MEASUREMENT OF THE COSMIC MICROWAVE BACKGROUND TEMPERATURE AT 1.5-cm WAVELENGTH*

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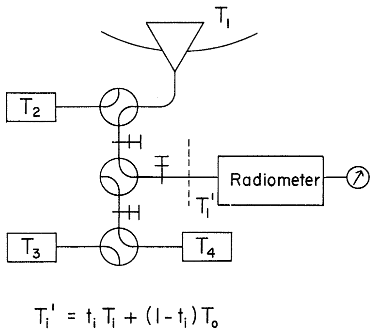
Recently Penzias and Wilson reported observing an excess antenna temperature of 3.5 ± 1°K at a wavelength of 7.4 cm,[1] a finding which was interpreted by Dicke et al. as evidence of redshifted thermal radiation emitted during a compact early stage of the universe.[2] Table I summarizes the measurements reported subsequently. It is the purpose of this note to report a measurement of the background temperature at 1.5-cm wavelength; our result is 2.0 ± 0.8°K.

Although at 1.5-cm wavelength there is very little radiation from the Milky Way or the known extragalactic radio sources to confuse this measurement, there is considerable emission from the atmosphere, due to the proximity of the 1.35-cm line of water vapor and the 0.5-cm band of oxygen. For this reason, the observations were made at Mount Barcroft, elevation 13 000 feet, in the White Mountains of eastern California. Above that altitude there remains less than 10-20% of the water vapor that is overhead at sea level, and accordingly the emission from the atmosphere was found to be only a few degrees at the zenith.

The apparatus used for the observations consists of a small pyradimal horn of 12° beamwidth connected to a conventional Dicke radiometer. By means of waveguide transfer switches, the radiometer input is connected alternately to the horn and then to several waveguide blackbody terminations for calibration. The microwave circuit is shown in Fig. 1. With the aid of these calibrations and knowledge of the circuit and horn losses, the temperature of the radiation incident upon the horn is measured. The contribution of the atmosphere to this radiation is obtained by tipping the horn; and the component remaining is the background brightness.

The three reference terminations were maintained at 330.0°K, 310.0°K, and the boiling temperature of liquid nitrogen, typically 73.6°K at 13 000-ft elevation. The cold load consists of a pyramid-shaped absorber at the end of a 12-cm length of silver-plated stainless steel K-band waveguide. The lower 8 cm of guide was encased in a heavy copper jacket which in turn was immersed in the liquid-nitrogen bath. The space in the guide above the absorber was filled with polystyrene foam, to prevent possible radiative heating of the tip of the absorber. From the measured temperature dis-



$$T_i' = t_i T_i + (1-t_i) T_0$$

FIG. 1. Diagram of the radiometer. T_2 is the liquid-nitrogen load; T_3 and T_4 are the heated loads. The voltage standing-wave ratio is 1.02 or less at each switch setting, and no emissivity correction is required.

Table I. Summary of background measurements.

Wavelength (cm)	Effective temperature (°K)	Reference
0.26	2.7-3.6	Field and Hitchcock[a]
0.26	3.75 ± 0.50	Thaddeus and Clauser[b]
1.50	2.0 ± 0.8	Present result
3.20	3.0 ± 0.5	Roll and Wilkinson[c]
7.35	3.3 ± 1.0	Penzias and Wilson[d]
20.7	2.8 ± 0.6	Howell and Shakeshaft[e]
21.0	3.2 ± 1.0	Penzias and Wilson[f]

[a] G. B. Field and J. Hitchcock, Astrophys. J. 146, 1 (1966).

[b] Patrick Thaddeus and John F. Clauser, Phys. Rev. Letters 16, 819 (1966).

[c] P. G. Roll and D. T. Wilkinson, Phys. Rev. Letters 16, 405 (1966).

[d] A. A. Penzias and R. W. Wilson, private communication.

[e] T. F. Howell and J. R. Shakeshaft, Nature 210, 1318 (1966).

[f] A. A. Penzias and R. W. Wilson, American Astronomical Society Meeting, Los Angeles, 1966 (unpublished).

tribution along the waveguide wall, and the measured dependence of wall loss on temperature, the radiation temperature at the top of the load was calculated to be 0.42 ± 0.1°K higher than the bath temperature. The latter was measured with a platinum-resistance thermometer, to an accuracy of better than 0.05°K, and checked against ambient atmospheric pressure. A second cold termination in which the side of the absorber clear to its tip was in contact with the waveguide wall was constructed and was found to have the same brightness temperature as the former within 0.1°K. For the hot terminations a regulated heating element was used in place of the bath. The measured voltage standing-wave ratio of each termination was 1.02 or smaller, so that no correction for emissivity less than unity need be applied.

Figure 1 shows the arrangement of the microwave circuit. T_0 is the ambient temperature of the circuit. t_i is the circuit transmission coefficient between the ith port and the reference plane (with the appropriate switch setting) and must be known with some precision. The circuit losses were measured with a Weinschel model BA-5 attenuator calibrator equipped with a model ND-2 differential null indicator. This system is capable of measuring small losses with an accuracy of 0.002 dB. The measured values of t_1, t_2, t_3, and t_4 are, respectively, -0.311, -0.251, -0.016, and -0.020 dB. For a large number of loss measurements made throughout the observing period, the standard error in the difference between t_1 and t_2, the most significant difference, was found to be 0.005 dB, which contributes an uncertainty of 0.3°K to the result of the experiment.

To check the accuracy of the system when measuring temperatures close to the actual brightness of the sky at Mount Barcroft, a liquid-helium termination was prepared and connected to the apparatus in place of the horn in the laboratory. The calculated temperature of this load is 8.0 ± 0.5°K at the top, with the uncertainty due to imprecise knowledge of the contribution of the wall losses to the load temperature. The measured temperature of this load was 8.3 ± 0.5°K which is in satisfactory agreement with the expected value. In addition, nonlinearities in the radiometer were found not to exceed 1 part in 10^3 over two decades of input power level. Since the various terminations did not differ from each other by more than 10% of the system temperature, approximately 3000°K, there are no significant inaccuracies due to system nonlinearity.

The antenna used for measurements is a pyramid-shaped horn, 63 cm long with an aperture 7.5 by 10 cm, having a gain of approximately 24 dB and a beamwidth at half-power of 12°. The radiation pattern was measured over a dynamic range of about 55 dB; thus the side lobes were measured to a level of about 30 dB below the isotropic level. A weak sidelobe which extended into the back hemisphere of the horn in its E plane was found. In order that the effect of the lobe be eliminated during observations, the horn aperture was placed at the focus of a 75-cm-diam parabolic reflector. When, in the course of the observations, the horn (with its reflector) was tipped away from the zenith to measure the contribution from the atmosphere, it was tipped in the H plane. From the pattern measurements, it was estimated that the contribution of the ground to the antenna temperature was less than 0.1°K for all zenith angles less than 65°.

The loss in the horn was measured by making it into a resonant cavity and measuring the Q of the cavity mode associated with the normal field distribution in the horn. A transmission loss of 0.030 ± 0.003 dB was obtained. The loss was also calculated. When the effective wall conductivity given in a handbook was used,[3] the calculation yielded a total horn loss of 0.025 dB. However, the same calculation, using the effective wall conductivity derived from laboratory measurements of the loss in a piece of standard silver waveguide, gave 0.036 dB. The disparity in these results indicates how much the actual wall loss depends on wall roughness, and how unreliable waveguide loss calculations may be at these short wavelengths. Accordingly, the measured value of 0.030 ± 0.003 dB has been adopted, from which the emission from the horn is calculated to be 1.9 ± 0.2°K. The horn voltage standing-wave ratio was measured to be less than 1.02, so that no emissivity correction is required for it.

On the assumption that the background brightness temperature is isotropic, a plot of antenna temperature against the secant function convolved with the antenna pattern should be a straight line, with the intercept at $\sec z = 0$ being just the background temperature.[4,5] Fig. 2 shows a typical single group of antenna temperatures at different zenith angles, and the least-squares-fit straight line. A separate calibration was

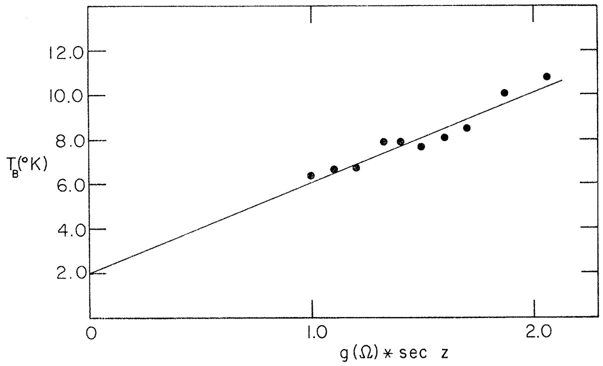


FIG. 2. A typical run of antenna temperatures. The abscissa is the secant of the zenith angle convolved with the horn pattern $g(\Omega)$.

made at each angle. 33 separate runs similar to Fig. 2 yield an average background temperature of 2.0°K. A histogram of the results from the separate runs was found to be closely Gaussian, with a standard deviation of 1.1°K, and hence a variance of the mean of 0.2°K. For most runs the horn was tipped to the west or to the south. When the data are grouped according to these directions, a difference of only 0.1°K is found. The difference is also 0.1°K when the data are grouped for each of the three months of observation. Finally, no systematic tendency is found for the antenna temperatures in the individual runs to depart from a straight line as shown in Fig. 2. From all the sources of error discussed above, a standard error of 0.4°K, and a 95% confidence interval which is ±0.8°K are computed.

The present result provides direct evidence that the excess background radiation discovered at the longer wavelengths does indeed extend to the short wavelengths. However, the blackbody radiation temperature which we have observed, 2.0°K, lies somewhat below the longer wavelength direct measurements and the 2.6-mm CN results, all of which are clustered about 3.0°K as shown in Table I. This would seem to imply a possible dip in the background temperature near 1-cm wavelength. If the interpretation of Dicke *et al.*[2] that this radiation is the residue of the primordial fireball is correct, the spectrum should be very closely that of a black body at these wavelengths, and an absorption feature would be difficult to understand. In any case, because of the quoted uncertainties in all of the determinations, a blackbody curve corresponding to a temperature of about 2.5°K will pass through the error flags of all the measurements, including the present one. Further measurements near 1-cm wavelength will be very valuable.

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[2] R. H. Dicke, P. J. E. Peebles, P. G. Roll, and D. T. Wilkinson, Astrophys. J. __142__, 414 (1965).

[3] "The Microwave Engineers Handbook and Buyers Guide," Horizon House-Microwave, Inc., Dedham, Massachusetts, 1967, p. 20.

[4] R. B. Partridge and D. T. Wilkinson, Phys. Rev. Letters __18__, 557 (1967).

[5] E. K. Conklin and R. N. Bracewell, Phys. Rev. Letters __18__, 614 (1967).