Measurement of the cosmic background radiation temperature at 3.0 cm

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We describe a measurement of the cosmic background radiation temperature at a wavelength of 3.0 cm. The experiment was made in conjunction with measurements at four other wavelengths in an effort to measure the long-wavelength spectrum to high accuracy. The result at 3 cm, $T_{\text{CBR}}=2.91\pm0.19$ K, is in good agreement with the values at neighboring wavelengths, and consistent with previous results.

The spectrum of the cosmic background radiation (CBR) may have been distorted from a Planckian distribution due to the release of energy in the early universe.[1] Detection of such a distortion would yield important information about the magnitude and epoch of energy release. This paper describes a measurement of the intensity of the CBR at 3.0 cm (10 GHz). This was part of an experiment[2] to search for distortions by making measurements at five wavelengths in the Rayleigh-Jeans region.

The Dicke-switched superheterodyne radiometer used to make the measurement is shown schematically in Fig. 1. The receiver has a noise temperature of 490 K, and an RF bandwidth of 910 MHz. The rms noise fluctuations were measured to be 50 mK $\text{Hz}^{-1/2}$. The Dicke switch is driven at 100 Hz. The radiometer is mounted on bearings so that it can rotate in a vertical plane. It has two low-sidelobe corrugated-horn antennas, with 12.5° half-power-beam-width (HPBW) beams, which are perpendicular to each other. The primary antenna can swing through 360° to view any desired zenith angle. The rotation axis is coincident with the axis of the secondary antenna whose beam is reflected by a fixed mirror toward the vertical sky.

The atmospheric emission is measured with zenith scans, by directing the primary antenna 30° away from vertical in the east and west directions. The vertical sky emission is found by direct comparison with a liquid-helium-cooled load. The measured atmospheric emission, and contributions from the Galaxy and other small sources, are subtracted from the vertical sky. The residual is the CBR signal.

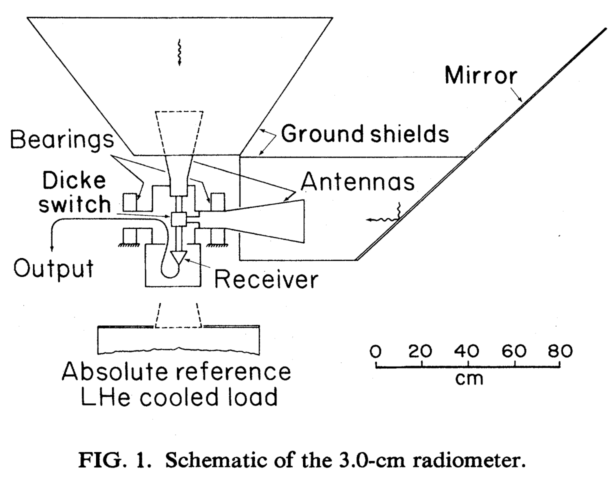

FIG. 1. Schematic of the 3.0-cm radiometer.

The function of the secondary antenna is to provide a constant, low-temperature reference signal; the sky serves as a convenient source. Radiation reflected from the mirror is partially linearly polarized. However, this antenna is sensitive to circular polarization, which ensures that the rotation of the radiometer does not introduce a significant systematic error.

When the two antennas viewed identical cold loads, asymmetry in the apparatus produced an output equivalent to a 1.1-K temperature difference between the loads. Tests were made to ensure that this offset did not change excessively as the radiometer was rotated from one orientation to another. This was first done by firmly attaching ambient-temperature pieces of Emerson & Cuming Eccosorb CV-3, a microwave absorber, to each antenna, entirely covering the apertures. As the radiometer was rotated through each position, the output changed by less than 10 mK.

Certain kinds of flip offsets will be revealed only by using loads which are not at ambient temperature. We tested for these in two ways.

(1) Horizontal flip tests were made by alternately directing the primary antenna horizontally east and west. Large reflectors on each side of the radiometer, mounted at 45°, redirected the beam toward the zenith. The output difference between looking east and looking west was compared to the same difference when the reflectors were interchanged, in order to remove the effect of asymmetric reflectors. This double difference is a measure of the intrinsic change within the radiometer, due to rotation, when it is directed horizontally. This horizontal flip offset was measured to be 30 mK.

(2) Vertical flip tests were made with the primary antenna in either the straight-up or straight-down position. A piece of Eccosorb which had been dipped and saturated with LN was placed in front of the primary at each position. The secondary antenna viewed the sky as usual. We were able to set a 55-mK limit on the change in output

when the primary antenna was rotated from up to down. The dipped Eccosorb stayed cold for about 15 sec. The radiometer thermal noise is 13 mK for this integration time, so that statistical noise did not make a large contribution to this limit.

The 55-mK value is an upper limit, set by the mechanical and thermal stability of the dipped Eccosorb load. The true vertical offset may be less than this. In fact, due to the way in which the antennas and other components were mechanically supported, the greatest stress existed when the primary was horizontal, and we may expect this to be the worst case.

There was a degradation in performance of the equipment after transportation to the observing site at White Mountain, California. Although the vertical offset did not change, there was an additional offset introduced at the zenith angles of $\pm 30°$ due to a combination of mechanical stress on the radiometer, and misalignment of the ground shield-reflector system. This offset increases by about 100 mK the error of the atmospheric temperature, up to a value of 160 mK, and causes a corresponding increase in the error of the cosmic-background-radiation temperature. This represents the single largest source of error in the measurement.

Rotation of the instrument in the Earth's magnetic field changed the offset by less than 4 mK. Twisting of the power, signal, and sensing cables introduced no measurable effect.

The gain of the radiometer was measured by using two blackbody calibration loads at widely different temperatures. The first was an ambient-temperature Eccosorb calibrator, enclosed in a thermally insulating styrofoam box. The emissivity of the Eccosorb was greater than 0.999. Its temperature was automatically recorded every 16 sec. During these ambient-temperature calibrations, when there was a large input-power difference between the two antennas, a nonlinearity in the lock-in amplifier depressed the output voltage by $6 \pm 2\%$. The calibration is corrected for this effect. The gain of the radiometer varied by less than 0.4% during any measurement period (approximately 1 h).

The second calibrator was a liquid-helium-cooled load, and is described in another paper.[2] The physical temperature of the liquid helium was 3.77 ± 0.01 K, and the additional contribution due to insertion loss and reflection was 0.03 ± 0.02 K at 3 cm. Hence, the effective radiometric temperature of the load was 3.80 ± 0.02 K.

A complete set of data for the 3-cm radiometer was taken every 160 sec. Each set consists of five 32-sec periods with a different target observed during each period. The targets were always viewed in the same order: cold calibrator, vertical sky, sky 30° west of zenith, sky 30° east of zenith, and ambient-temperature calibrator. This sequence of measurements was repeated continuously during the observing runs.

All data were automatically recorded on magnetic tape and by hand for later analysis. The lock-in-amplifier output was integrated for 2 sec and recorded. The basic cycle time for the data recorded was 16 sec, and 2 cycles transpired for each target. Output values taken while the radiometer was rotating from one position to the next were removed from the raw data.

Screens were erected around both antennas to reduce sidelobe reception of ground radiation. At tilt angles of $\pm 30°$ the measured sidelobe pickup contributed an additional 5 mK to the primary antenna. The data were corrected for this.

The galactic background, due to synchrotron and (H II) thermal emission, contributes a significant signal only within about 20° of the galactic plane. The correction for the synchrotron flux is estimated by scaling the data of Haslam *et al.*,[3] using a spectral index of -2.8. An estimate of the (H II) emission comes from a source list[4] scaled with a spectral index of -2.1. The maximum correction at 3 cm due to emission from galactic sources is 14 mK, but most of the data require corrections of less than 10 mK. This scaling model agrees to better than 20% with the galactic background emission values that were measured during this experiment at 6.3 cm, and to better than 10% at 12 cm. Moreover, due to the position of the Galaxy in the sky during the observations, the final value of the background-radiation temperature that we find is very insensitive to the exact model used for this correction.

The measured value of the vertical atmosphere antenna temperature is $T_{\mathrm{ATM}} = 0.93 \pm 0.16$ K. This was determined by using the zenith scan data and assuming a spherical, uniform density atmosphere convolved with the antenna beam pattern. Assuming an exponential instead of a uniform atmosphere changes T_{ATM} by less than 2 mK. This value of T_{ATM} is 0.1 K lower than the value determined at the same time by Partridge *et al.*[5] at 3.2 cm.

After making these corrections we find that the value of the thermodynamic temperature of the cosmic background radiation is

$$T_{\mathrm{CBR}} = 2.91 \pm 0.19 \text{ K} .$$

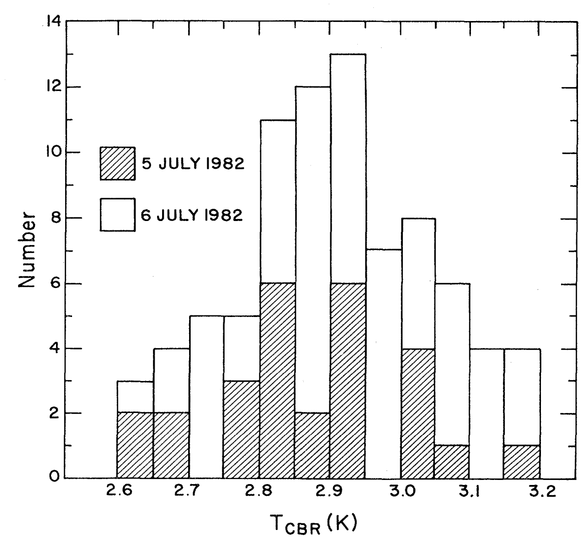

FIG. 2. Histogram showing the results of measurements of the CBR. 82 individual measurements were made over the course of two nights of observations.

This is the mean of 82 independent measurements. The total error is the quadrature sum of the individual errors, and is dominated by the rotation offset described previously. A histogram of the results is shown in Fig. 2.

These measurements were repeated in September 1983 with an improved apparatus. The rotation offset was reduced by moving the ground shields farther away from the secondary antenna. The atmospheric emission was measured more accurately by making zenith scans at ±40° and ±30°. Preliminary analysis of the new data indicates a value of $T_{\rm CBR}$ consistent with the present results, but somewhat lower. These results will be described in a paper now in preparation.

There have been two previous measurements of $T_{\rm CBR}$ at the nearby wavelength of 3.2 cm. In 1965, shortly after the discovery of the cosmic background radiation, Roll and Wilkinson[6] found $T_{\rm CBR}=3.0\pm0.5$ K from data taken at Princeton, New Jersey. Stokes *et al.*[7] made measurements from White Mountain in 1967, with the result $T_{\rm ATM}=1.37\pm0.1$ K and $T_{\rm CBR}=2.69^{+0.16}_{-0.21}$ K. This value of $T_{\rm CBR}$ is compatible with our result, differing by less than 1.4 standard deviations. However, their value of $T_{\rm ATM}$ is considerably higher than our result and that of Partridge *et al.*[5]

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