such materials. (b) Fe and Co show evidence of similar but weaker satellites; this is consistent with the present theory but requires further study. (c) A satellite has not been observed in Pd despite a value of U similar to that for Ni; however, Pd has fewer 3d holes and a calculation predicts a lifetime tailing of the main d-band peak but no satellite.

Several very useful conversations with Dr. C. J. Powell and Professor L. M. Falicov are gratefully acknowledged.

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Spectrum of the Cosmic Background Radiation

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New measurements of the emission spectrum of the night sky have been made in the frequency range from 1.7 to 40 cm^{-1} using a fully calibrated, liquid-helium–cooled, balloon-borne spectrophotometer. The results show that the spectrum of the cosmic background radiation peaks at 6 cm^{-1} and is approximately that of a 3-K blackbody out to several times that frequency. However, the data show deviations from a simple blackbody curve.

Previous measurements[1] of the cosmic background radiation (CBR) have shown that its spectrum is approximately that of a 3-K blackbody over the frequency range from 0.02 to 17 cm^{-1}. These observations have been instrumental in establishing the big-bang theory of cosmic expansion as the accepted model of the Universe. In its most elementary version this theory predicts a blackbody spectrum for the CBR. The experimental results reported to date, however, have lacked the accuracy required to detect deviations from a Planck curve as large as 20%. We report in this Letter an observation of the CBR in the frequency range from 2.5 to 24 cm^{-1} with a flux accuracy of better than 10% of the peak flux of a 3-K blackbody at 6 cm^{-1}.

The apparatus used for this experiment was an improved version of the liquid-helium–cooled balloon-borne Fourier spectrophotometer developed for our previous measurement of the near-millimeter CBR, which is described in Woody *et al.*[2] and Mather, Richards, and Woody.[3] The sensitivity was increased by one order of magnitude over that of our previous system by the use of a ^{3}He-cooled composite bolometer.[4] Improvements were also made to the antenna by the use of a Winston concentrator[5] to define the $\approx 7^\circ$ field of view on the sky and by the addition of a large earthshine shield.

The cryostat containing the antenna and the spectrometer was mounted in a gondola with the required telemetry and launched from Palestine, Texas, by the National Center for Atmospheric Research (NCAR) at 19:40 CDT (Central Daylight Time) on 3 May 1977. The gondola was suspended 0.6 km below the (8.5×10^5)-m^3 balloon and was free to rotate about the vertical axis. Three hours of data were obtained at a float pressure which varied from 2.0 to 2.4 mbar. A total of 30 separate spectra were measured: 15 at a zenith angle of 25°, 5 at 36°, 5 at 43°, and 5 for characterizing the instrument.

The spectrophotometer was calibrated using both room-temperature and low-temperature sources. Spectra of the 300-K room measured before and after the flight showed that the instrumental responsivity had changed less than 3%. The low-temperature calibrations were carried out after the flight using a blackbody source inserted halfway down the cold antenna. The main helium bath was pumped so as to obtain flight values for the bolometer temperature and bias power. Spectra were measured with source temperatures of 5.44, 10.34, and 20.14 K. The instrumental responsivity obtained by averaging three 20.14-K spectra is shown in Fig. 1, curve *a*. Spectra of a 300-K blackbody outside the apparatus were also obtained, but with the bolometer biased so as to avoid saturation effects and with the main helium bath at 4.2 K to avoid the use of a thick window. Comparisons between all these calibrations show that the spectral shape of the flux responsivity in Fig. 1, curve *a*, is accurate to better than 3%. The low-frequency features which arise from mode structure in the antenna appear in all of the calibration experiments. Additional sources of calibration error which were essentially independent of spectral frequency arose from uncertainties in the temperature and emissibity of the low-temperature calibration source, the effect of a varying liquid-helium level in the optics, and the stability of bolometer, preamplifier, and telemetry systems. The estimated error for the calibration scale factor was + 4% and − 7%.

The antenna pattern was evaluated by diffraction calculations and by measurements on prototype systems.[3] Measurements made during previous flights of the apparatus showed that the detected emission from Earth and the antenna was less than 1% of the peak flux from a 3-K blackbody.[2] The details of these measurements and of the calibration procedure will be reported in a more extensive publication.

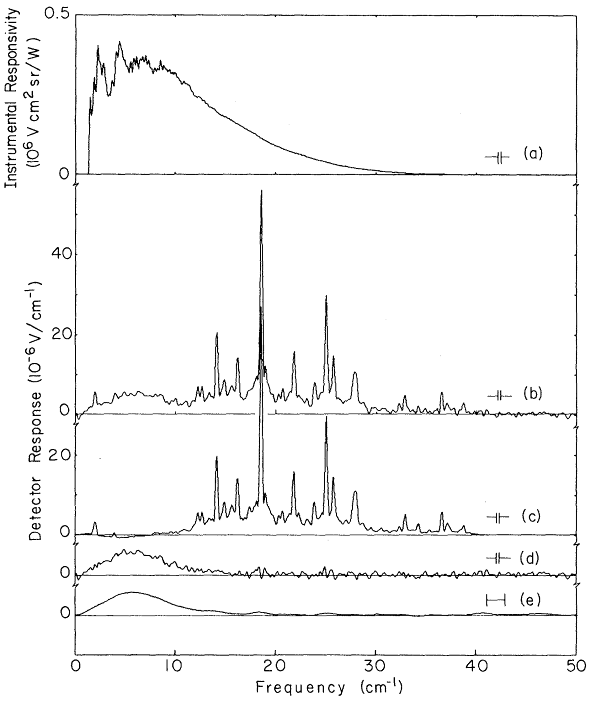

FIG. 1. Curve *a*, calibration of the flux responsivity determined from the response of the instrument to a cold blackbody; curve *b*, observed response to the night-sky emission; curve *c*, calculated response to the atmospheric emission, including the effect of the 1.67-K reference blackbody; curves *d* and *e*, response to the CBR at two different spectral resolutions obtained by subtracting curve *c* from curve *b*. The measured spectrum of the CBR shown in Fig. 2 is obtained by dividing the response data (curve *e*) by the flux calibration (curve *a*).

The response of the instrument to the emission of the night sky at a zenith angle of 25° is shown in Fig. 1, curve *b*. The broad contribution from the CBR is seen to peak at 6 cm^{-1} and to decrease at higher frequencies, even before corrections are made for the atmospheric line emission from H_2O, O_3, and O_2 which dominates the spectrum above 12 cm^{-1}. The width of spectral features in Fig. 1, curve *b*, was limited by the instrumental resolution which was much larger than the emission linewidths. The atmospheric contribution to the night-sky emission was removed by fitting a model of the line emission to the observed spectrum. The model was the same as that described in Ref. 1 with the addition of updated O_2 line parameters[6] and corrections for Doppler and Zeeman broadening.[7] The only free parameters in the model were the column densities of the three constituent gases at a zenith angle of 25°. These were determined to be $(2.76\pm0.16)\times10^{17}$ H_2O/cm^2, $(1.72\pm0.14)\times10^{17}$ O_3/cm^2, and (1.09 ± 0.15)

$\times 10^{22}$ O_2/cm^2. The fitted O_2 column density agrees with the value calculated using the known mixing ratio of 21% and provides a check that the calibration is correct to within 7%. Since the fit to the atmospheric model was dominated by the narrow features above 15 cm^{-1}, the fitted column densities were unaffected by the presence of the broad CBR. The response of the instrument to the atmospheric emission calculated from this model is shown in Fig. 1(c). In the region where the atmospheric emission is less than that from the 1.67-K reference temperature, the response is negative.

The response of the instrument to the CBR (corrected to a 0-K reference temperature) which remains after subtracting Fig. 1, curve *c*, from curve *b* is shown at resolutions of 0.28 and 1.79 cm^{-1} in Fig. 1, curves *d* and *e*. The quality of the atmospheric model can be judged by noting that the rms residual above 20 cm^{-1}, where the CBR is expected to make a negligible contribution, is comparable to the detector noise and is small compared with the observed spectral intensity.[8] The flux spectrum of the CBR is obtained by dividing Fig. 1, curve *e*, by curve *a*.

Figure 2 shows the $\pm 1\sigma$ (1-standard-deviation) error limits of the measured CBR flux for a triangular resolution function with ~1 cm^{-1} full width at half maximum. Important sources of error in the measured CBR, which are essentially uncorrelated across the spectrum, include detector noise, atmospheric fitting errors, and errors in the spectral shape of the instrumental responsivity. The shaded region in Fig. 2 is the rms sum of these errors. Additional solid lines are shown to represent the effect of changing the frequency-independent scale factor by $\pm 1\sigma$ and reoptimizing the atmospheric fit. The integrated flux of the CBR obtained from our measurement is equal to that from the $(2.96^{+0.04}_{-0.06})$-K blackbody curve which is also shown in Fig. 2.

The most striking feature of our data is the qualitative agreement with the Planck curve. The agreement covers nearly a decade in frequency and extends from the Rayleigh-Jeans part to the Wien part of the spectrum. This qualitative result is extended two decades further towards the Rayleigh-Jeans limit by inclusion of the microwave data[1] also shown in Fig. 2.

When our data are analyzed using a maximum-likelihood method in which the scale-factor uncertainty is properly included, they are consistent with our previous results[2,3] and with the work of Muehlner and Weiss[9] at the 90% confidence level. The measured spectrum deviates from the Planck curve, however, by 5σ. The deviation varies smoothly from ≈10% above the 2.96-K Planck spectrum at 6 cm^{-1} to 20% below it at 11 cm^{-1}.

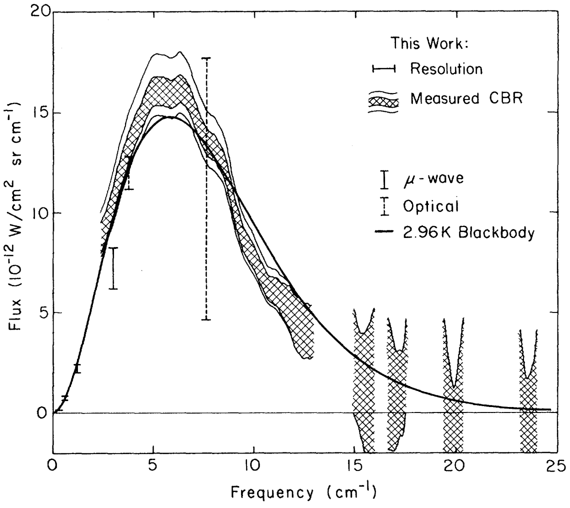

FIG. 2. Measured spectrum of the cosmic background radiation plotted as $\pm 1\sigma$ error limits. There are gaps in the data at the frequencies of strong atmospheric emission lines where the errors become very large. The shaded region includes contributions to the error which are uncorrelated across the spectrum. Additional solid lines are shown to represent the effect of changing the frequency-independent scale factor by $\pm 1\sigma$ and reoptimizing the atmospheric fit. The shaded region can be scaled up or down within these limits. The spectrum of the 2.96-K blackbody which best fits the measured integrated flux, and selected microwave and optical measurements of the CBR are also shown for comparison.

The spectral shape and measurements at different air masses put severe constraints on possible local sources of the deviation. It is seen in all of the scans (which cover ~1.7 sr of the sky) and thus the possibility of a few bright sources is eliminated. It does not fit a power-law spectrum and its magnitude is much larger than the continuum emission expected from the apparatus, Earth, or galactic dust clouds. The spectra measured at different zenith angles and float pressures place 85%-confidence-level limits on the deviation not being atmospheric in origin. It could not arise from errors in the correction for known atmospheric constituents which is only 5–30% for $\nu < 11$ cm^{-1}. No significant structure of the type expected for molecular emission is seen in the deviation at resolutions down to 0.13 cm^{-1}. Water vapor dimers and wings from high-frequency lines, which may be present at mountain-top and airplane altitudes, are completely negligible at the 2-mbar float pressure of our measurement. Common types of interferometer ghosts were also shown to be negligible.

The simplest cosmological models of an expanding universe predict blackbody radiation based on very few assumptions. These models fail, however, to predict many gross features of the Universe. Reality is clearly more complicated. Deviations from the Planck curve are expected at some level and their observation is of highest importance for the refinement of cosmological models.

Compton scattering of the CBR by "hot" electrons, radiation damping of turbulence, and annihilation of matter and antimatter are some of the mechanisms which could lead to deviations from a blackbody spectrum.[10] The net result of these mechanisms is to scatter low-energy photons to higher energy and hence to shift the peak in the spectrum to higher frequencies. These models do not fit the data as well as a simple Planck curve. The fit is degraded by 1σ for an energy exchange between the photons and an optically thin hot plasma equal to 3% of the energy in the CBR at the time of interaction.

The data are consistent at the 80% confidence level, however, with a two-parameter curve with the shape of a 2.79-K blackbody, but an emissivity of 1.27.[11] The possibility of a constant percentage error in the calibration curve has been carefully considered. No possible source of such an error has been identified. If it had occurred it would destroy the agreement of our data with the accepted column density of O_2. The addition of the microwave data to the fits has little effect on the values of the fitted parameters and, in particular, does not improve the limit on the interaction of the CBR with a hot plasma.[12]

In conclusion, the data reported here confirm the thermal character of the CBR at a temperature of ~ 3 K and definitely show the peak in the spectrum at 6 cm^{-1} and the decrease out to 24 cm^{-1} where the intensity has dropped by a factor of 10. The measured upper limit to the flux at 24 cm^{-1} places a useful limit on the flux from widely distributed cosmic dust. The data, however, do not fit a simple Planck curve with a single temperature, and the nature of the difference is not consistent with likely mechanisms that are expected to produce deviations. Further theoretical work and observations at both microwave and near-millimeter wavelengths are clearly desirable.

The authors are greatly indebted to many persons for assistance with this experiment. This work was a continuation of earlier experiments in which J. C. Mather and N. S. Nishioka were co-workers. Their earlier contributions and continuing support were invaluable. Professor K. A. Anderson provided the gondola and nearly ideal telemetry equipment. Mr. J. H. Primbsch gave invaluable assistance in all areas in the art of ballooning, Mr. S. C. McBride assisted with the flight preparation and launch, and the National Center for Atmospheric Research staff at Palestine, Texas, provided us with a successful balloon flight.

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[1] For a collection of data previous to this work, see L. Danese and G. de Zotti, Riv. Nuovo Cimento 7, 277 (1977).

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[8] The excellent agreement between the atmospheric model and our observations shows that the measurements reported by E. I. Robson *et al.*, Nature 251, 591 (1974), which are incompatible with the model, must be regarded as erroneous.

[9] D. J. Muehlner and R. Weiss, Phys. Rev. Lett. 30, 757 (1973).

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JETP 62, 1217 (1972)].

[11] It has been suggested that a change in the value of Planck's constant with time might influence the spectrum of the CBR. This speculation is based on the assumption that the photon occupation number is determined by the value of $\hbar$ when the CBR was last thermalized, while the density of states in the observer's reference frame is determined by the present value of $\hbar$ [P. D. Noerdlinger, Phys. Rev. Lett. 30, 761 (1973)]. A 27% increase in the value of $\hbar$ since the CBR photons were last in equilibrium with matter would be required to fit the data.

[12] A weighted average of the microwave data gives a temperature of 2.65 ± 0.08 K (see Ref. 1), but $\chi^2 = 10$ for 20 degrees of freedom, which indicates that the published errors are not statistical. According to the χ^2 test, blackbodies with temperatures which range from 2.44 to 2.92 K are consistent with the microwave data.

ERRATA

IS THE ENERGY DEPENDENCE IN p-p SCATTERING DUE TO SPIN? James A. McNeil and Stephen J. Wallace [Phys. Rev. Lett. 42, 17 (1979)].

In Eq. (7), $K_2(\beta b)$ should read $K_3(\beta b)$.
In Eq. (8), $\mathcal{E}_{1z}\sigma_{2z}$ should read $\mathcal{E}\sigma_{1z}\sigma_{2z}$.
In Eq. (10), the factor $(4k_a s^{1/2})^{-1}$ should be omitted and replaced by a minus sign.

MONTE CARLO STUDY OF AN ORDERING ALLOY ON AN fcc LATTICE. Mohan K. Phani, Joel L. Lebowitz, M. H. Kalos, and C. C. Tsai [Phys. Rev. Lett. 42, 577 (1979)].

Table I, referred to on page 578 and inadvertently omitted, is reproduced below:

TABLE I. The transition temperatures for different α's.

α	$kT_c/4J$	$\Delta E/kT_c$
0.00	0.4415 ± 0.001	0.20
0.00[a]	0.4733	0.25
0.05	$0.5089 + 0.0013$	0.19
0.1667	0.6821 ± 0.0023	0.09
0.25	0.8036 ± 0.0032	
0.445	1.0672 ± 0.0029	
1.0	1.7699 ± 0.015	
6.0	7.5758 ± 0.142	

[a] Cluster variation (Ref. 1).