# Measuring the Large-Scale Anisotropy in the Microwave Background Radiation [and Discussion]

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# Measuring the large-scale anisotropy in the microwave background radiation

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Measurements of large-scale anisotropy in the 2.7 K microwave background radiation are reaching a sensitivity of $\Delta T/T = 10^{-4}$ in the amplitudes of low-order spherical harmonics. At this level, interesting conditions and processes in the early Universe can be studied. However, the measurements are difficult and very susceptible to systematic errors. The microwave instruments and techniques are discussed with the emphasis on the reduction and evaluation of spurious effects. The subtraction of foreground radiation, mainly from diffuse Galactic sources, is a major problem that already limits the accuracy of measurements near 1 cm wavelength. Current results for the dipole and quadrupole moments are compared and discussed.

## 1. Introduction

In their discovery paper, Penzias & Wilson (1965) noted that the microwave background radiation was isotropic to within the limits of their observations – about 10 %. Realizing that isotropy is necessary to the Big Bang remnant interpretation of this radiation (Dicke *et al.* 1965), Partridge & Wilkinson (1967) designed an experiment that demonstrated isotropy near the celestial equator to ± 0.1 %. Thus a Galactic origin for the microwave background radiation was excluded. However, the measurements fell just short of detecting the expected dipole effect due to the Sun's velocity with respect to the radiation reference frame. It was 10 years before the dipole effect was clearly seen (Smoot *et al.* 1977) above instrumental noise and systematic errors.

However, the main motivation for doing these difficult observations has always been to look for intrinsic effects in the cosmic radiation itself. These might be built in from the beginning, and tell us something about large-scale structure in the early Universe, or they might originate later from interactions with an inhomogeneous matter component. Large-scale (and small-scale) anisotropy measurements of the 2.7 K radiation now exceed an accuracy ($\Delta T/T$) of $10^{-4}$, and are our best means of probing structure and physical processes in the early Universe.

Instruments and techniques may finally have reached the point where intrinsic effects are being detected in the form of a quadrupole moment in the angular distribution of the radiation. Fabbri *et al.* (1980) have reported a second harmonic signal at wavelengths near 1 mm, while Boughn *et al.* (1981) find statistically significant quadrupole components in the data from two radiometers with wavelengths near 1 cm. If these results are validated by more sensitive observations, now being analysed, the anisotropy experiments will finally tell us about nonuniformity in the early Universe. Indeed, Peebles (1981) has shown that gravitational red shift from early mass clustering could reasonably explain the observed quadrupole effects. The theory also predicts a 'noise' spectrum for $\Delta T/T$ that is proportional to (angle)$^{\frac{1}{2}}$. Even if this effect is not observed, at the improved accuracy now possible, the theory is sufficiently well based, and quantitative, for interesting constraints to be placed on cosmological parameters and processes (Peebles 1982).

The current state of research on anisotropy of the 2.7 K background is unsettled. Four experimental groups (Berkeley, Florence, M.I.T. and Princeton) are doing difficult observations where instrument noise, systematic errors and Galactic background all contribute effects at the level where interesting signals are expected. Low signal:noise ratio, long integration times and abundant systematic errors make marginal detections of cosmic signals suspect, and difficult to check.

This paper discusses the problems (some solvable, others not) associated with making large-scale anisotropy measurements of the 2.7 K background radiation. It is aimed at the theorist who wishes to understand better the shortcomings and qualifications of the experimental results and at the experimentalist exploring the field. In §2 the instrument, techniques and systematic errors associated with measurements at centimetre wavelengths are examined; in §3 foreground (mostly Galactic) sources are discussed; in §4 current (published) results for dipole and quadrupole distributions are compared.

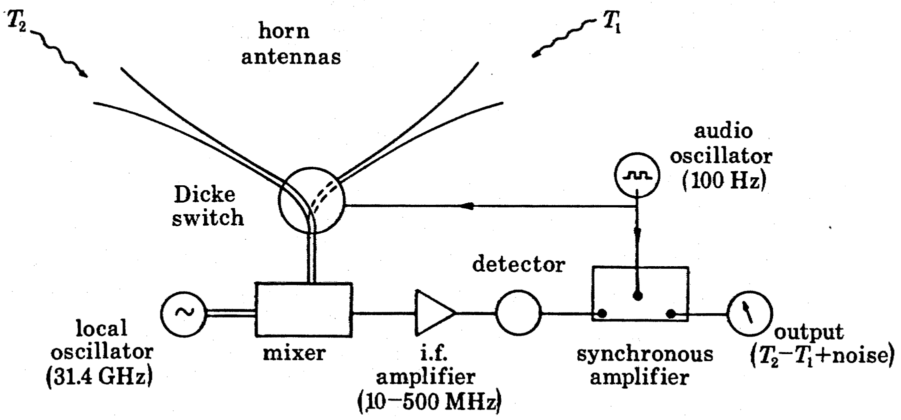

Figure 1. Dicke radiometer. The horn antennas are especially designed for low sidelobe response. The Dicke switch usually employs a ferrite (magnetic) device. The mixer generates most of the system noise, and converts the microwave signal to an intermediate frequency (i.f. = 10–500 MHz) convenient for high-gain amplification. The synchronous amplifier (lock-in) is usually driven at a frequency between 10 and 1000 Hz.

## 2. INSTRUMENTS AND TECHNIQUES

### (a) *Dicke radiometer*

Anisotropy measurements at centimetre wavelengths are all made with one form or another of the familiar Dicke radiometer (Dicke 1946). It is the only instrument with sufficient long-term stability to permit the required long integration times. The basic Dicke system is sketched in figure 1. All anisotropy measurements so far have used antennas on both switch arms to avoid building a very stable, cold comparison source. So the measurements are differential; the difference $\Delta T$ between the radiation temperature from two sky positions is measured. Differential measurements, though technically easier, discard valuable information by cancelling some harmonics of the sky signal.

In anisotropy observations the radiometer output is dominated by instrument noise. The room-temperature mixers, used so far, give system noise temperatures of typically 500 K and an intermediate frequency (i.f.) bandwidth, $B$, of 500 MHz. The r.m.s. instrument noise in $\Delta T$ is, for an integration time $t_{\mathrm{int}}$,

$$\Delta T_{\mathrm{r.m.s.}} = 2T_{\mathrm{system}}/(Bt_{\mathrm{int}})^{\frac{1}{2}} = 45\ \mathrm{mK\ s^{-\frac{1}{2}}}, \tag{1}$$

against which the scientifically interesting signal must be seen. A signal of 0.3 mK (10% of the dipole amplitude) is an interesting level; over 25 h of integration time is required to reduce the r.m.s. noise to 50% of the signal level.

However, the instrument as described will not work, because of unavoidable drift in instrument offset (see § 2*c* (i)). Offsets in $\Delta T$ associated with asymmetries in the switch and antennas cannot be held constant to ± 0.3 mK over periods of hours. A second level of switching is therefore introduced by rotating the entire instrument with a period over which the offsets are stable. The Berkeley instrument is rotated about every 20 min by turning its platform – a U-2 aircraft – through 180°. The Princeton balloon package is rotated by a motor at 1 rev. $\mathrm{min^{-1}}$.

With instrument rotation, the stability question becomes: what effects, other than a sky signal, can cause $\Delta T$ variations synchronous with rotation? Notice that spurious synchronous effects do not integrate to zero when the output is correlated with instrument direction. So the spurious effects on $\Delta T$ must not vary with rotation angle by more than 0.3 mK. This is the most difficult, and most dangerous, problem associated with anisotropy experiments. Important synchronous effects are discussed in § 2*c* below.

### (*b*) *Balloon technique*

Ground-based anisotropy observations are severely limited by gradients in atmospheric radiation from oxygen and water vapour. Partridge & Wilkinson (1967) observed for a year, and Conklin (1969) went to a mountain top to minimize this problem. In restrospect, Conklin probably detected the dipole effect, but not convincingly. Henry (1971) first used a balloon-borne instrument, and again, probably detected the dipole. But a large synchronous offset due to the Earth's magnetic field, and insufficient sky coverage, made his result suspect. All subsequent anisotropy experiments have been borne by balloons or high-altitude aircraft.

In the centimetre bands, modest altitudes (30 km) and small balloons (20000 $\mathrm{m^3}$) suffice, but the millimetre observations require higher altitudes (40 km) and more sophisticated ballooning techniques. The U-2 aircraft used by the Berkeley group is an attractive platform, but its availability and cost are uncertain.

A sketch of the Princeton balloon experiment is shown in figure 2. Precautions are taken to minimize ground radiation and to maintain geometrical and thermal symmetry between radiometer antennas. Observations are made only on nights near new Moon to avoid differential heating and a large lunar signal ($\Delta T \approx 1$ K with Moon in one beam).

Hall probe magnetometers measure the orientation of the radiometer beams with respect to geomagnetic north. At float altitudes, the gondola rotation rate is remarkably constant at 1 rev. $\mathrm{min^{-1}}$ with few, if any, signs of torques from wind shear. A ground speed of 80 km $\mathrm{h^{-1}}$ is typical.

Most of the problems associated with having to use balloons are logistic and technical rather than scientific. The main effects on the anisotropy results are associated with (1) remote observing and (2) long intervals between observations. Remote observing means that the experimenter cannot tinker with the instrument to assure proper operation and test for systematic effects. The experimental environment (−55 °C and 0.025 atm; *ca.* 2.5 kPa) must be carefully anticipated in instrument design. (Note the rigorous requirement for thermal and mechanical symmetry ahead of the Dicke switch.) Furthermore, realistic laboratory testing of the radiometers is difficult because cold sources of sufficient temperature stability (±0.3 mK) would be very difficult to build and prohibitively expensive. Basically, remote observing with high-sensitivity instruments makes experimenters worry about what their instrument is really doing. Remotely sensed 'engineering data' are essential, but never sufficient.

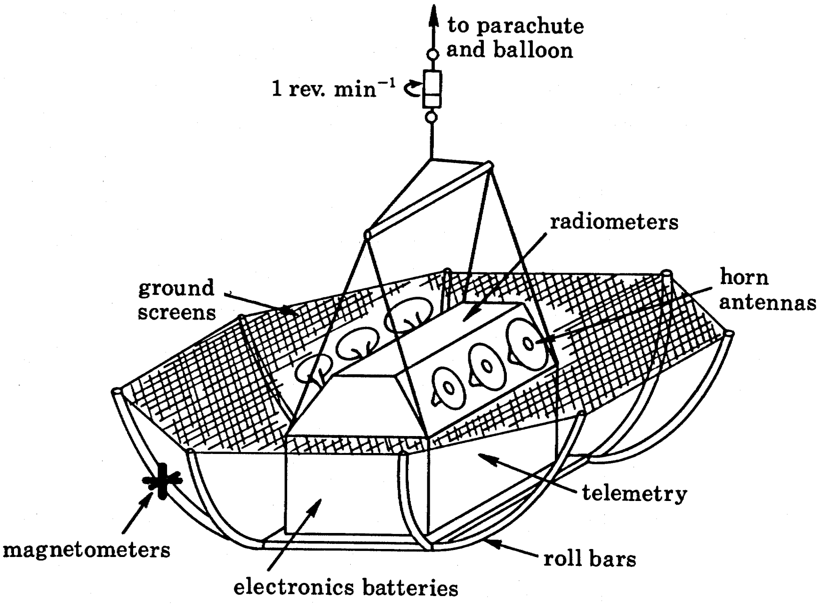

FIGURE 2. The Princeton anisotropy experiment. Three differential radiometers at 24.8, 31.4 and 46.0 GHz use antennas constructed from musical instrument bells (two baritones and a trombone) for low sidelobe response. Ground screens provide further attenuation of the strong (300 K) ground signal and possible interfering radio and radar signals.

Ballooning costs, sky coverage requirements and experimenter exhaustion regulate the rate of observations to one or two per year. Since one or two 'engineering' flights are usually required for a new instrument, the typical time for each new instrument to yield results is 5 years. And, of course, there is a non-negligible risk that the entire instrument will be lost or destroyed by a ballooning accident.

### (*c*) *Systematic effects synchronous with rotation*

In this section possible spurious effects, which are synchronous with instrument rotation, are discussed. As noted above (§2*a*), effects that change $\Delta T$ by 0.3 mK will compete with signals of interest. Current experiments, at lower noise levels, require an even better understanding of systematic effects.

#### (i) *Effects on radiometer offset*

With the horn antennas viewing identical cold sources, the radiometer output will not be exactly zero. This offset is caused by asymmetry in the radiation from the Dicke switch and from the walls of the horn antennas. Typically, the switch and wall radiation each amount to *ca.* 10 K (equivalent source temperature), so a change of 0.01 K in the physical temperature of one horn with respect to the other gives a 0.3 mK change in $\Delta T$. Asymmetric heating of the horns by ground radiation can give a synchronous temperature difference of this magnitude. Horn temperatures are monitored with sensitive thermometers to detect, and correct for, this effect.

Another difficult problem arises from the Earth's magnetic field coupling with the Dicke switch, which is a magnetic device. Henry (1971) found that the Earth's field had introduced an asymmetry, which depended on radiometer orientation, in the radiation from his switch. Note that the effect only has to be 0.003% to give a 0.3 mK spurious signal. Subsequent radiometers have used magnetically shielded switches and have been tested in laboratory magnetic fields.

### (ii) *Radio interference*

Radio interference can come from radar signals in the radiometer bandpass, or from radio, television or telemetry transmitters in the i.f. passband (see figure 1). The power level of the cosmic signal at the i.f. amplifier input is about $10^{-18}$ W. Since radiofrequency leakage is directional, the amount of interference reaching the amplifier depends on radiometer orientation. A 50 kW station 100 km away will illuminate the radiometer with about $10^{-7}$ W, so isolation of $10^{-11}$ is required. Dicke switching makes the radiometer much more resistant to i.f. interference, but small nonlinear effects become important when small signals compete with large interference. Careful testing for interference, especially from the onboard telemetry transmitter (2–3 W), is required.

Interference from radar transmitters, especially if they are tracking the balloon, cannot be shielded out. If such signals are apparent in the data, the data are discarded. Fortunately, this is rare, but one constantly worries that the balloon is being illuminated by weak radar signals which are not detected against the radiometer noise. In this event, directional radar interference can easily masquerade as cosmic signal, and be difficult to detect. 'Signals' which come and go are suspect; but steady interference, just at the level of detection, is a serious source of systematic error.

### (iii) *Anisotropy from ground radiation*

The horn antennas must be well shielded from ground radiation. Imagine that the balloon is at the edge of a bank of high clouds whose tops are 30 K colder than the ground. To avoid a 0.3 mK signal from anisotropic ground radiation an isolation of $10^{-5}$ (50 dB) is needed. Since ground shields cannot be used on the U-2 aircraft, Smoot and his colleagues at Berkeley used a corregated horn with a very low sidelobe response. The Princeton balloon experiment uses a combination of ground screens (15 dB) and smoothly tapered horns with sidelobes below 35 dB (see figure 1) to achieve the required isolation from ground radiation.

### (iv) *Atmospheric and balloon emission*

Balloon altitudes are chosen to keep the emission from residual atmosphere low, usually below 10 mK. Water vapour, which is particularly troublesome at wavelengths around 1 cm, is not a problem at altitudes above 25 km.

Emission and reflexion from the $10^{-3}$ in (*ca.* 25 μm) thick skin of the plastic balloon give a negligible contribution to the horn signal. Symmetry further reduces the balloon's contribution to $\Delta T$. Estimates of water vapour carried aloft by the balloon also indicate negligible contribution to the anisotropy signal.

## 3. Foreground radiation

At wavelengths near 1 cm, sky radiation is dominated by the 2.7 K background. However, at levels of interest in anisotropy measurements it is necessary to evaluate, and subtract, contributions due to discrete and diffuse foreground sources. The small horn antennas used for large-scale anisotropy measurements have beam widths (f.w.h.m.) of about 7°. Thus only strong discrete sources are detected, but the radiometers are very sensitive to large regions o low-brightness radio emission.

The diffuse radiation consists of two components: (1) synchroton radiation ($T \propto \nu^{-2.8}$) due to energetic electrons orbiting in Galactic magnetic fields, and (2) free–free emission ($T \propto \nu^{-2.1}$) from optically thin interstellar plasmas. At long wavelengths (10–100 cm), where diffuse galactic radiation is well mapped, the sychrotron component dominates. However, at wavelengths near 1 cm the free–free component is also important. Even thermal emission from Galactic dust must be considered. Extrapolation from submillimetre measurements are very uncertain because the frequency dependence of the dust emissivity is not known (Weiss 1980).

### (*a*) *Discrete sources*

The strongest discrete sources at wavelengths near 1 cm are H II regions: dense plasma excited by hot O and B stars. Cygnus X, the strongest source, is actually a superpositio of many sources in a direction tangent to a spiral arm of the Galaxy. The main region (diamete *ca.* 5°) is well studied at several wavelengths (Downes & Rinehart 1966; Wendker 1970 Hirabayashi 1974) and contains many H II regions embedded in a background of strong free-free emission. Other important H II regions include the Orion, Rosette, Lagoon and Gu nebulae. These and many weaker H II regions (Lang 1974) make substantial contributions t Galactic radiation at 1 cm wavelength.

Supernova remnants like Cas A and the Crab nebula, and most extragalactic radio sources have spectra steeper than that of H II regions. Since their fluxes and spectral indices are known they are easily included in the foreground radiation map.

### (*b*) *Diffuse synchrotron radiation*

The several long-wavelength ($\lambda > 6$ cm) maps of the Galaxy measure mostly the synchro tron component of diffuse radiation; the diffuse free–free component is relatively weak at thes wavelengths. By using such maps (Pauliny-Toth & Shakeshaft 1962; Haslam *et al.* 1982) th diffuse synchrotron radiation at 1 cm can be found if the spectral index is known. Measurement of the spectral index at 4 GHz (Penzias & Wilson 1966) and at 15.5 GHz (Hirabayashi 1974 give a spectral dependence of $T \propto \nu^{-2.9}$ near the Galactic plane. Hirabayashi's work is the bes evidence that the synchrotron spectrum is not flattening out at centimetre wavelengths However, little is known about Galactic synchrotron emission at $\lambda \approx 1$ cm, so extrapolatio of long-wavelength maps (over 1 to 2 orders of magnitude in $\nu$) must be viewed with scepticism

### (*c*) *Diffuse free–free radiation*

Large-scale maps of the diffuse Galactic free–free emission at 1 cm do not exist, so this component of the foreground radiation map must be estimated from other observations of the Galactic plasma. These include measurements of H$\alpha$, radio recombination lines, pulsar dispersion and attenuation of radio sources at low frequencies.

The brightness temperature of radiation from optically thin plasmas with electron temperature $T_e$ and electron density $n_e$ is given by

$$T = 0.4\ T_e^{-\frac{1}{2}}\nu^{-2}E, \tag{2}$$

where

$$E = \int n_e^2 \mathrm{d}s\ \mathrm{cm}^{-6}\ \mathrm{pc} \tag{3}$$

is the emission measure and $\nu$ is the radiation frequency in gigahertz. The plasmas that contribute most to free–free emission in the centimetre wavelength band have $T_e \approx 10^4$ K; hot plasmas have low $E$. So, to give a radiation temperature $T > 0.3$ mK, a line of sight through the Galactic plasmas must have $E > 70\ \mathrm{cm}^{-6}$ pc.

Sensitive observations of H$\alpha$ emission and of radio recombination lines in hydrogen are giving a clearer picture of the origins and distribution of warm (*ca.* $10^4$ K) plasmas in the Galaxy. The diffuse component seems to be due to superimposed discrete H II regions and extended sources associated with them (Lockman 1980), dense shells around early-type stars (Weaver *et al.* 1977; Elmergreen 1976) and the interfaces between hot supernova remnants and cold, dense media (McKee & Ostriker 1977). A few such sources are isolated enough to be mapped in H$\alpha$ or recombination lines; examples are Orion (Reynolds & Ogden 1979), the Gum nebula (Reynolds 1976) and IC1795(W3) (Hart & Pedler 1976). The contributions of these regions to a map of the diffuse free–free radiation are well determined, because scattering and absorption of H$\alpha$ is small and known.

In the Galactic plane, where the mean free path of H$\alpha$ photons is only *ca.* $10^3$ pc, H$\alpha$ surveys (R. J. Reynolds, personal communication 1982) give lower limits to $E$. Recombination line surveys (Lockman 1980) probe the entire line of sight, but are of limited extent. Pulsar dispersion measures (Manchester & Taylor 1981) and low frequency absorption in radio sources (Dulk & Slee 1972; Gordon 1972) obtain $E$ in some directions. These measurements, and a crude model of Galactic structure, are used to estimate the diffuse free–free emission from the Galactic plane. This part of the foreground radiation map is probably not accurate enough for current anisotropy results.

Away from the Galactic plane, $|b| > 10°$, one must worry about large (more than 30°) regions of weak centimetre wavelength emission that would not have been detected in radio surveys: regions like the Gum nebula. Fortunately, the high-sensitivity H$\alpha$ maps of Reynolds *et al.* (1974) and Sivan (1974) detect large-scale emission where $E > 20\ \mathrm{cm}^{-6}$ pc. The general Galactic background away from H II regions is sampled by Reynolds's (1977) high-sensitivity measurements of H$\alpha$ intensity towards pulsars. Recent results (Reynolds, personal communication 1982) indicate that $E = 2(1+\csc|b|)\ \mathrm{cm}^{-6}$ pc is a reasonable representation of the general free–free background for $|b| > 10°$, indicating a negligible contribution to the anisotropy measurements.

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## 4. DISCUSSION OF CURRENT RESULTS

Measurements of dipole anisotropy in the 2.7 K background have been reported by four groups: Berkeley (Smoot & Lubin 1979), Florence (Fabbri *et al.* 1980), M.I.T. (Weiss 1980) and Princeton (Boughn *et al.* 1981). Three groups also have attempted to fit a quadrupole anisotropy to their data. The results are shown in table 1.

TABLE 1. DIPOLE AND QUADRUPOLE ANISOTROPY RESULTS

| | Berkeley | Princeton | Florence | M.I.T. |
|---|---|---|---|---|
| $T_{\text{dipole}}$/mK | $2.86 \pm 0.30$ | $3.78 \pm 0.30$ | $2.9^{+1.3}_{-0.6}$ | $2.8 \pm 0.8$ |
| dec./deg | $-4 \pm 6$ | $-12 \pm 5$ | $3 \pm 10$ | $-9 \pm 20$ |
| r.a./h | $11.1 \pm 0.4$ | $11.6 \pm 0.2$ | $11.4 \pm 0.7$ | $9.6 \pm 1.5$ |
| $Q_1$/mK† | $0.38 \pm 0.26$ | —‡ | $T_Q = 0.9^{+0.4}_{-0.2}$§ | — |
| $Q_2$/mK | $-0.34 \pm 0.29$ | $0.28 \pm 0.22$ | — | — |
| $Q_3$/mK | $0.02 \pm 0.24$ | $0.13 \pm 0.21$ | — | — |
| $Q_4$/mK | $-0.11 \pm 0.16$ | $-0.31 \pm 0.15$ | — | — |
| $Q_5$/mK | $0.06 \pm 0.20$ | $-0.54 \pm 0.14$ | — | — |
| $\chi^2$(d.f.) | 203 (158) | 124 (119) | 24.6 (16) | — |

† $T_{\text{quadrupole}}(\alpha, \delta) = Q_1(\frac{3}{2}\sin^2\delta - \frac{1}{2}) + Q_2 \sin 2\delta \cos\alpha + Q_3 \sin 2\delta \sin\alpha + Q_4 \cos^2\delta \cos 2\alpha + Q_5 \cos^2\delta \sin 2\alpha$, where $\alpha$ = right ascension and $\delta$ = declination.

‡ Princeton sky coverage does not allow separation of $T_z$ and $Q_1$ (see Boughn *et al.* 1981).

§ Second harmonic signal in millikelvins. Limited sky coverage did not permit evaluation of $Q$'s. However, see Fabbri *et al.* (this symposium) for results from more data.

### (*a*) *Dipole results*

The dipole directions found by the four groups are in good agreement; however, the Berkeley and Princeton dipole amplitudes show substantial disagreement. A statistical test, which assumes that the errors are gaussian (and which accounts for correlations between components) shows that random errors would cause a difference as large as that between the Princeton and Berkeley results only 7.6% of the time. The probable causes for the disagreement are:

(*a*) an unknown calibration error,

(*b*) incorrect subtraction of foreground radiation,

(*c*) 'leakage' of higher order moments, not fitted by the dipole + quadrupole model (this depends on sky coverage), and

(*d*) undetected radio interference, or any of the other systematic errors listed in §2*c*.

Measurements of the dipole effect now extend over sufficient frequency range to demonstrate convincingly that the dipole spectrum is nearly black-body. Figure 3 shows the dipole temperature plotted against frequency. The best fit to a power law ($T \propto \nu^{-a}$) gives $a = -0.3 \pm 0.2$, consistent with a black body. Known sources of Galactic radiation do not fit, but could be contributing to individual points if not correctly subtracted. The two most likely explanations for a nearly black-body spectrum for the dipole effect are (1) solar motion through the 2.7 K radiation and (2) an intrinsic anisotropy in the temperature of the radiation.

### (*b*) *Quadrupole results*

The Florence group have reported (Fabbri *et al.* 1980) a quadrupole-like anisotropy based on a large second harmonic signal (see table 1). Also, the Princeton group (Boughn *et al.* 1981) find two statistically significant quadrupole components: $Q_4$ and $Q_5$ in table 1. These results are not in conflict with the Berkeley group's stated upper limit of 1 mK for quadrupole components; however, their value for $Q_5$ conflicts with the Princeton result. The Florence second harmonic signal is about double what would be expected from the quadrupole reported by the Princeton group.

As pointed out in §2*c*, there are abundant opportunities for systematic effects to enter at the level of 0.3 mK. These are very hard to uncover in instruments with system noise temperatures above 300 K, because of the very long integration times involved. The most probable causes of quadrupole-like systematic errors are:

(*a*) incorrect subtraction of Galactic radiation (a quadrupole distribution), and

(*b*) spurious signals due to interference in a substantial fraction of data.

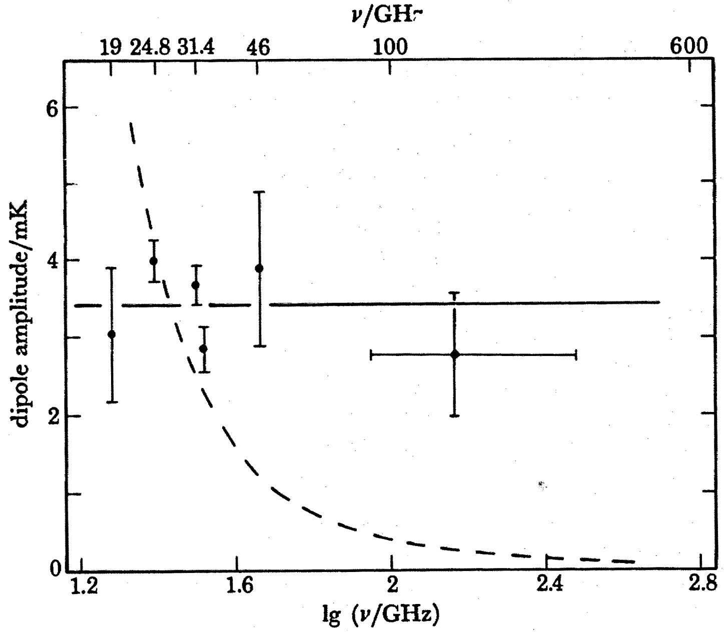

FIGURE 3. Spectrum of the dipole anisotropy. The solid line is the best-fit black-body spectrum; free–free emission is best fitted by the dashed line. Clearly the dipole effect has a nearly black-body spectrum.

Boughn *et al.* (1981) argue that known Galactic sources must have been underestimated by a factor of 5 to have introduced the measured quadrupole, $Q_5$. The estimate should be good to better than a factor of 2. Two balloon flights (6 months apart) were needed to get sufficient sky coverage to be sensitive to a quadrupole effect. Low-level interference lasting for several hours during either of those flights could have given a false quadrupole signal.

Significant disagreements between the measurements of dipole and quadrupole anisotropies indicate that current published results should be viewed with some scepticism. Fortunately, significant progress is being made in several areas: the Florence and M.I.T. groups have flown their high-sensitivity bolometers again, with better sky coverage and more wavelength resolution; the Berkeley group has perfected and flown a cooled radiometer at 90 GHz, which is well above Galactic radio emission, but into the tail of dust emission; and the Princeton group has made three balloon flights, including one in the Southern Hemisphere, of a maser amplifier at 24.8 GHz; the system noise is 10 times lower than that of the radiometers described in §2*a*. Measurements of large-scale anisotropy in the 2.7 K radiation should improve substantially in the next 2 years.

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## *Discussion*

R. D. Davies (*University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, U.K.*). Dr L. Hart and I have made observations of the apparent motion of the backdrop of spiral galaxies of type Sbc to determine the velocity of the Sun relative to a reference frame in the Universe extending over a volume considerably larger than the Local Supercluster. In our observations the region covered extended to a red shift of 5000 $\mathrm{km\,s^{-1}}$ (a radius of 75 Mpc). Distances were derived by using only H I observations in which the 'luminosity distance' was determined from the apparent H I flux density and by using the observed H I line profile width as a third parameter. This method obviates some of the difficulties met with in the corresponding optical studies in which problems arise from obscuration by the widely distributed dust in our Galaxy and from obscuration in the galaxies themselves. The solar motion obtained from these H I measurements agreed with that derived from our analysis of the H I data given by Rubin and associates for Sc galaxies.

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When corrected for the peculiar motion of the Sun, these results show that the Local Group is moving at $484 \pm 65$ km s$^{-1}$ towards Galactic coordinates $l = 258° \pm 13°$, $b = 42° \pm 9°$. This value may be compared with the mean of the Princeton and Berkeley measurements of the cosmic microwave background dipole anisotropy, which, if interpreted as a motion of the Local Group, indicates a velocity of $580 \pm 50$ km s$^{-1}$ towards $l = 266° \pm 9°$, $b = 32° \pm 8°$ for a microwave background temperature of 3.0 K. The close agreement between these values has important implications for cosmology. Firstly, the dipole anisotropy in the cosmic background is evidently the result of the solar and Local Group motion, leaving much less than 30% (less than 1 mK) as an intrinsic dipole anisotropy. Current theories suggest that quadrupole components should be one-third less than the dipole component at the most. Secondly, the large motion of the Local Group is probably the result of gravitational infall towards the Virgo supercluster, having been acquired over the age of the Universe. A velocity of this magnitude implies a density of the Universe relative to the closure density of $\Omega = 0.15$ to $0.50$ based on published values for the density of galaxies in the supercluster.

D. T. Wilkinson. This is an important new result, made particularly interesting because the reference frame lies beyond the Virgo cluster and should resemble that of the 2.7 K radiation. Surely the Galaxy's peculiar velocity contributes most of the dipole effect, but the common assumption that all of the measured effect is due to velocity is not justified. As noted by Peebles (1981), a dipole component due to gravitational red shift from early mass clustering is compatible with existing data. The model predicts an intrinsic dipole effect of 10–20% of the observed dipole amplitude.