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Measurement of the Microwave Background Radiation [and Discussion]

D. T. Wilkinson, M. Rowan-Robinson, R. J. Tayler and M. J. Rees

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Measurement of the microwave background radiation

BY D. T. WILKINSON

Joseph Henry Laboratories, Physics Department, Princeton University, Jadwin Hall, P.O. Box 708, *Princeton, New Jersey* 08544, *U.S.A.*

Absolute flux measurements of the 2.7 K background radiation show a blackbody spectrum with good accuracy (*ca.* ±5%) over two orders of magnitude of wavelength (12 cm to 1 mm). This is in agreement with the thermal history of matter and radiation envisaged by the hot Big Bang model. In particular, experimental limits on spectral distortion constrain processes that release energy into the early Universe.

The extreme isotropy of the 2.7 K radiation on small angular scales (10″ to 1°) sets interesting limits on models for the formation of mass structure. Some types of perturbations can be ruled out because the accompanying spatial fluctuations in radiation temperature are not seen ($\Delta T/T \leqslant 10^{-4}$). Large-scale (1–90°) anisotropy of the radiation is plausible because at the time of decoupling ($z \approx 1000$), regions separated by more than a few degrees in the sky were not in causal contact. Explanation of the observed isotropy is a major feature of inflationary models. Finally, the observed dipole anisotropy is mostly due to the peculiar velocity of the Galaxy with respect to the radiation frame. An interesting question is: how much of this velocity is primordial and how much can be accounted for by local mass attractors?

1. INTRODUCTION

Some connections between the 2.7 K background radiation and the material content of the Universe have already been made by several speakers at this conference. We have heard how limits on anisotropy at small angular scales seriously constrain models of structure formation in the material, with and without the presence of dark matter. Also, observations of anisotropy at large angular scale, the dipole effect, measure the velocity of the Galaxy through the radiation, generally assumed to be the comoving reference frame. This peculiar velocity is probably caused by the net gravitational force due to local mass anisotropy. Thus we are presented with the opportunity to find the extent of our local mass anisotropy by finding the nearest shell of galaxies which gives the same peculiar velocity. Alternatively, if no such reference frame is found in visible matter, we have evidence for a large-scale anisotropy in dark matter, or primordial dipole anisotropy in the radiation. The search is underway with promising results from visible and 21 cm redshift measurements, and from the recent Infrared Astronomy Satellite catalogue. (See discussion by Rowan-Robinson *et al.*, this symposium.)

On the other hand, we have heard no mention here of the spectrum of the 2.7 K radiation. Spectral distortion can be expected for any process where the material releases radiant energy into the Universe. (For reviews, see Sunyaev & Zeldovich 1980; Lyubarsky & Sunyaev 1983.) Given the wide range of new particles currently being considered as dark matter candidates, I am surprised not to have heard about some constraints set by expected decay or other radiative processes. (For example, see Silk & Stebbins 1983.) Perhaps the recently improved spectral measurements will stimulate theorists to look again for such processes.

Since the review by Weiss (1980) significant progress has been made on observations of the spectrum and the anisotropy of the 2.7 K radiation. Following a 10-year hiatus, three recent experiments have greatly improved the accuracy of spectral measurements over the wavelength range $\lambda = 12$ cm–$\lambda = 1$ mm. The results agree with the prediction of a hot Big Bang model by showing no significant deviations from a 2.75 K blackbody spectrum. Ground-based observations of anisotropy at small angular scale are reaching limits below $\Delta T_{\mathrm{rms}} = 100$ µK, however, the prospects for reaching 10 µK with current telescopes and techniques are not good. Balloon-borne instruments measure the dipole effect to $\pm 5\%$ accuracy and search for anisotropy on angular scales from 10–90° at levels of $\Delta T_{\mathrm{rms}} \approx 100$ µK. None has been found. A major advance in technique has been made with the successful flight of the Soviet RELICT experiment. This paper reviews these recent developments and (with apologies to my experimental colleagues) attempts to make some projections for what theorists might expect over the next five to ten years.

2. Recent measurements of the spectrum

There are three basic methods for measuring the absolute flux in the microwave background radiation. At long wavelengths, where the atmosphere is relatively transparent, ground-based experiments employing standard Dicke radiometers are used. Near the peak of the blackbody spectrum (see figure 1) cryogenic bolometers are flown in balloons to avoid atmospheric emission. One would be hard pressed to design a better thermometer for the cosmic background radiation than Nature's interstellar CN molecules. The lowest rotational levels of CN are excited by photons near the peak of the blackbody curve, and the molecules exist in places where excitation by 2.7 K radiation dominates excitation by collisions and shorter wavelength radiation.

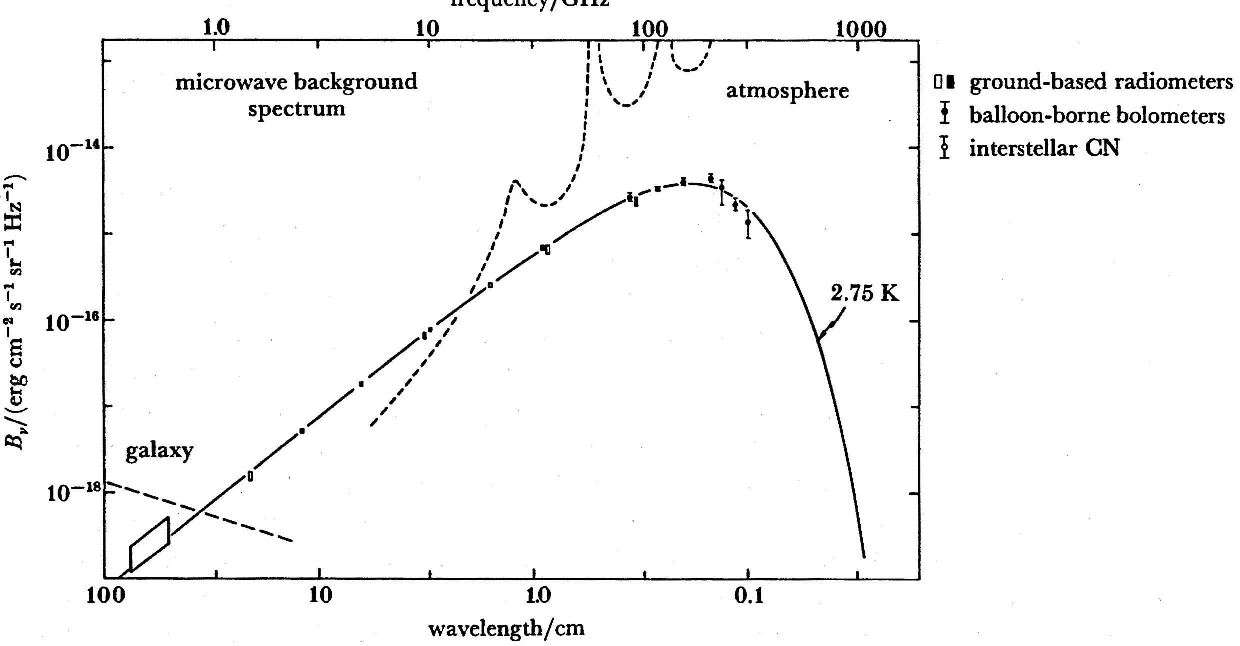

Figure 1. Recent measurements of the spectrum of the microwave background radiation agree well with a 2.75 K blackbody spectrum. For comparison a few older ground-based results are shown as open rectangles. The new measurements are described in the text. B_ν is the monochromatic brightness of the background radiation. 1 erg $= 10^{-7}$ J.

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(a) *Excitation temperature of interstellar* CN

This classical experiment, in which the microwave background was detected 30 years before its discovery (for a review, see Thaddeus 1972), has recently been repeated by Meyer & Jura (1984). Their observations from the Lick Observatory 3 m telescope have a signal:noise ratio of 2000, higher than previous work, but their resolution of 0.075 Å did not allow an independent measure of line-saturation effects. The measured line strengths give $T = 2.83 \pm 0.04$ K at $\lambda = 2.64$ mm. Using the line width measured by Hegyi *et al.* (1972, 1974) to correct for line saturation, Meyer & Jura obtained $T = 2.73 \pm 0.04$ K. Weak excitation of the $J = 1 \rightarrow 2$ transition is also observed, but with much lower statistical precision. The resulting excitation temperature is $T = 2.8 \pm 0.3$ K at $\lambda = 1.32$ nm. An important systematic effect was uncovered in this work with the detection of an atmospheric absorption feature, which in May is Doppler shifted into the weak line which measures the temperature at $\lambda = 1.32$ mm. The results of Meyer & Jura are plotted as open circles on either side of the peak in figure 1; the importance of the CN points is obvious. However, one needs to keep in mind that the error bars (± 40 mK at $\lambda = 2.64$ mm) are based on statistical counting errors only. As Meyer & Jura point out, an important systematic uncertainty, possible collisional excitation, still exists. Thaddeus (1972) has shown that collisional excitation by electrons is the principal worry; $n_e = 0.35$ cm^{-3} could contribute 0.15 K to the measured excitation temperature. Although most modern estimates of n_e are less than 0.35 cm^{-3}, Meyer & Jura clearly state that their result is an upper limit. Even so, the result is important as it conflicts with the spectral distortion near $\lambda = 2.6$ mm found by Woody & Richards (1979, 1981).

(b) *Ground-based radiometer measurements*

The results of a large ground-based experiment have recently been published by a group including researchers from Berkeley, Milano, Bologna, Haverford and Padova (Smoot *et al.* 1985). Five specialized Dicke radiometers were designed to measure the background radiation temperature at $\lambda = 12.0$ cm, 6.3 cm, 3.0 cm, 9.1 mm and 3.3 mm. A sixth radiometer continuously measured atmospheric emission at $\lambda = 3.2$ cm. By using a common, well-understood reference load immersed in liquid He, and making simultaneous measurements from the same site (White Mountain, California) several errors in older work (reviewed by Weiss 1980) were reduced. The results are listed in table 1 and plotted as shaded rectangles in figure 1. Great care was taken to measure and monitor atmospheric emission, however, this was the main contributor to the final error at the four shortest wavelengths. At $\lambda = 12.0$ cm uncertainty in radiation from the walls of the reference load contributes the main error.

Readers should be warned that, following established practice (for which you may blame the author), the several systematic and statistical errors are combined *by quadrature* to arrive at the errors in table 1. Thus the quoted error reflects mainly the dominant error, systematic or statistical. The experimenters attempt to report their best estimate of a one-standard-deviation error, even though the main error may be a systematic one. By averaging the results of all measurements and computing the chi-square statistic (as though the errors were completely statistical) one gets a measure of the experimentalists' degree of optimism about their errors. Combining their results with those of Meyer & Jura, and previous radiometer measurements, Smoot *et al.* find a weighted average of 2.73 ± 0.04 K and a chi-square of 9 for 22 degrees of freedom. If anything, experimentalists are somewhat overestimating their one-sigma final

TABLE 1. RESULTS OF RECENT MEASUREMENTS OF THE SPECTRUM

wavelength/cm	radiation temperature/K	reference
12.0	2.77 ±0.13	Smoot *et al.* 1985
6.3	2.70 ±0.08	
3.0	2.75 ±0.08	
0.91	2.81 ±0.12	
0.33	2.56 ±0.14	
0.35	2.80 ±0.16	Peterson *et al.* 1985
0.20	2.95 +0.11 −0.12	
0.15	2.92 ±0.10	
0.11	2.65 +0.09 −0.10	
0.10	2.55 +0.14 −0.18	
0.26	2.73 ±0.04	Meyer & Jura 1984
0.13	2.80 ±0.30	
weighted mean	2.746±0.026	

errors. Another measure of confidence is consistency. Peebles (1971) computed a similar mean, using 14 ground-based radiometer results available at that time. The result was $T = 2.72 \pm 0.08$ K with a chi-square of 7 for 13 degrees of freedom.

(*c*) *Balloon-borne bolometric measurements*

Of the three methods for measuring the temperature of the microwave background radiation, this is the most difficult. Flux is measured near and above the peak of the 2.7 K spectrum where the spectral density in 2.7 K radiation is dropping and that of 300 K radiation is rising rapidly. Atmospheric and ground radiations are severe problems, forcing the experimenters to use high-altitude balloon platforms, rockets, and (eventually) satellites. The detector and the optical path must, of course, be cooled with liquid helium, and careful shielding of antenna sidelobes is essential. Finally, the crucial tests for systematic errors must be scrupulously anticipated and included in the design of the experiment.

Such measurements have been made by several groups (see Weiss 1980; Gush 1981). The most recent work by Peterson *et al.* (1985) is a notable advance, exhibiting good control of systematic effects. A well-understood Dicke switch allows the sky signal to be compared to an absorber whose temperature (*ca.* 3 K) is accurately known. This technique greatly reduces systematic errors associated with downstream components such as the chopper, filter and detector. In earlier work (Woody & Richards 1981; Mather *et al.* 1974) the critical antenna system had been developed and measured, and valuable experience with sensitive cryogenic bolometer systems in the ballooning environment had been gained.

The work of Woody & Richards (1979, 1981), which had suggested deviations from the 2.7 K blackbody spectrum, was done with a scanning Fourier-transform spectrometer. The latest Berkeley experiment uses a different technique, a set of bandpass filters, to scan in frequency. The results are listed in table 1 where I have quoted the author's 'conventional' error limits, calculated by combining systematic errors by quadrature. The authors prefer to use 'conservative' error limits which are two to three times larger than those in table 1. Their final result is that the range of temperature 2.78±0.11 K is consistent with their data in all five wavelength bands.

In spite of careful control of systematic effects an unexplained drift in the sky signal (2%

per hour) was observed throughout the flight. Peterson *et al.* believe that this is due to frozen air settling into the cold antenna, or to steadily decreasing atmospheric emission. The latter was measured by varying the zenith angle of observation, but a busy operational schedule prevented frequent observations of the atmospheric emission. Another flight of this important experiment is currently being prepared.

(*d*) *Summary and prospects*

Considering the great diversity of the methods used by the three experiments discussed above, I find it quite remarkable that the results are in such excellent agreement. Two comments are in order: (1) all three methods have been under development for 10–15 years and have reached an advanced state; (2) experimenters are motivated to find deviations from the blackbody curve, because this is where the most is to be learned about the early Universe. The general result to be seen in table 1 is that over two orders of magnitude of wavelength the measurements agree with a 2.75 K blackbody spectrum to within a few percent. Ignoring the fact that the important errors are systematic, we can calculate a weighted mean, error in the mean, and a chi-square statistic for the 12 results in table 1.

$$\langle T \rangle = 2.746 \pm 0.026 \text{ K},$$

and $\chi^2 = 10.8$ for 11 degrees of freedom. Assuming that the radiation spectrum is blackbody, the chi-square indicates that the experimental errors are being estimated at about the 1σ level. The 1% error in the mean should not be taken seriously as it depends heavily on the estimated error in the CN measurement, which does not include possible saturation effects.

The prospects for even further improvement in spectrum measurements are good. David Johnson and I have flown a new experiment at $\lambda = 1.2$ cm in a balloon to circumvent atmospheric noise. Midway through the error analysis it appears that even this first attempt has achieved accuracy better than ground-based work at this wavelength. The recent work at centimetre wavelengths is anticipating the major advances at shorter wavelengths expected from the Cosmic Background Explorer (COBE) satellite. A helium-cooled Fourier-transform spectrometer will measure the spectrum from 8 to 1 mm with unprecedented accuracy. Statistical errors are expected to be ± 1 mK near the spectral peak for each 7° resolution element. Systematic errors in absolute temperature are expected to be less than 10 mK and spectral deviations of a few mK should be detectable (Mather 1982). An early 1988 launch is expected for the COBE.

3. Measurements of the anisotropy

Anisotropy in the 2.7 K radiation is of interest on all angular scales; measurements on small (10″ to 1°), intermediate (1–10°), and large (10–90°) angular scales probe different physical processes in the early and present Universe. The experimental techniques also differ, mainly because beam size is determined by antenna aperture. Large ground-based antennae are used for small-scale measurements, and uniform atmosphere is required. On large angular scales small antennae are used in high altitude aircraft, balloons, and spacecraft to minimize noise from fluctuations in atmospheric emission. The current situation is summarized in figure 2. Upper limits have been established at or below $\Delta T/T \approx 10^{-4}$ from 10″ to 90°, and a dipole effect is well established and measured to 5% accuracy.

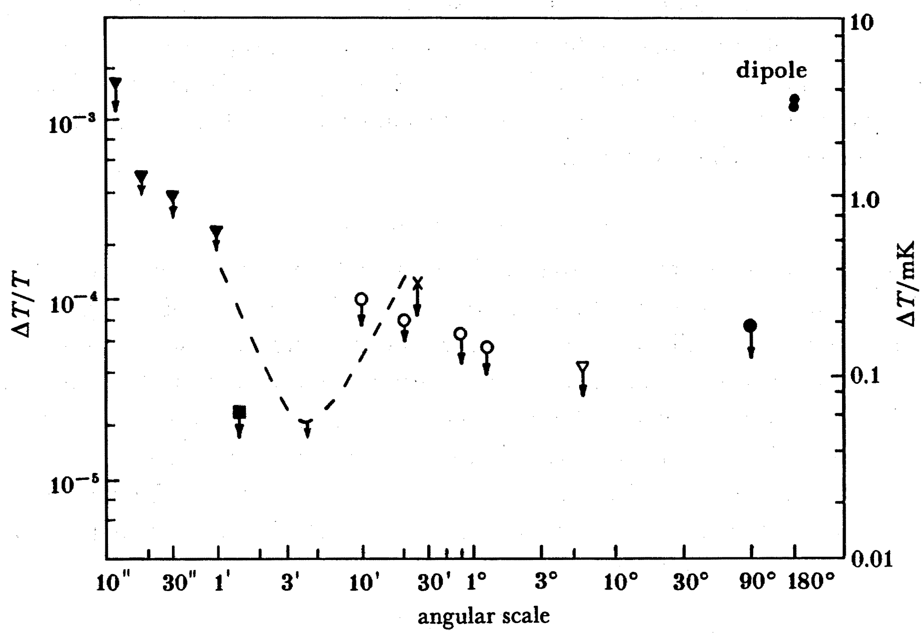

FIGURE 2. Summary of the lowest observational limits on anisotropy in the 2.7 K radiation (95% confidence levels). The various experiments are discussed in the text. Most limits assume that the anisotropy is uncorrelated Gaussian noise. The dashed curve assumes monochromatic waves of random direction and phase.

(*a*) *Searches for small-scale anisotropy*

The four points between 10″ and 1′ in figure 2 were established by searching for structure in radio maps made from long integrations with the Very Large Array (Fomalont *et al.* 1984; Knoke *et al.* 1984). The sensitivity of these early results is mainly limited by instrumental effects in the background roughness; interferometers are not normally used to look for small background fluctuations on scales large compared to their angular resolution. Novel observing and data reduction techniques are being developed to understand or eliminate instrumental effects, and more observing time has been allocated. I think we can look forward to substantial improvement in sensitivity from the next series of observations.

Most measurements have been made on angular scales between 3′ and 1°. This is the scale where theorists predict anisotropy in the 2.7 K radiation due to the density fluctuations that lead to present mass structure (Silk 1967, 1968; Peebles & Yu 1970). Figure 2 shows the lowest observational limits in this range of angles; these results have been used to rule out models with adiabatic fluctuations in a Universe dominated by baryonic matter (Wilson & Silk 1981; Wilson 1983). Recent theoretical work also uses measured limits on small-scale anisotropy to constrain the amplitude of adiabatic fluctuations in models dominated by cold, dark matter, including axions and photinos (Vittorio & Silk 1984; Bond & Efstathiou 1984). The limits between 1′ and 10′ (Uson & Wilkinson 1984*a*, *b*) are currently of particular interest to theorists, so I will come back to them below.

The open circles in figure 2 between 10′ and 75′ are based on data from the RATAN-600 telescope in the Caucasus (Parijskij *et al.* 1977). The values shown here are two to three times larger than those given in the original paper, following the revision of Lasenby & Davies (1983). The large size of the RATAN-600 allows Parijskij and his colleagues to take advantage of the low receiver noise and smoother atmospheric emission available at longer wavelengths. At $\lambda = 7.6$ cm they achieve a measured sensitivity of 2 mK $s^{-\frac{1}{2}}$, remarkably low for a ground-based system. However, at $\Delta T/T \sim 10^{-5}$ confusion due to discrete radio sources becomes a problem at wavelengths longer than 1 cm (Danese *et al.* 1983). The Soviet group plans to identify discrete sources, and noise due to atmospheric and galactic emission, by observing at several wavelengths between $\lambda = 1.38$ cm and $\lambda = 31$ cm. Fluctuating sources are identified by the wavelength channels where they are strongest, and then removed from the 7.6 cm channel which has the best sensitivity. Preliminary results indicate that levels of $\Delta T/T \sim 10^{-5}$ (95% confidence) are attainable (Berlin *et al.* 1983).

Juan Uson and I have used the Green Bank 42 m antenna and $\lambda = 1.2$ cm maser to look for small-scale anisotropy with a beam diameter of 1.5′ and a beam chop angle of 4.5′. By observing spots at 85° declination, long integration times were achieved with minimum motion of the telescope with respect to the ground. Other important technicalities were: (1) the use of an observing procedure such that atmospheric and ground radiation are cancelled; (2) the elimination of sources of low-frequency noise and interference from the receiver and (3) the use of a telescope with remarkable day-to-day reproducibility.

To minimize ground and atmospheric effects a 'ground-synchronous chop and wobble' procedure was used; the telescope beam was chopped at 3.3 Hz through 4.5′ as the eastern beam tracked the 'source' spot for time, t. Then the telescope was moved to put the western beam on the source for time t; the difference of these two integrations is a data point. The integration time t was chosen so that the telescope moved through the same angles with respect to the ground and atmosphere for each integration. This procedure cancelled atmospheric and ground radiation to first order, but produced an odd sampling pattern on the sky. The data point represents the temperature in the source position minus the average temperature in two 'reference' positions 4.5′ away on opposite sides of the source position. The need for very accurate cancellation of systematic effects forced us to use this pattern.

Data were taken for a total of 174 h on 12 fields evenly spaced along $\delta = 85°$. The results, corrected for beam efficiency (55%), are shown in figure 3. From the figure it is clear that no anisotropy larger than $\Delta T/T \approx 10^{-4}$ (95% confidence) has been observed in any one of the 12 fields. More accurate limits can be set by making assumptions about the nature of the underlying anisotropy σ_{sky}. Basically, one asks: how large can σ_{sky} be without causing the scatter of points in figure 3 to exceed that expected from measured statistical errors due to instrument, atmosphere, and ground fluctuations (the error bars shown in the figure)? Because the scatter is consistent with measured errors, only an upper limit can be set on σ_{sky}. However, the value of the limit will depend on the observed pattern on the sky, and on the statistics and angular correlations assumed for σ_{sky}. The value of the limit also depends on the particular formulation of the statistical test chosen to search for a σ_{sky} effect (Boynton & Partridge 1973; Lasenby & Davies 1983). Indeed, it is not difficult, or uncommon for observational limits to shift by factors of *ca.* 2 for different models or different statistics. A careful comparison of experiment and theory must match a specific observation against a specific model, and the statistical test must be clearly described.

Uson and I (Uson & Wilkinson 1984*a*) have interpreted our Green Bank results in terms of two simple assumptions about σ_{sky}. The point in figure 2 at angular scale 1.5′ ($\sigma_{sky}/T < 2.4 \times 10^{-5}$, 95% confidence) applies to a Gaussian sky signal with a standard

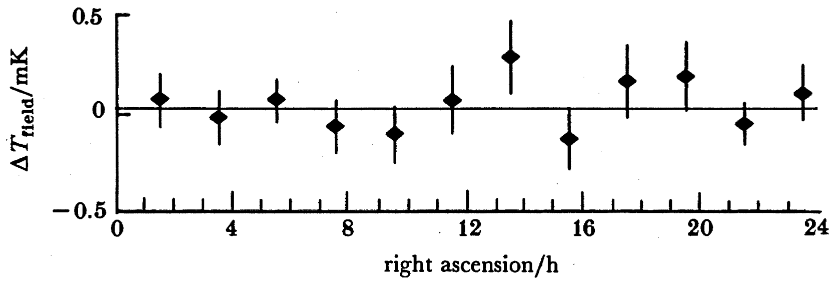

FIGURE 3. The results for each of the 12 fields observed by Uson & Wilkinson (1984*a*). The error bars are well-determined statistical errors derived from scatter in individual data points. No adjustments of the means are made on data from different days. The overall mean (26 μK ± 39 μK) is shown.

deviation of σ_{sky}, and no correlation on scales of 4.5′, the beam chop angle. All samples, source and reference spots in all 12 fields, are assumed to be statistically independent. Also shown in figure 2 is a dashed limit, reaching a minimum of $\sigma_{\text{sky}}/T = 2.1 \times 10^{-5}$ (95% confidence) at 4′. This limit assumes that σ_{sky} is best represented by a Gaussian distribution of sinewaves of fixed angular scale but random direction and phase on the sky. The sensitivity of the observations at each angular scale is determined by the Fourier transform of the scan pattern, the angle filter. Note that this model generates anticorrelation and increased sensitivity on scales near the beam chop angle.

Because of the need to compare specific observations with specific models, the limits shown in figure 2 should only be used as a rough guide to current experimental accuracy on various angular scales. The methods used by observers to derive limits from their data vary, and in some cases the methods have been incorrect. Some limits have been revised upward by Partridge (1980) and Lasenby & Davies (1983). Another problem has been misinterpretation of experimental limits by theorists testing their models. A good trend is evident in two recent theoretical papers (Vittorio & Silk 1984; Bond & Efstathiou 1984) where the observing pattern is explicitly taken into account. (This was in part due to discussions with Uson at the Inner Space–Outer Space Conference at Fermilab.) Another good sign is the increasing discussion of experimental errors by theorists at conferences like this one. For example, N. Kaiser has shown me a statistical analysis of the Uson–Wilkinson data based on the likelihood function. The upper limit is increased by a factor of two over that shown in figure 2.

(*b*) *Prospects for improving small-scale anisotropy measurements*

At angular scales below 1° anisotropy measurements have been made by a few ground-based instruments having especially low antenna sidelobes and state-of-the-art low-noise receivers. Current levels for upper limits are set primarily by receiver and atmospheric noise or by source confusion at longer wavelengths.

A straightforward way to lower limits is to schedule more observing time on a well-suited instrument and integrate down the statistical errors. A Caltech group led by T. Readhead is trying this at Owens Valley, using a maser receiver similar to the one at Green Bank. In spite of unusually poor sky conditions last winter (1984–5), preliminary results are encouraging and one can foresee substantial improvement over current sensitivity in the 5′ range from a single good observing season. Of course, unknown systematic effects lurking just below the level of current statistical errors might limit accuracy in the end. The only way to find such systematic effects is to look for them in real data.

Several groups are now trying to make a technological jump, following the early work of groups led by Weiss, Melchiorri, Richards and Boynton. Cryogenic bolometers can achieve higher sensitivity than coherent microwave receivers by using much wider bandwidth. Systems with instrumental noise below 1 mK $s^{-\frac{1}{2}}$ are possible at $\lambda \approx 3$ mm. This wavelength is near the minimum between galactic radio emission and expected galactic dust emission. Atmospheric emission will probably be a problem, but the angular power spectrum of fluctuations at good sites is still unknown. Encouragement can be gained from the point (x) in figure 2 at 25′ (Caderni *et al.* 1977). The data were obtained using a bolometer detector at $\lambda = 1.2$ mm from a high mountain site (Testa Grigia) in the winter. Most observers are anticipating observations from balloons or special ground-based sites, such as the Antarctica. The first results will probably be available in two or three years.

Another promising idea is a variation of the VLA technique. A closely packed interferometer array of N telescopes could be used to achieve better angular resolution, lower overall receiver noise and relative immunity to ground radiation. Receiver noise goes down by a factor of $\sqrt{N}$, beam size decreases by $\sqrt{N}$, and beam switching can be accomplished by switching local oscillator phase, thus permitting higher efficiency in the signal path. Ground radiation averages to zero at the interferometer output, but phase coherent sidelobe spikes will occur. Such systems have been proposed, but results are probably several years away.

On a longer time scale, large millimetre antennas in space promise the ultimate in sensitivity if the best detectors are used. Small-scale anisotropy has been proposed as an objective of the Large Deployable Reflector, now under study. However, care must be taken that the special millimetre characteristics of the antenna and the low noise level of the millimetre detector are not compromised by extending the wavelength coverage to shorter wavelengths.

(*c*) *Searches for intermediate- and large-scale anisotropy*

Measurements of anisotropy in the angle range between 1–10° are difficult. Ground-based work is hampered by atmospheric fluctuations which are large on this angular scale (typical cloud size), and balloon observations at $\lambda \approx 1$ cm must use large, unwieldy antennas. The most accurate upper limit in this angular range (see figure 2) was obtained with a balloon-borne bolometer sensitive to wavelengths between 0.6 and 3 mm (Fabbri *et al.* 1980; Melchiorri *et al.* 1981). The 5.2° beam was chopped through an angle of 6° which sets the angular scale of the measurement. Because of its short-wavelength response the instrument was sensitive to emission from galactic dust. Large signals were obtained in directions of large gradients in the density of neutral hydrogen which is known to coexist with galactic dust. From fluctuations observed at high galactic latitude an upper limit on anisotropy in the 2.7 K radiation was set at $\Delta T/T < 4 \times 10^{-5}$ (95% confidence), the level of uncertainty in the contribution of high altitude dust. Higher sensitivity to anisotropy could be achieved by a similar experiment which rejected short wavelength radiation from dust, especially with the more sensitive detectors now available.

At larger angular scales the most sensitive measurements have been made by balloon-borne microwave radiometers (Lubin *et al.* 1983; Fixsen *et al.* 1983; Lubin *et al.* 1985). These observations have refuted earlier reports of detection of a quadrupole effect (Fabbri *et al.* 1980; Boughn *et al.* 1981) that were probably due to incomplete subtraction of galactic radiation, a quadrupole shaped distribution. The upper limit for a quadrupole anisotropy in the 2.7 K radiation is $\Delta T/T < 7 \times 10^{-5}$ (90% confidence). The observations were made at $\lambda = 3$ mm and $\lambda = 1.2$ cm. The shorter wavelength observations were not contaminated by galactic radio emission and show no evidence for dust emission. A maser amplifier allowed the 1.2 cm instrument to achieve lower statistical error, but a correction for galactic radiation had to be made. Each experiment was flown three times, including once in the southern hemisphere, to get 80% sky coverage.

A strong dipole effect is seen in both of these experiments; it is interpreted as primarily due to the Sun's velocity through the 2.7 K radiation. Even the earth's orbital velocity has been detected as a shift in the dipole measured in balloon flights six months apart. The most recent dipole results (referred to the heliocentric frame) are:

$$T = 3.46 \pm 0.17 \text{ mK}, \quad \delta = -6.0 \pm 1.4°, \quad RA = 11.3 \pm 0.1 \text{ h}$$

(Lubin *et al.* 1985).

$$T = 3.18 \pm 0.17 \text{ mK}, \quad \delta = -8 \pm 2°, \quad RA = 11.2 \pm 0.1 \text{ h}$$

(Fixsen *et al.* 1983).

It should be noticed that the directions are in good agreement and the magnitudes are in reasonable agreement. The main error in these measurements now comes from uncertainty in the flight calibration of the radiometers which does not affect the direction determination.

The peculiar velocity of the Galaxy can be used as a probe of the distribution of matter (bright and dark) out to the scale of the largest matter inhomogeneities. Subtracting the Sun's velocity with respect to the Local Group from the velocity measured with respect to the 2.7 K radiation gives the velocity of the Local Group through the radiation. Averaging the two dipole results gives

$$v_{LG} = 600 \pm 50 \text{ km s}^{-1}, \quad \delta_{LG} = -27 \pm 4°, \quad \alpha_{LG} = 10.1 \pm 0.4 \text{ h}.$$

The magnitude is large compared to typical velocity dispersions of galaxies in clusters. Also, the direction is 45° from the direction of the Virgo cluster (the nearest large visible mass clump). Perhaps, the Virgo cluster is not the dominant mass attractor for the Galaxy as previously suspected. Other visible clusters or invisible matter may be making a significant contribution to the net gravitational force on the Galaxy.

Two groups have recently reported an interesting result based on the distribution of galaxies in the IRAS catalogue (Meiksin & Davis 1985; Yahil *et al.* 1986). The sample of infrared galaxies is large (6700 members), uniformly sampled, and relatively immune to obscuration by galactic dust. A dipole effect of about 10% amplitude is found, and the direction is only 25° from the direction of $\boldsymbol{v}_{LG}$ measured against the 2.7 K radiation. The implication is that infrared galaxies (mostly spirals) correlate well with the total local mass distribution.

Another important recent development is the success of the Soviet RELICT experiment aboard the PROGNOZ-9 satellite. The orbit was extremely eccentric (apogee was 7×10^5 km), and the satellite spun (30 Hz) and pointed away from the Sun. These are ideal conditions for a large-scale anisotropy experiment. A radiometer was operated at $\lambda = 8$ mm for more than 7 months, comparing the radiation temperature at the anti-solar point with that on a circle 90° away; the whole sky was scanned in 6 months. The preliminary heliocentric dipole result (Strukov *et al.* 1985) is

$$T = 2.5 \text{ mK}, \quad \delta = -3.3°, \quad RA = 10.8 \text{ h},$$

in agreement with the direction of the dipole distribution measured from balloons, but smaller in amplitude. A possible problem is indicated in the paper reporting early results (Strukov &

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Skulachev 1984). Sidelobe response of the scanning antenna is large (greater than 10^{-5} of the maximum) out to 60° from the beam centre. Thus, the earth and moon cause significant contamination when in these sidelobes. In principle the earth and moon signals can be calculated and removed if the antenna response is known everywhere.

(*d*) *Prospects for improving intermediate- and large-scale anisotropy measurements*

Plans for more balloon-borne experiments are going ahead. The main improvements will come from lower noise receivers in the 3 mm wavelength range. New cryogenic mixers and broadband bolometers cooled with ^{3}He promise to improve sensitivity by factors of three or four. Of course, better calibration techniques are planned. As statistical errors due to receiver noise are lowered, systematic effects such as ground and balloon radiation, non-uniform atmospheric emission, and galactic dust emission will have to be eliminated or measured with improved accuracy. Systematic effects and limited observing time will eventually set the lower limit that can be reached from balloons.

The successful operation of RELICT ushers in a new era of anisotropy measurements from space. Long duration, rapid scanning, and full sky coverage help to reduce or understand many systematic effects. The Cosmic Background Explorer (Mather & Kelsall 1980; Mather 1982) will carry three anisotropy radiometers at wavelengths of 8, 5.6 and 3.3 mm. The Soviet group at the Institute for Space Research is also planning to orbit three radiometers at similar wavelengths in 1990 or 1991. These missions should produce a measurement of the dipole effect with 1% accuracy, and improve the sensitivity to anisotropy in the angular range between 10° and 90° to $\Delta T/T \approx 10^{-5}$.

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Discussion

M. Rowan-Robinson (*School of Mathematical Sciences, Queen Mary College, University of London*).

Determination of the dipole component of the local gravitational field by using IRAS galaxies

I will give a very brief report on some work we are doing at Queen Mary College with the IRAS survey to obtain some interesting cosmological results. An identification programme and redshift survey carried out in the north galactic polar cap ($b > 60°$) shows that outside obvious clouds of interstellar dust, and after exclusion of sources which are clearly stars, over 99% of IRAS 60 μm sources can be identified with galaxies (Lawrence *et al.* 1986). The characteristic depth of the IRAS survey is 180 ($H_0/50$) Mpc.

With A. Yahil, of Stony Brook University, we have used the IRAS 60 μm sources to map the local gravitational field, analysing this into spherical harmonics. Areas affected by emission from interstellar dust (the 'cirrus') have been masked out by using the IRAS catalogue flags. The dipole component of the local gravitational field, assuming that IRAS galaxies trace the matter, is found to be in the direction $l = 248 \pm 9°$, $b = 40 \pm 8°$, only 26° (±10°) away from the direction of the dipole component of the microwave background radiation. This strongly suggests that the latter is due to motion induced by the combined gravitational attraction of galaxies and clusters within 200 Mpc (Yahil *et al.* 1986).

Using the 60 μ luminosity function of Lawrence *et al.* (1986), we can estimate how much matter there must be in the Universe, distributed like the IRAS galaxies, to generate our observed motion with respect to the microwave background radiation. Using the linear perturbation theory of Peebles (1980), we find

$$\Omega = 0.85 \pm 0.16$$

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and estimate that correction for nonlinear effects should increase this figure by 15%, to give

$$\Omega = 1 \pm 0.2.$$

A large-scale collaboration involving British and U.S. astronomers is under way to carry out an all-sky redshift survey of IRAS sources and test this fascinating result.

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R. J. Tayler (*Astronomy Centre, University of Sussex*). Could I ask someone such as Martin Rees or Michael Rowan-Robinson to say whether or not the limits on isotropy would raise greater problems in a cold Big Bang model in which the microwave radiation was thermalized light from Population III stars?

M. J. Rees (*Institute of Astronomy, University of Cambridge*). The limits on small angular scales would depend not only on the initial fluctuation spectrum, but also on how homogeneously distributed the postulated radiation sources were. However, there is certainly no reason why the fluctuations should necessarily be larger than in 'standard' models.

There is, however, one distinctive prediction that these models make (see, for instance, Hogan *et al.* 1982). The 'last scattering surface' would not be dominated by Thomson scattering, but by wavelength-dependent absorption processes. Consequently, there is no reason why observations of a given strip of sky at different wavelengths should show the same $\Delta T/T$ as a function of position (because the effective scattering surface would be at a wavelength-dependent redshift). In the standard model, of course, the variations in T measured at two different frequencies should track each other closely. This test can be made as soon as we have positive anisotropies rather than just upper limits.

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