimed to have evidence for a quadrupole component at about the 0.5 to 1 mK level. The Florence work was done in the millimeter wavelength range using broad-band incoherent techniques with sensitivity from 0.5 to 3 mm and fairly limited sky coverage. The Princeton results used narrow-band centimeter wavelength coherent techniques at several frequencies from 19 to 46 GHz (*) and had good sky coverage

(*) Coherent experimenters (those using coherent techniques such as mixers) tend to use frequency rather than wavelength. Incoherent experimenters, on the other hand, use wavelength or even wave numbers (cm^{-1}). As some of my best friends are incoherent experimentalists, I will not belabor the point.

(essentially the entire northern hemisphere). The limited sky coverage of the Florence results makes direct spherical-harmonic decomposition difficult because the correlations between the harmonics would be high. A direct comparison between the Florence and Princeton quadrupole results is not available, but the amplitudes are similar. These results generated a flurry of theoretical activity with excellent work being done by PEEBLES [5] at Princeton and SILK and WILSON [6] at Berkeley, as well as others. The main theoretical thrust is to correlate mass inhomogeneities at various scales with anisotropies at various scales. For simple models the anisotropy is correspondingly larger at larger angular scales. If so, this would mean that a portion of the dipole would also be intrinsic and hence interpretation of our motion relative to nearby matter would need to take this into consideration.

2. – Backgrounds and systematic errors.

2·1. *Galactic emission.* – There are a number of systematic errors and backgrounds which need to be addressed in any anisotropy measurement. One of these backgrounds is the radiation from our Galaxy. At long wavelengths ($\lambda > 1$ cm) the dominant emission is from synchrotron radiation and thermal bremsstrahlung (H II). At short wavelengths ($\lambda < 1$ mm) dust emission is thought to dominate. At very low frequencies ($\nu \sim 1$ GHz) full sky surveys exist and can be scaled to higher frequencies using theoretical arguments as well as a few limited sky coverage measurements at higher frequencies [7]. This is difficult to do precisely because at 1 cm wavelength, for example, the scaling ratio from 1 GHz is very large: $30^{2.1} \sim 10^3$ for H II and $30^{2.8} \sim 10^4$ for synchrotron in terms of equivalent antenna temperatures. Small errors in the exponent can give large errors in the scaling. Because absolute flux measurements are difficult, the low-frequency surveys are also subject to substantial errors, especially in regions of the sky which are relatively uniform in emission (away from the galactic plane). Recent measurements by the Princeton group [8] suggest that the previous estimates of galactic emission at centimeter wavelengths were underestimated. Because the Galaxy has somewhat of a quadrupole distribution, it must be considered in the centimeter anisotropy measurements.

Dust emission from the Galaxy is not well mapped on a large angular scale, although it is concentrated near the plane of the Galaxy. The spectral index of the dust emission is not known, with estimates of the frequency spectral index of emissivity running between 0.5 and 2. Recent measurements by WEISS (private communication) and associates at MIT suggest a spectral index closer to 2.

The recent results mentioned and our own measurements at 3 mm give the galactic background estimates shown in fig. 1. In a few years, with more precise experiments already planned, better estimates should be available. There appears to be a minimum in the galactic emission somewhere in the 2 to 5 mm wavelength range, although because of qualitative differences between synchrotron, H II and dust emission a simple comparison may be misleading.

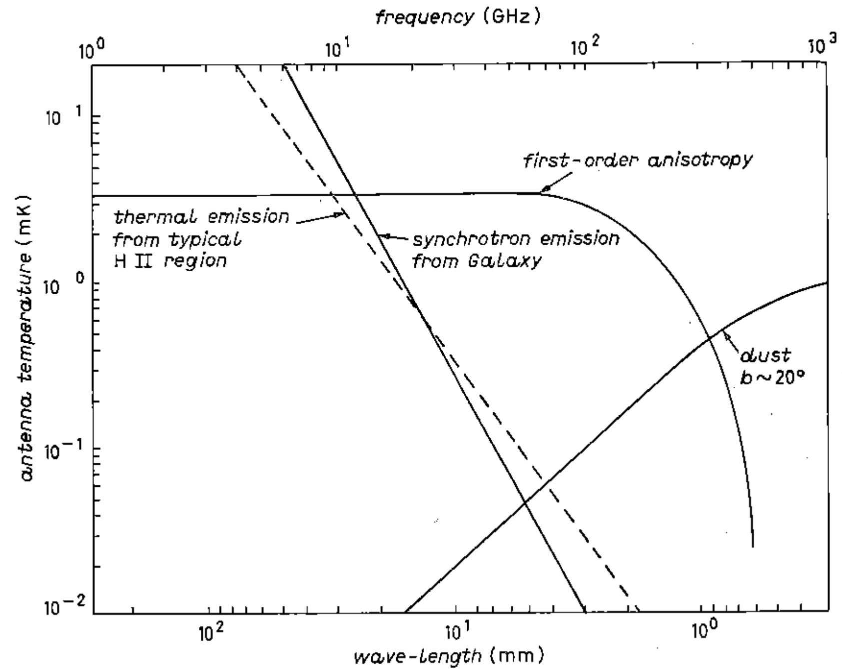

Fig. 1. – Estimated galactic backgrounds in antenna temperature as a function of wavelength. Numbers are tentative as few good measurements exist. Dust is based on cosecant fits to high-frequency data $\lambda < 3$ mm from Weiss and to our own fit at 3 mm. b is galactic latitude.

It is clear, however, that because of the quadrupole nature of the Galaxy and because the Galaxy is a background in both the Princeton and Florence quadrupole results, the Galaxy needs to be modeled very carefully in searching for any possible cosmological quadrupole.

2·2. *Sky coverage.* – Good sky coverage is critical in obtaining reliable estimates of quadrupole and higher-order anisotropies. With poor sky coverage, correlations between the various dipole and quadrupole components can lead to erroneous results in the sense that power from the dipole components can be transferred to the quadrupole components by various systematic errors such as pointing and calibration (from flight to flight) errors.

3. – 3 mm experiment.

3'1. *Motivation.* – The motivations for doing an isotropy experiment at 3 mm wavelength are 1) to check for the effects of the spectral distortions reported by WOODY and RICHARDS [9], 2) to search for higher-order distortions such as quadrupole, 3) to obtain data in a region linking the microwave and infra-red measurements where the galactic backgrounds should be very low, and 4) to operate a cryogenic system which is much more sensitive than corresponding ambient temperature systems at centimeter wavelengths.

3'2. *Spectral distortions.* – Several authors [10-12] have suggested using anisotropy measurements at various wavelengths to check for and measure spectral distortions.

Consider a radiation field not necessarily isotropic or black-body in frame O. How will this radiation field appear in frame O' moving with velocity β with respect to frame O?

By conservation of photon number

$$N\,\mathrm{d}^3x\,\mathrm{d}^3p = N'\,\mathrm{d}^3x'\,\mathrm{d}^3p'\,, \tag{1}$$

where N is the photon density in phase space. Since phase-space volume is conserved,

$$N = N'\,. \tag{2}$$

Since flux is proportional to $N\nu^3$ (ν^2 for number of modes, ν for energy), we have

$$I' = \left(\frac{\nu'}{\nu}\right)^3 I\,, \tag{3}$$

where $\nu' = \nu\gamma(1+\beta\cos\theta)$.

For an isotropic black-body (Planckian) spectrum this gives the usual temperature transformation, while, for an isotropic spectrum with ν^3 dependence only, there is no anisotropy because the spectrum is changing just as rapidly as the effects of the contraction in solid angle ($\sim\nu^2$) and the change in photon energy ($\sim\nu$).

For an isotropic spectrum and for $|\beta\alpha|\ll 1$ this reduces to

$$I' = I[1+\beta(3-\alpha)\cos\theta]\,, \tag{4}$$

where α is the spectral index of the flux (same in both frames)

$$\alpha = \frac{\mathrm{d}\log I}{\mathrm{d}\log\nu} = 3 - \frac{\mathrm{d}\log f}{\mathrm{d}\log\nu}\,, \tag{5}$$

where f is the distribution function. For $\alpha > 3$ the maximum flux is in the backward ($\theta = 180°$) direction, while, for a black-body, $\alpha = 2$ in the low-frequency limit of the spectrum (Rayleigh-Jeans) and decreases with increasing frequency, becoming increasingly negative at high frequencies. For a black-body of temperature T two measurements of the dipole at different frequencies can determine both the temperature T of radiation and the velocity β if $\beta \neq 0$. For a temperature near 3 K the error in the determination of the temperature for two isotropy (ΔT_A) measurements, one at 3 mm and one at, say, 1 cm is given by [10]

$$\sigma_T \simeq 8 \left[\left(\frac{\sigma_{\Delta T_A}}{\Delta T_A}\right)^2_{3\text{mm}} + \left(\frac{\sigma_{\Delta T_A}}{\Delta T_A}\right)^2_{1\text{cm}}\right]^{\frac{1}{2}} \text{K}. \tag{6}$$

The isotropy measurements being analyzed now have an accuracy of about 5 %, being limited by calibration errors, although in theory 1 % should be possible (from a satellite for example). If 1 % could be achieved, this would yield an accuracy in temperature of $\sigma_T \sim 0.1$ K; the current 5 % accuracy gives $\sigma_T \sim 0.5$ K. Clearly there are better ways to measure the temperature, although this is an interesting side benefit of isotropy measurements. It is also an important check to see if there is some frequency dependence of the dipole or any other anisotropy. These arguments can be used similarly for some types of higher-order distortions and polarizations as well.

There is one area where anisotropy measurements could be very useful in spectral distortion measurements and that is where there is any rapid change in slope of the spectrum. Since the dipole is very sensitive to slope (the dipole essentially measures the product of the flux and its first derivative), any region of large distortion could change the amplitude of the dipole dramatically.

The balloon measurement by WOODY and RICHARDS [9] of the spectrum of the cosmic background radiation confirms the approximate black-body nature of the radiation and clearly shows the turn-over and subsequent decrease in flux at higher frequencies. The data also suggest that the spectrum may be distorted from a pure black-body, and in any case their data are not consistent with the 2.7 K black-body near the peak (2 mm) that is suggested by the experiments with wavelengths longer than 3 mm [13]. It is difficult to make an accurate prediction of the anisotropy due to their reported spectrum, because the spectral resolution is fairly coarse, about 1 cm^{-1}; so a precise determination of the spectral index α is difficult.

Figure 2 shows a fit to the data of Woody and Richards [14]. It is not possible to put a meaningful error on the predicted anisotropy without invoking a model for their data. If we assume that a smooth fit to the mean is correct, then the predicted anisotropy is given by the upper curves which give the enhancement over a 2.7 or 3.0 K black-body. At 3 mm, the wavelength of our experiment, the enhancement is approximately $(30 \div 40)$ %, which should be observable. At the moment there is not an accurate low-frequency (Rayleigh-

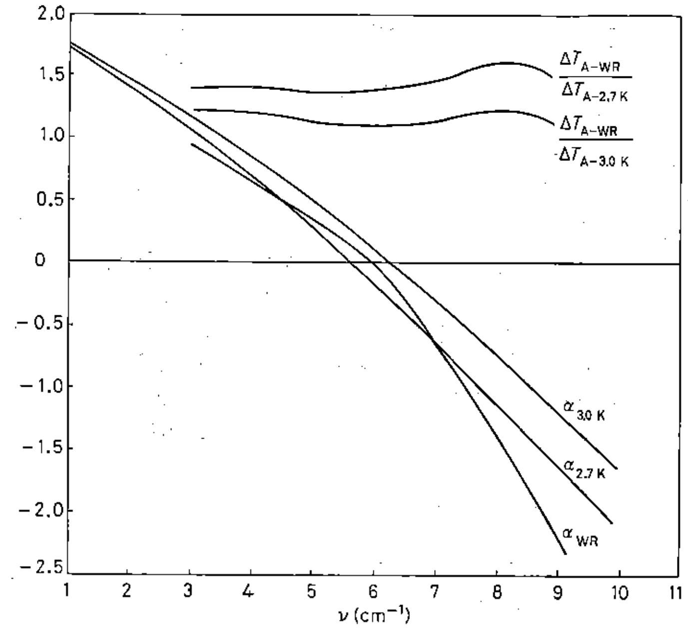

Fig. 2. – Estimated effect of Woody-Richards spectrum on dipole anisotropy compared to a 2.7 K and 3.0 K black-body. Errors are difficult to asses because of uncertainties in spectral index. Based on data from D. Woody: private communication. Data suggest an enhancement of dipole at 3 mm.

Jeans) anisotropy measurement for us to compare with. The existing low-frequency measurements are not in good agreement (see, for example, [4, 15]) and, even if they were, they lack the accuracy to make a comparison meaningful. The Princeton maser experiment should rectify this. The problem of absolute calibration of radiometers is now becoming important, since the statistical errors are small enough that calibration errors will dominate statistical errors for the dipole in the near future.

3'3. *Backgrounds at* 3 mm. – Figure 1 shows the expected galactic backgrounds. From this it appears as though there is a minimum in interference from the Galaxy somewhere near 3 mm with emission off the galactic plane estimated at about 0.1 mK or less. In our data there is no obvious signature when the beam crosses the galactic plane, although fits to models of the Galaxy yield some significance, consistent with the above. The problem of galactic emission from 1 cm to 1 mm is just now being addressed experimentally and we should know much more in the next few years.

In nonsatellite experiments the problem of atmospheric emission requires attention. In the infra-red numerous ozone lines and generally greater oxygen and water emission require flights at very high altitudes ((35÷40) km), and even then it can be troublesome. At centimeter wavelengths lower altitudes

((20÷30) km) yield good results as ozone is not a serious problem; and, except for oxygen emission at about 60 GHz and water emission at about 22 GHz, the atmospheric emission is manageable. At our frequency (90 GHz) water and oxygen emission are not great and there is a broad minimum in ozone emission centered near 3 mm. At our balloon altitude of 30 km, atmospheric emission in our band is calculated to be of the order of several millikelvin, dominated by oxygen. Since the beams are symmetric about the zenith, a typical gondola wobble of $\frac{1}{2}°$ introduces a signal of less than 0.1 mK. In theory this could be corrected for or reduced if necessary. Anisotropic atmospheric emission from temperature and pressure inhomogeneities and other sources are potential problems, but little quantitative information is known about these.

Terrestrial sources of 3 mm radiation are rare and, in fact, our band is protected by international frequency allocations. Military interest in nearby (94 GHz) frequencies may pose a problem in the future for measurements at 90 GHz, although good shielding techniques and band-pass filters will help.

3'4. *Current and future technology.* – The region around 3 mm has just begun to be explored seriously and the technology involved is changing rapidly. The « quantum limit » places a fundamental limit on the minimum noise of a system operating at a frequency ν. This limit is given by an equivalent noise temperature of $T_{QL} \simeq h\nu/k \ln 2$. At 90 GHz this is about 7 K. At 90 GHz the best receivers to date have a noise figure of about 60 K double side band (DSB) or 120 K single side band. Our receiver has a noise temperature of 80 K DSB (minimum spot noise; mixer + IF only) with an overall system noise of about 120 K DSB averaged over a 600 MHz band width. Promising new technologies, such as the SIS (superconductor-insulator-superconductor) mixers developed by RICHARDS at Berkeley [16] and others may soon allow system noise temperatures to approach the quantum limit. In the infra-red new bolometric techniques such as the ^{3}He bolometers being developed by WEISS at MIT and others also promise increased sensitivity for anisotropy measurements. The next 5 to 10 years should yield many breakthroughs in this field.

3'5. 3 mm *radiometer.* – Our experiment is shown schematically in fig. 3. Some of the system parameters are listed in table I. It is a classical Dicke radiometer which uses a rotating mirror to chop between two positions in the sky 90° apart. A mirror was used rather than a ferrite switch, because ferrites are very lossy at 90 GHz. The instrument hangs about 70 m below a $3\cdot10^4$ m^3 ($1\cdot10^6$ ft^3) balloon and rotates at about 0.5 revolutions per minute. Typical float altitude is near 30 km (0.01 atm) with a float duration of 10 h. A small black-body is used to calibrate the radiometer in flight with calibrations about every 25 min. Two sets of three-axis magnetometers, fluxgate and Hall effect, provide the orientation of the package.

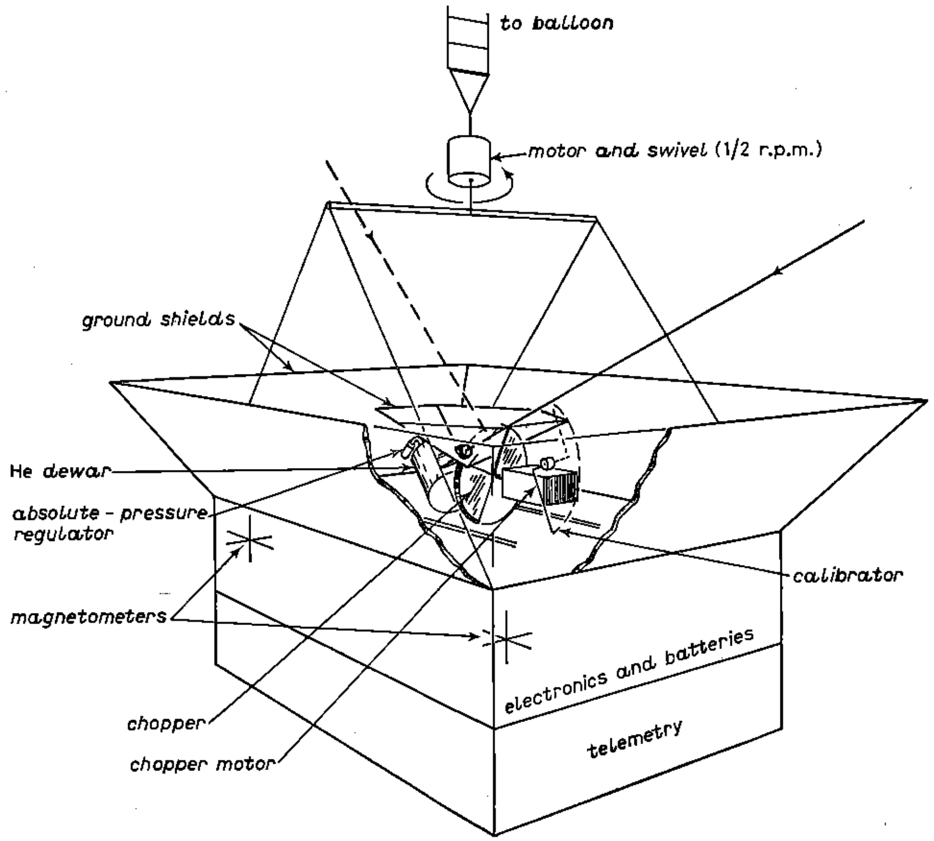

Fig. 3. – Balloon gondola and instrument used in 3 mm anisotropy measurement. Gondola is suspended 70 m below balloon and rotates at $\frac{1}{2}$ r.p.m.

The radiometer is shown schematically in fig. 4. The receiver consists of a low-doped Schottky-diode mixer cooled to 4.2 K (liquid helium) and pumped by a fundamental 90 GHz Gunn oscillator. After the incoming signal is mixed, it is amplified by a two-stage GaAs FET IF amplifier also cooled to 4.2 K. The Gunn-oscillator signal is filtered by a ring coupler to reduce its side band noise contribution. The IF amplifier frequency is centered on 1.4 GHz with a 600 MHz band width. The antenna used is a scaled version of the type used in the Berkeley U2 airplane anisotropy experiment [17]. It is a corrugated scalar horn with a beam width of 7° FWHM and is cooled to 77 K (liquid nitrogen) to reduce losses. The incoming radiation enters the dewar through a 130 μm (5 mil) mylar window. Since the receiver is temperature sensitive, the pressure, and hence the temperature, of the liquid helium and nitrogen are stabilized by absolute-pressure regulators. The temperatures of various receiver parts are also monitored. The cooled part of the receiver is in a small 3 l LHe dewar from Infrared Labs.

TABLE I. – 3 mm *system parameters*.

frequency	90.0 GHz
band width	± 0.6 GHz
polarization	linear horizontal
noise temperature (average)	125 K DSB
spot noise minimum	80 K mixer + IF only
mixer	single 2 μm GaAs Schottky @4.2 K
IF(1st)	2-stage GaAs FET @4.2 K
figure of merit	12 mK s$^{\frac{1}{2}}$
duty cycle	80%
chop rate	23 2/3 Hz phase-locked
gondola rotation period	110 s
antenna	corrugated scalar
beam width	7° FWHM
beam opening angle	90°

The beam is chopped by a mirror which is a highly polished rotating aluminum plate phase-locked to a crystal oscillator to chop at 23 $\frac{2}{3}$ Hz. To reduce diffraction effects, the signal is blanked as the edge of the mirror crosses the beam, giving a duty cycle of 80%. This 20% loss in time results in a 10% loss in sensitivity for a given integration time, since sensitivity goes as $1/\sqrt{\tau}$, where τ is the integration time. The chopped signal is demodulated by a lock-in amplifier and then recorded on a small cassette tape as well as telemetered to the ground.

The chopper mirror introduces an offset into the signal since it has a non-zero emissivity. For a simple model of a good conductor the emissivity can be calculated to be

$$\varepsilon \simeq \frac{2\delta}{\lambda\!\!\!^{-}_0} \cos\theta \,, \tag{7}$$

where δ is the skin depth, $\lambda\!\!\!^{-}_0$ is the reduced free-space wavelength, and θ is the angle of incidence (45° here). This applies for the electric field normal to the plane of incidence as is the case here. Using the d.c. conductivity of aluminum, this gives an emissivity of $\varepsilon \sim 1\cdot 10^{-3}$. The measured emissivity in flight is in good agreement with this and leads to an offset of about 200 mK. The typical rate of change of the offset is about 1 mK/h.

A receiver with noise temperature T, band width B, frequency ν and inte-

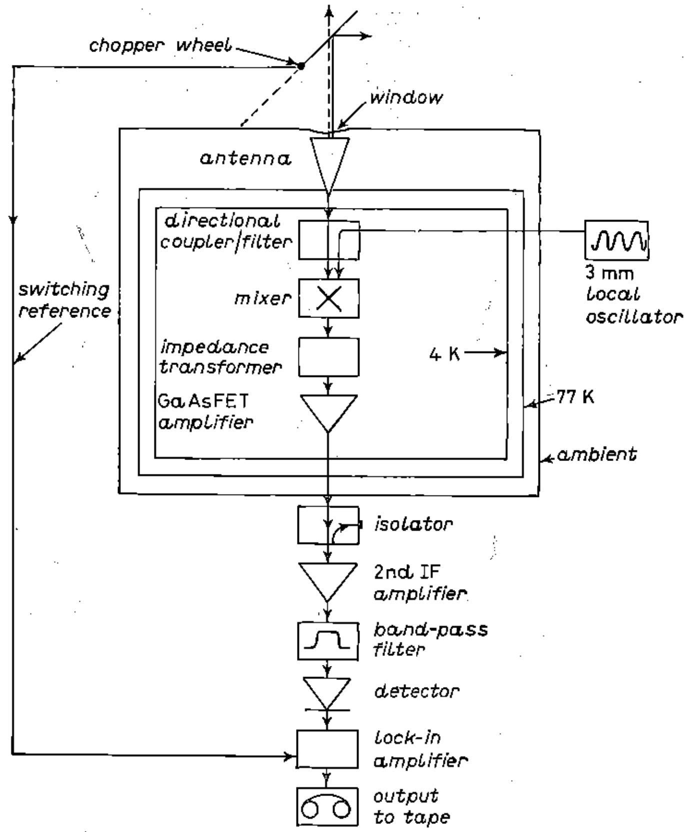

Fig. 4. – 3 mm radiometer used in measurement. Parts not cryogenically cooled are thermally regulated at 30 °C during flight (except chopper).

gration time τ has an equivalent r.m.s. fluctuation in T of

$$\Delta T_{\text{receiver}} = \frac{\sinh x/2}{x/2} \frac{T}{\sqrt{B\tau}}, \tag{8}$$

where $x = h\nu/kT$.

For a square-wave switched square-wave demodulated radiometer like ours, the equivalent fluctuation is twice this or

$$\Delta T_{\text{radiometer}} = \frac{\sinh x/2}{x/2} \frac{2T}{\sqrt{B\tau}}. \tag{9}$$

In our system $T \simeq 120$ K and $B = 500$ MHz (corrected for gain variation), so $\Delta T_{\text{rad}} \sim 12$ mK s$^{\frac{1}{2}}$. Because of the 20% blanking time this is increased to $\Delta T_{\text{rad}} \sim 13$ mK s$^{\frac{1}{2}}$, which is in good agreement with the actual in-flight fluctuations. In one rotation of the gondola ($\tau \sim 110$ s), the equivalent fluctuation should be about 1 mK, so the dipole (~ 3 mK) should be readily seen. In fact, as is seen in fig. 5 taken from the strip chart recording during the flight with a 55 s *RC* filter attached, the dipole is easily seen.

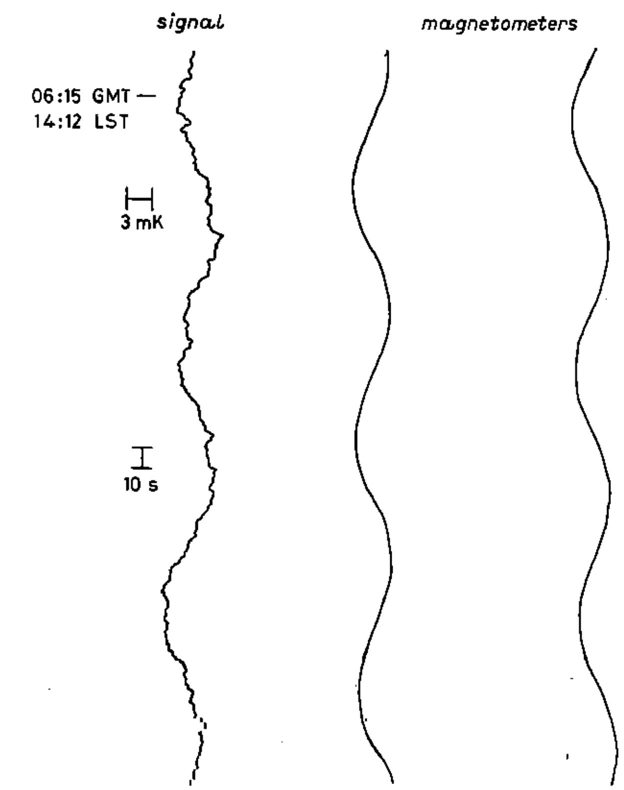

Fig. 5. – Part of real-time strip chart telemetry recording taken during flight which clearly shows the dipole anisotropy (April 26, 1982, flight).

4. – Results of 3 mm experiment.

4·1. *Data analysis and interpretation.* – The instrument has flown three times. The first flight was a collaborative effort with WILKINSON of Princeton in July 1981 and was primarily an engineering flight. The second flight was made in collaboration with WEISS of MIT in November 1981. The third one was a dedicated flight in April 1982. All flights were launched from Palestine, Texas, at the National Scientific Balloon Facility (latitude 31.8° N). The sky coverage obtained is shown in fig. 6. The entire northern hemisphere has been surveyed.

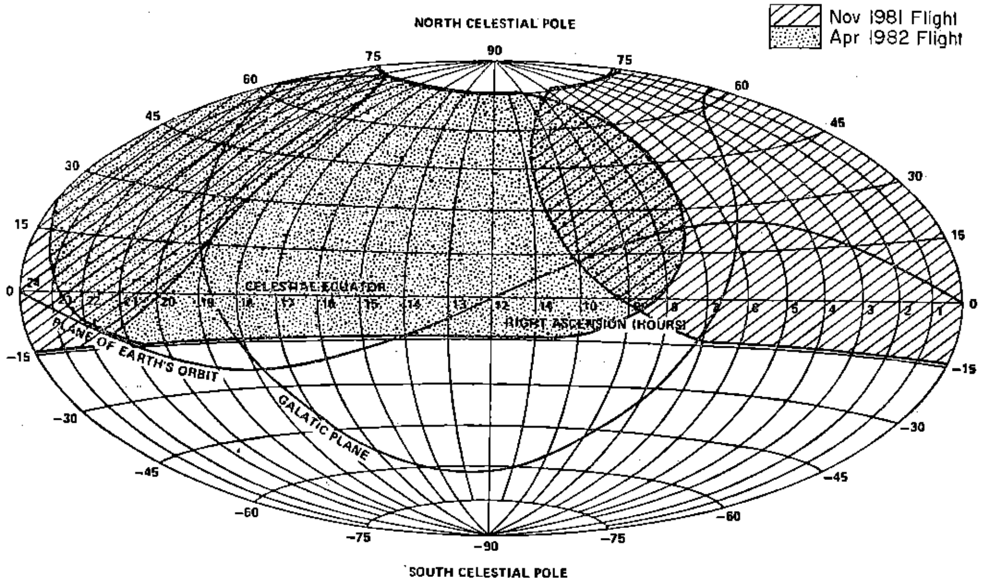

Fig. 6. – Sky coverage achieved from November 1981 and April 1982 flights.

The data have been fitted to first- and second-order spherical harmonics as well as to various Galaxy models. The spherical-harmonic convention follows that in Smoot and Lubin [15]. Because of the lack of good southern-hemisphere sky coverage the axially symmetric second-order spherical harmonic Y_{20}, or Q_1 in the notation used, cannot be fitted in a significant manner.

The statistical errors on the fits are between 60 and 100 μK for the various dipole and quadrupole parameters (except Q_1). The data are still being analyzed, so the numbers are preliminary and the errors are statistical only and do not include any possible systematic errors.

4.2. *Dipole*. – The dipole seen in real time agrees in magnitude and phase with what would be expected from previous measurements [3, 4, 15]. A dipole fit to the data gives

$$T_x = (-2.89 \pm 0.07)\ \text{mK}\,,$$

$$T_y = (0.51 \pm 0.07)\ \text{mK}\,,$$

$$T_z = (-0.27 \pm 0.07)\ \text{mK}\,.$$

Fit is preliminary; errors are statistical only.

The temperatures are antenna temperatures. To convert to thermodynamic temperature the spectrum needs to be known, as discussed before. If we assume the spectrum is described by a 2.7 K black-body, the numbers given should be increased by about 20%. This is then within the range of measurements taken at lower frequencies. To make a meaningful determination of the spectrum from these measurements, better low-frequency measurements are needed.

4·3. *Quadrupole.* – The quadrupole claimed by BOUGHN, CHENG and WILKINSON [4], which has comparable sky coverage, has most of its power in the terms Q_4 and Q_5 with $Q_5 = (-0.54 \pm 0.14)$ mK being the most significant term.

Our data are in serious disagreement with these fits. We find less than (0.1 ± 0.1) mK amplitude in Q_4 and Q_5. The Galaxy at their wavelength (~ 1 cm) is a contaminant, but should not produce a one-half millikelvin quadrupole. We do not understand the source of the disagreement, but our data are *inconsistent* with the quadrupole they claim. Table II summarizes the notation and fit.

TABLE II. – *Preliminary dipole plus quadrupole fit.*

Coefficient	Fit (mK)	Statistical error	Correlation coefficient						
T_x	−2.90	0.09	1.00	−0.07	0.03	−0.39	0.23	−0.02	0.05
T_y	0.50	0.09		1.00	−0.02	0.27	−0.32	−0.11	0.02
T_z	−0.23	0.07			1.00	0.03	0.10	−0.02	0.20
Q_2 (*)	0.19	0.10				1.00	−0.11	−0.08	0.05
Q_3 (*)	0.22	0.09					1.00	−0.01	0.09
Q_4	−0.08	0.07						1.00	0.00
Q_5	0.05	0.06							1.00

$$T = T_x \cos\delta \cos\alpha + T_y \cos\delta \sin\alpha + T_z \sin\delta + Q_1(\tfrac{3}{2}\sin^2\delta - \tfrac{1}{2}) + Q_2 \sin 2\delta \cos\alpha + Q_3 \sin 2\delta \sin\alpha + Q_4 \cos^2\delta \cos 2\alpha + Q_5 \cos^2\delta \sin 2\alpha .$$

(*) We do not consider these to be significant. Note that they are correlated with T_x and T_y. Q_2 and Q_3 are also more sensitive to various galactic models, cuts and other systematic errors we have tried than are Q_4 and Q_5. The above are without any galactic corrections.

The quadrupole claimed by FABBRI *et al.* [3] has a 0.9 mK amplitude. Because of limited sky coverage and other reasons, they did not analyze the data in terms of spherical harmonics. The analysis technique used by FABBRI *et al.* [3] is based on a graphical technique used by the Berkeley group to display their U2 data, but not to analyze it. In fact, this technique should not be used to look for quadrupole and other higher-order anisotropies because these can be «generated» from a pure dipole by pointing errors and other systematic errors. A recent paper by FABBRI *et al.* [18] re-analyses their data by spherical-harmonic decomposition. The analysis shows an anomalously large value for T_z ((-2.0 ± 0.2) mK) as well as a (0.5 ± 0.09) mK quadrupole in Q_3 and a (-0.3 ± 0.1) mK quadrupole in Q_4. In Q_5 where the Princeton quadrupole is most significant, they find little power ($Q_5 = -0.1\pm0.1$). Because they do not give the correlations between the components and because T_z is in disagreement with other measurements, it is difficult to judge their significance. A great deal of caution is called for in interpreting the current quadrupole claims. Our analysis is continuing and will be published in more detail soon [19].

5. – Future experiments.

This field has a promising future as new technologies allow more and more sensitive experiments. The experiments are not easy and will require careful consideration of low-level systematic errors and in particular of the galactic emission. By the end of this decade the COBE satellite should give us a great deal of information about large- and possibly medium-scale anisotropies as well as excellent data on the spectrum and diffuse infra-red radiation [20].

In the next few years sensitive new balloon experiments are being planned which will explore more accurately the centimeter through submillimeter anisotropy. The potential for discovery is great and warrants the continued attention of experimentalists and theorists alike.

* * *

This experiment was performed by G. EPSTEIN, G. SMOOT and myself, but had a great deal of support from other groups and individuals. Without the support and encouragement of D. WILKINSON of Princeton the project never would have begun. D. WILKINSON also allowed us to fly on his gondola for the first flight. The second flight was made possible by R. WEISS of MIT on very short notice when he allowed us to fly on one of his gondolas, even though this involved substantial modification and possible compromise of his experiment. For the third flight, N. BOGGESS, R. KUBARA and R. NOCK from NASA and NSF were crucial to our flight. We are grateful to the entire crew of the National Scientific Balloon Facility at Palestine, Texas, for their tremendous enthusiasm and support for all of our flights. H. DOUGHERTY, J. GIBSON and J. YAMADA provided exceptional technical support from the University of California. S. FRIEDMAN, CH. WITEBSKY, G. DE AMICI, PH. MELESE-D'HOSPITAL and N. GUSACK provided useful discussions and support. Very special thanks go to B. PRICE, of the Space Sciences Laboratory, UC Berkeley, without whose support and help we could not have proceeded. This project was supported by the California Space Institute, the National Aeronautics and Space Administration, the National Science Foundation and the Department of Energy.

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