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Repository Citation
(with G. Smoot et al.) Low-Frequency Measurement of the Spectrum of the Cosmic Background Radiation, Physical Review Letters, 51, No. 12, 1099, 1983.

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Low-Frequency Measurement of the Spectrum of the Cosmic Background Radiation

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(Received 25 May 1983)

Measurements have been made of the cosmic-background-radiation spectrum at five wavelengths (0.33, 0.9, 3, 6.3, and 12 cm) with use of radiometers with wavelength-scaled corrugated-horn antennas having very low sidelobes. A single large-mouth (0.7-m-diam) liquid-helium–cooled absolute reference load was used for all five radiometers. The results of the observations are consistent with previous measurements and represent a significant improvement in accuracy at low frequencies.

PACS numbers: 98.70.Vc, 98.80.Bp

A careful measurement of the shape of the cosmic-background-radiation spectrum is crucial to the understanding of processes that occurred in the early universe. Several of these processes are thought to be capable of causing distortions from a blackbody distribution, particularly in the Rayleigh-Jeans region. However, previous measurements at wavelengths greater than 0.35 cm, all made before 1968, typically have errors of (10–20)%.[1] A significant distortion therefore may have gone undetected. At infrared wavelengths a distortion has been reported by Woody and Richards.[2] We report here an experiment to measure, in a systematic way, the intensity of the cosmic background radiation at five wavelengths (0.33, 0.91, 3.0, 6.3, and 12 cm) and the atmospheric emission at an additional wavelength (3.2 cm). This paper describes the experiment and summarizes the results. The companion papers[3-7] discuss each instrument and the observations in more detail.

The standard big-bang model predicts that the cosmic background radiation has a Planckian (blackbody) spectrum to very high accuracy. However, the extra energy associated with perturbations in the early universe produces distortions in the cosmic-radiation spectrum, with the fractional distortion approximately equal to the ratio of the energy released to the energy in the cosmic radiation field.[8,9]

A number of early processes could have caused a large energy release: dissipation of primeval turbulence, dissipation of sound and shock waves associated with adiabatic density perturbations or with gravity waves, isotropization of an anisotropic universe, and matter-antimatter annihilation. After the lepton era ($t \gtrsim 1$ h, corresponding to a red shift $z \lesssim 10^8$), processes which would relax a distorted spectrum to a Planckian form were, in general, so weak that the presently observed spectrum should still retain most of its original distortions, thus providing information about the initial energy release.[9]

The primary interaction between matter and radiation after the lepton era was Compton scattering, which conserves the photon number. Energy released after the lepton era would result in the cosmic background radiation assuming a Bose-Einstein distribution, with a consequent depletion of photons at low frequency compared to high frequencies.[10] Radiative processes would be unable to produce sufficient photons to reestablish a Planckian distribution except at wavelengths longer than 15 cm.

The goal of this experiment is to measure the low-frequency spectrum of the cosmic background radiation at several frequencies with small systematic errors to provide data on important cosmological processes.

The concept of the measurement is simple: Compare the power received by an antenna directed upward at the sky with that received when the antenna is looking downward into an absolute reference cold load. The power received looking at the sky is the sum of power from the cosmic background radiation, galactic emission, atmospheric emission, diffracted ground emission, and miscellaneous other sources. The difference in power received (sky minus cold load) plus the known power of the absolute reference cold load is the power from the sky. By carefully accounting for all radiation entering the antenna, one can determine the power received from the cosmic background radiation.

The experimental design reduces the extraneous sources of radiation as much as is practical and then determines the residual values. Atmospheric emission is reduced by roughly a factor of 3 compared to sea level by going to a high, dry site (University of California's White Mountain Research Station at 3800 m). The remaining atmospheric signal is then determined by zenith scans. The galactic background is minimized by taking data at high galactic latitudes where the emission is low and is estimated by scans and modeling. Other extraneous sources of radiation are greatly reduced through the use of low-sidelobe antennas[11] and ground shields.

We used an ambient-pressure liquid-helium–cooled target (Fig. 1) to provide a cold-load temperature near 3 K, which prevents the uncertainty in the measured gain of the instruments from contributing significantly to the error in the measured cosmic background signal. The liquid-helium Dewar is a large cylinder with an open-mouth diameter of 70 cm. The interior radiometric walls of the cold load are made of aluminum-coated Mylar. The aluminum is 13 μm thick, or seven skin depths at 12 cm wavelength. Completely covering the floor of the cold load is a 20-cm-thick circular slab of Eccosorb (Emerson and Cuming VHP-8), whose microwave emissivity is greater than 0.999 at all of our wavelengths. During operation, the Eccosorb is completely submerged in more than 100 l of liquid helium. Two 18-μm-thick polyethylene windows, spaced about 15 cm apart, were installed near the top of the Dewar. Boiled off helium gas was warmed and then passed through the space between the two windows to prevent condensation on the top window. The cold load was operated at a very slight (2 mm Hg) pressure above ambient in order to maintain positive flow through the system.

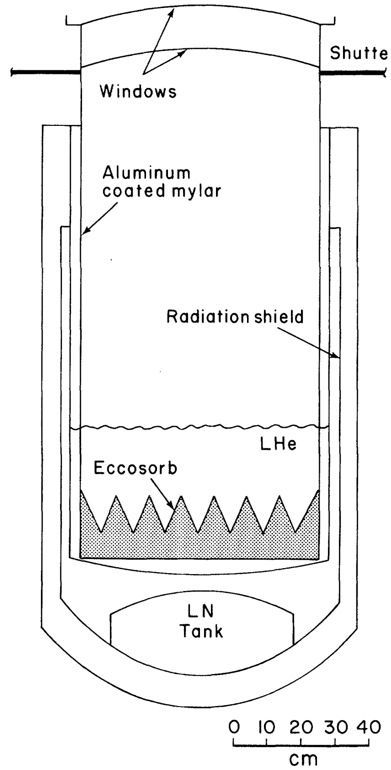

FIG. 1. Schematic representation of the absolute reference cold load. Only two 18-μm-thick windows are between the antenna and the liquid-helium–immersed Eccosorb target.

The temperature of the liquid helium was 3.77 $\pm$ 0.01 K during the entire measurement period as determined by measuring the ambient air pressure. The cold load has a measured reflection coefficient less than 10^{-3} (typically 2×10^{-4}). We estimate that more than 99% of the emitted power came from the cooled Eccosorb target.

The instruments used to measure the cosmic

TABLE I. Radiometer properties.

Wavelength (cm)	Frequency (GHz)	Antenna rf bandwidth	Antenna Half-power beam width (deg)	T_{rms} (K/Hz$^{1/2}$)
12.0	2.5	160 MHz	12.5	0.2
6.3	4.75	160 MHz	12.5	0.1
3.2	9.4	1 GHz	12.6	0.1
3.0	10.0	910 MHz	12.5	0.05
0.9	33.0	1 GHz	7.5	0.08
0.33	90.0	2 GHz	7.5	0.11

background radiation are all differential, Dicke-switched radiometers, each composed of two wavelength-scaled corrugated-horn antennas and superheterodyne receivers. The properties of the various radiometers are summarized in Table I.

All five radiometers were mounted on carts which rolled on a 20-m-long set of rails and thus could be positioned over the cold load, which was in a hole and suspended below the middle of the rails. In a set of measurements each radiometer in turn was positioned above the cold load and made a series of observations of the cold load and the vertical sky, together with zenith scans, gain calibrations, and related measurements. During this period (typically 1 h) the other radiometers made zenith scans or galactic background measurements.

The most significant background that we face is atmospheric emission; errors in determining the atmospheric signal translate directly into errors in the antenna temperature of the cosmic background radiation. A sixth radiometer, operating at 3.2 cm (9.4 GHz), provided automated measurements of the atmospheric emission continuously during all the cosmic-background-spectrum observations. The other radiometers, particularly the 0.33- and 0.91-cm instruments, were often operated to make atmospheric measurements. Atmospheric emission at 0.33 cm is particularly sensitive to water vapor and thus provides a good monitor of the atmospheric water-vapor content. We have made models of atmospheric emission which presently are limited to an accuracy of about 0.1 K[5] at the three largest wavelengths, and about 0.3 K and 0.6 K at 0.91 and 0.33 cm, respectively.[3-7]

Perhaps the most important of the remaining systematic errors is the difference in signal level that may result from mechanical stresses or changing alignments and couplings when the radiometer is pointed up at the sky and then down into the cold load or during zenith scans. We have tested for these effects. They are typically of the order of 0.1 K and are discussed separately for each of the radiometers.[3-7]

Measurements were made on 5 and 6 July 1982. The data were digitized and recorded both on magnetic tape and by hand. The results of the measurements are summarized in Table II and

TABLE II. Summary of results. T_{cbr} is the measured thermodynamic temperature of the cosmic background radiation; T_{atm} is the antenna temperature of the atmosphere observed vertically; T_{gal} is the maximum antenna temperature estimated for galactic backgrounds during our observations; and T_{gnd} is the estimated antenna temperature from the Earth.

Wavelength (cm)	Frequency (GHz)	T_{cbr} (K)	T_{atm} (K)	T_{gal} (K)	T_{gnd} (K)
12.0	2.5	2.62 ± 0.25	0.95 ± 0.05	0.3	0.2
6.3	4.75	2.71 ± 0.2	1.0 ± 0.1	0.1	0.05
3.2	9.4	...	1.03 ± 0.03	0.05	0.03
3.0	10.0	2.91 ± 0.19	0.93 ± 0.16	0.03	0.01
0.9	33.0	2.87 ± 0.21	5.0 ± 0.1	0.01	0.01
0.33	90.0	2.4 ± 1.0	12.3 ± 0.8	0.01	0.01

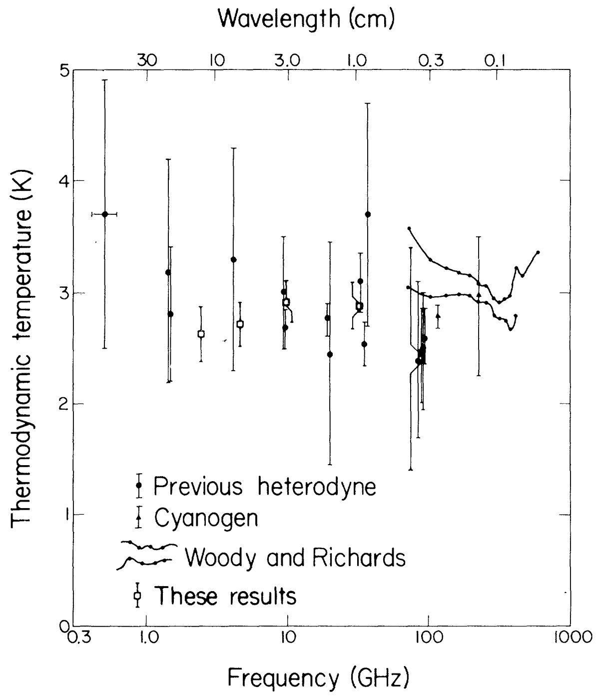

FIG. 2. Plot of the present results together with previous measurements of the temperature of the cosmic background radiation.

plotted in Fig. 2, together with the results of previous measurements. As can be seen in Fig. 2 our data are in good agreement with previous results but represent an improvement in the low-frequency region. This agreement is underscored when one compares the weighted average of our measurements, 2.79 ± 0.10 K, with that of the previous data at these frequencies, which have a weighted average of 2.74 ± 0.09 K.[1] Our results are also in agreement with the infrared-measurement value of Woody and Richards[12] of 2.96 ± 0.08 K.

What conclusions can we draw from our results? First, let us suppose that the results of Woody and Richards[12] are high by 25% because of an error in calibration, as suggested by Weiss.[1] Then from 0.07 to 12 cm, the observed spectrum of the cosmic background radiation is consistent with a blackbody of $T = 2.74 \pm 0.07$ K. However, if the Woody and Richards calibration is correct, their data and ours may provide evidence for a spectral distortion, with the temperature of the cosmic background radiation smaller in the Rayleigh-Jeans region than near the peak. This distortion is consistent either with a Bose-Einstein spectrum with temperature 2.92 ± 0.03 K and chemical potential term $\mu = (5 \pm 3) \times 10^{-3}$ for $\Omega = 0.1$ or $\mu = (1.4 \pm 0.9) \times 10^{-2}$ for $\Omega = 1$, or with spectra produced by an early generation of stars.[13] A value of $\mu = 1.4 \times 10^{-2}$ precludes the possibility that turbulence had the major role in initiating the formation of galaxies.[14] If the universe contains large amounts of antimatter, the matter and anitmatter must be segregated into regions larger than galactic masses; otherwise annihilation would have produced a distortion larger than we observe. We can also put a limit on the amplitude of adiabatic perturbations: $\Delta e/e < 0.1$ for $M > 10^5 M_{\odot}$.[10]

We thank the staff of the White Mountain Research Station of the University of California, and Alan Benner, Hal Dougherty, Bruno Falconi, John Gibson, Nancy Gusack, Enrico Mattaini, Faye Mitschang, and Stefano Silvestri for their help.

This research was supported by National Science Foundation Grants No. PHY80-15694 and No. AST 800737, by the U. S. Department of Energy under Contract No. DE-AC03-76SF00098, and by Consiglio Nazionale delle Richerche Fellowship No. 203.2.13.

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