RECENT MEASUREMENTS OF THE COSMIC MICROWAVE RADIATION

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ABSTRACT. Recent measurements of the spectrum and anisotropy of the cosmic microwave may be showing deviations from a perfectly homogeneous blackbody flux. Improved spectral measurements at wavelengths of 3 cm and 1.2 cm disagree weakly; and new results from a rocket show large excess flux at wavelengths of 0.71 and 0.48 mm. The same instrument measured a radiation temperature at $\lambda = 1.16$ mm of 2.795 ± 0.018 K in good agreement with results at longer wavelengths. The observed excess flux at short wavelengths may be due to: local contaminants; dust emission from active galaxies at high redshift; or inverse Compton scattering of microwave photons from hot electrons at large redshift (Sunyaev-Zel'dovich effect). Anisotropy of $\Delta T/T = 3.7 \times 10^{-5}$ has been reported on an angular scale of 8° at a wavelength of 3 cm. Measurements on a similar angular scale at $\lambda = 6$ cm (reported at this meeting) do not show the anisotropy at the flux level expected if Galactic emission were the source of the anisotropy at $\lambda = 3$ cm. The standard model has not yet predicted anisotropy this large at 8°, but without doubt it soon will. Long integrations with the Very Large Array at $\lambda = 6$ cm are showing resolved structures on angular scales of 15 to 30 arcseconds. Observations at another wavelength are needed to see if these are radio sources at high redshift or perturbations in the 2.77 K radiatoin.

1. INTRODUCTION

Measurements of the 2.77 K radiation still provide our best hope of learning about physical conditions in the early, and not-so-early, universe. Until now, observations have agreed with the predicted isotropic blackbody with frustrating regularity. As the need for precision and accuracy increases, the experiments get harder and longer. Direct measurements of the spectrum have only within the last year been made at high enough altitudes to avoid any limitations by atmospheric emission. Now at the 1% level of accuracy, the experimental errors are dominated by systematic effects originating inside the instruments, or nearby. By contrast, searches for

J. Audouze et al. (eds.), Large Scale Structures of the Universe, 7–14.
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anisotropy are still limited by instrument noise and bandwidth. The biggest strides here are being made by improving detectors and finding new observing strategies that minimize the effects of atmospheric fluctuations.

This brief reveiw will emphasize the considerable progress made within the last year. Earlier work is reviewed and referenced in the proceedings of the 13th Texas Symposium[1] held in Chicago, December 1986.

2. SPECTRUM MEASUREMENTS

Figure 1 and Table I summarize the results of recent measurements of the cosmic micrwoave radiation temperature. The measured flux has been converted to an equivalent blackbody temperature, taking into account the instrument bandpass. At wavelengths longer than 20 cm, measurements are ultimately limited by uncertainty in the Galactic emission ($>$ 7.0 K at $\lambda = 50$ cm), although the preliminary result[2] at 50 cm in Table I still suffers from excessive sensitivity to ground emission (6.0 K) -- a difficult problem with large antennas. Long wavelength measurements are very important in recognizing the Sunyaev-Zel'dovich effect and in searching for bremsstrahlung emission from reheated plasma at high redshift.[12] Experimenters are showing renewed interest in this important part of the spectrum. The 'ground-based' measurements with $\lambda < 30$ cm were obtained from the same site (White Mountain California) and using the same liquid helium reference load. However, since atmospheric emission and systematic corrections for the reference temperature are wavelength dependent, colocation turned out not to be an important advantage over the older measurements[13]; however accuracy was improved by factors of 2 to 3.

Work continues at Berkeley with filtered bolometers, flown in balloons to reduce atmospheric emission. Data from a recent flight with a modified instrument is now being analyzed; the older results shown in Fig. 1 and Table I have been widely discussed.[10],[1] Although not confirming the earlier finding[14] of an average temperature well above the ground-based radiometer results, the hint of a spectral distortion repeats. The important new measurements of interstellar CN excitation temperature confirm older measurements[13] and significantly reduce the errors. Accurate temperature measurements in three clouds are in agreement[8], and higher resolution[9] is giving a better (and different) measurement of the line width. The current errors arise mainly from uncertainty about the contribution of possible collisional excitation of the CN.

Within the last year several new measurements have been reported. Smoot, et al.[3] have new results at $\lambda = 21.3$ cm and 8.2 cm. Most of the error in the important 21.3 cm result arises from uncertainty in the coherent reflection of mixer noise from the reference load. This effect, which was only recently pointed out[6], can be large unless good isolation is provided between the mixer and horn and the reference load has exceptionally low reflection ($< 10^{-4}$ in power). Earlier results

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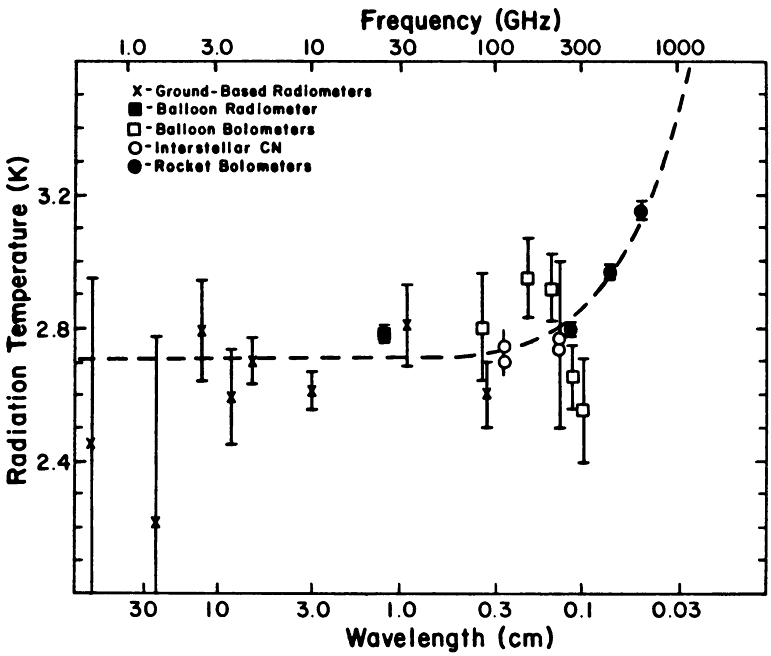

Fig. 1. Recent Measurements of the CMR Temperature.

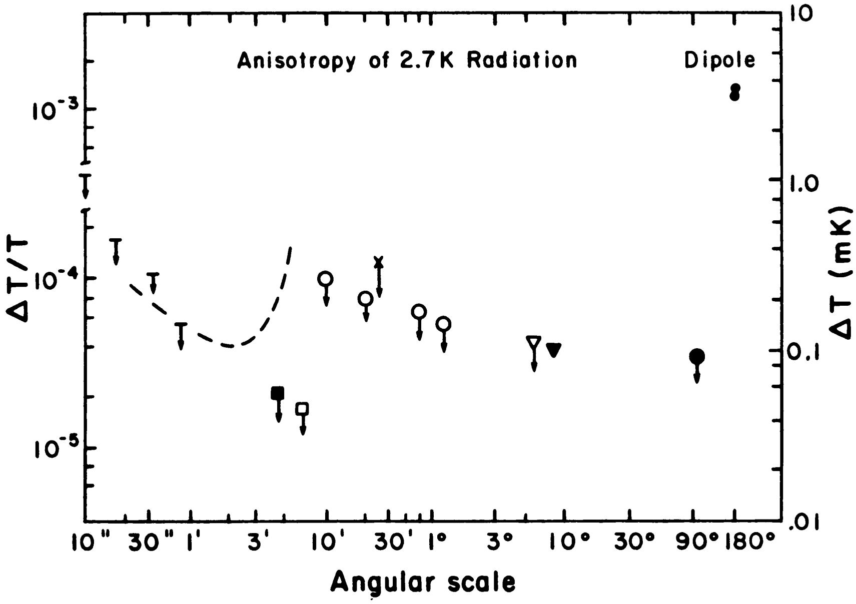

Fig. 2. Recent Measurements of the CMR Anisotropy.

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should be reexamined[15] to assess the possible effects of coherent reflection.

The points at λ = 3.0 cm and 0.33 cm are based on data from four observing seasons and are probably approaching the limit of accuracy achievable from the ground. The point at λ = 1.2 cm was obtained using a balloon-borne radiometer with its early stages cooled and nearly in thermal equilibrium with the incoming radiation. Thus, many systematic effects such as reflections, calibration accuracy, and emission from antenna walls, are greatly reduced in magnitude; and the cold load can be cooled in the same dewar. Under remote control, the radiometer alternately measured the radiation temperatures of the sky and the cold load (temperature known to ± 10 mK); these differed by less than 100 mK, so corrections were small. The discrepancy between the points at λ = 3.0 cm and λ = 1.2 cm is the most significant yet found at centimeter wavelengths. Though the errors are dominated by systematic effects, experimenters try to estimate them at confidence levels comparable to a standard deviation. In that sense, the disagreement between these two points is roughly 2.5 σ.

Finally, the solid circles in Fig. 1 are preliminary results[11] from a joint Nagoya-Berkeley rocket flight. Three points at still shorter wavelengths are clearly affected by Galactic dust emission, so they are not included here. In spite of a careful analysis by the experimenters of possible systematic effects, some questions remain such as, possible contamination by the rocket exhaust cloud, and emission by frozen contaminants in the optical path. (A large heat pulse was seen when the cover was removed.) Further analysis and laboratory measurements should resolve these doubts; until then, interpretation of the rocket results should be regarded with some caution, in my opinion.

First, if the rocket results are ignored, the points in Fig. 1 give a weighted mean of T = 2.740 ± 0.016 K with a χ^2 of 22 for 17 degrees of freedom. Again, I make the unwarranted assumption that the error bars are standard deviations. The weighted mean of all 21 points has a χ^2 of 249, clearly constant T is a poor hypothesis. Compton scattering by hot electrons gives an effect[16] at shorter wavelengths like that shown by the rocket data. The dashed curve in Fig. 1 is the best fit of the inverse Compton effect (Eq. V in reference 16) to the points. The fitted parameters are T_{RJ} = 2.705 ± 0.015 K and y = 0.018 ± 0.001; the χ^2 for this fit is 33 for 19 degrees of freedom. The fit improves dramatically if the λ = 1.2 cm point is ignored by the fit: T_{RJ} = 2.667 ± 0.018 K and y = 0.021 ± 0.002 with χ^2 = 19 for 18 degrees of freedom. This last fit is, of course, quite attractive if the rocket results hold up. However, this would leave the λ = 1.2 cm point above the fitted curve by 120 mK -- 4.8 times the estimated error and 1.3 times the maximum error of ± 89 mK.

Another possibility mentioned by Matsumoto, et al. is that the rising flux at short wavelengths could be due to dust emission in galaxies or stars at large redshift. The energy requirements are extreme if the dust is put at high redshift {energy density $\sim (1 + z)^4$}. However, models with dust at modest redshift have trouble fitting the much lower flux observed at a wavelength of 0.26 mm.

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3. ISOTROPY MEASUREMENTS

Searches for anisotropy at small angular scales must use large antennas and so are carried out from the ground. Nonuniform emission from the ground and the atmosphere are the main problems, but most experimenters use special scanning strategies to reach sensitivity levels near those set by instrument noise. At larger angular scales balloons and satellites are used to avoid atmospheric emission and to obtain good sky coverage.

Current results are summarized in Fig. 2. At the smallest angular scales two groups[17] have used the Very Large Array to obtain upper limits. Actually, resolved sources are seen in the maps, but there may be some correlation with faint clusters of galaxies[18] seen on deep CCD pictures. So the radio emission at $\lambda = 6$ cm may be originating in the galaxies; the fluxes are not unreasonable. It is important to observe these fields with the VLA at a shorter wavelength to get a spectral index for the blobs.

On scales of a few arcminutes, two groups have used similar instruments and techniques to reach low limits. The maser-equipped 140' telescope at NRAO's Green Bank Observatory was used to scan 12 regions near the north celestial pole. The scanning pattern was dictated by the need to reduce systematic effects and consisted of 3 beams (1.5' diameter) in line and separated by 4.5'. The solid square in Fig. 2 shows the result[19] of combining 174 hours of data into one point by the "standard" statistical method. Basically, the measured point-to-point fluctuations are compared to those expected from instrument noise alone, and any excess is attributed to anisotropy on the sky. The test is very sensitive to the estimate of instrument noise and to statistical fluctuations. In this experiment the measured fluctuations were statistically unlikely and the method estimates a low sky noise.

A better method[20] compares the experimental results to Monte Carlo models of the experiment using an assumed model for the sky fluctuations. The amplitude (or upper limit) of the sky signal is that which gives agreement between observed and modeled results. The only disadvantage of this method is that the limit depends on the choice of sky fluctuation model. The dashed line in Fig. 2 is the result of interpreting the Uson-Wilkinson data for a Gaussian model of sky fluctuations. The lowest point is about a factor of 2 higher than the result from using the older method, and the best sensitivity occurs at about 2'.

The open square in Fig. 2 shows a new result[21] from the Owens Valley Radio Observatory. The instrumentation is similar to that at NRAO, except that the telescope mount allows access to the pole. More time can be devoted to this observation, and the atmospheric noise is low for a larger fraction of the time. The current result is a very impressive $\Delta T/T < 1.5 \times 10^{-5}$ at the 95% confidence level.

A similar limit was reported at this conference by Parijskij, based on work at the RATAN-600 telescope. Earlier results of this group have had to be revised upward[22] because of questions about the beam efficiency and statistics used in data analysis. A serious

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problem for western colleagues has been a lack of details in the brief papers[23] from this group. We were very happy to receive reprints of a review paper[24] at this Symposium.

In Fig. 2 the points between 10' and 6° are due to pioneering work by the Florence[25] and RATAN-600 groups. The results have been reviewed[1,22] elsewhere. The open square at 8° angular scale is a new result[26], a possible detection, using ground-based radiometers at 10 GHz and 5 GHz. The sky anisotropy reported[27] at $\lambda = 3$ cm is about the magnitude to be expected from Galactic radiation by extrapolating the rms fluctuations found in long-wavelength maps. However, at this meeting Lansenby reported that sky signals are not seen at $\lambda = 6$ cm at the levels expected if the anisotropy were due to Galactic emission (Galactic radiation temperature $\sim \lambda^{2-2.8}$). Indeed, if the anisotropy is due to the CMR, the rms fluctuations will soon be seen at $\lambda = 6$ cm, and correlated anisotropies of the same ΔT would surely signal the discovery of CMR anisotropy. On the other hand, there are several possibilities for spurious signals in the 3 cm apparatus: Cygnus and the Galactic center are strong sources and may be leaking into "switched" sidelobes due to the reflector edge; contamination by the moon in far sidelobes; synchronous heating of the reflector (a gradient of .01 K will do). Small effects count because the anisotropy signals are tiny: 3×10^{-7} below the ambient temperature; 10^{-4} of the maximum moon signal and a factor of 10^{-3} weaker than the brightest Galactic regions.

On large angular scales, important new results[28] from the Relikt experiment aboard Prognoz-9 were reported by Strukov. Sidelobe contamination by the earth and moon have now been removed from the data. The dipole result: (3.16 ± 0.12)mK directed toward $\delta = -7.5 \pm 2.5$ deg and $\alpha = 11.3 \pm 0.16$ hr, is in good agreement with older results from the Berkeley and Princeton groups. Likewise, an upper limit of $\Delta T/T < 3 \times 10^{-5}$ is placed on a possible quadrupole, about the same limit found from the balloon work. However, the Moscow group goes on to make a multipole analysis through $\ell = 15$. No signals are found, and upper limits are about $\Delta T/T < 6 \times 10^{-5}$ for $\ell = 3$ through 10, and $\Delta T/T < 10^{-4}$ for $\ell = 11$ through 15. The group plans next to place 4 or 5 radiometers ($\nu = 20$ GHz to 150 GHz) near the libration point L2, with a possible 1991 launch.

I wish to thank I. Strukov, G. Sholomitskij, R. Sunyaev and A. Lasenby for helpful discussions at the conference. S. Boughn, D. Cottingham, C. O'Neil and P. Timbie explained the new isotropy analysis to me, and G. Wright shared his work on emission by high z dust.

This research was supported in part by the National Science Foundation.

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TABLE I.

Recent Measurements of CMR Temperature

Wavelength (cm)	Temperature (K)	Ref.
50	2.45 ± 0.5	2
21.2	2.22 ± 0.55	3
12.0	2.79 ± 0.15	4
8.2	2.59 ± 0.14	3
6.3	2.77 ± 0.07	5
3.0	2.61 ± 0.06	3
1.21	2.783 ± 0.025	6
0.91	2.81 ± 0.12	7
0.33	2.60 ± 0.10	3
0.264	2.70 ± 0.04	8
0.266	2.74 ± 0.05	9
0.132	$2.75 \, ^{+0.24}_{-0.29}$	9
0.351	2.80 ± 0.16	10
0.198	$2.95 \, ^{+0.11}_{-0.12}$	10
0.148	2.92 ± 0.10	10
0.114	$2.65 \, ^{+0.09}_{-0.10}$	10
0.100	$2.55 \, ^{+0.14}_{-0.18}$	10
0.116	2.795 ± 0.018	11
0.071	2.963 ± 0.017	11
0.048	3.150 ± 0.026	11

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