noble, France.

‡Visitor from Gesellschaft für Schwerionenforschung, 61 Darmstadt, Germany.

[1]E. Moll, H. Schrader, G. Siegert, M. Asghar, J. P. Bocquet, G. Bailleul, J. P. Gautheron, J. Greif, G. I. Crawford, C. Chauvin, H. Ewald, H. Wollnik, P. Armbruster, G. Fiebig, H. Lawin, and K. Sistemich, Nucl. Instrum. Methods 123, 615 (1975).

[2]G. Siegert, H. Wollnik, J. Greif, G. Fiedler, M. Asghar, G. Bailleul, J. P. Bocquet, J. P. Gautheron, H. Schrader, H. Ewald, and P. Armbruster, Phys. Lett. 53B, 45 (1974).

[3]S. Amiel and H. Feldstein, in *Proceedings of the Third IAEA Symposium on Physics and Chemistry of Fission, Rochester, New York, 1973* (International Atomic Energy Agency, Vienna, Austria, 1974), Vol. 2, p. 65.

[4]A. C. Wahl, A. E. Norris, R. A. Rouse, and J. C. Williams, in *Proceedings of the Second IAEA Symposium on Physics and Chemistry of Fission, Vienna, Austria, 1969* (International Atomic Energy Agency, Vienna, Austria, 1969), p. 813.

Measurement of the Spectrum of the Submillimeter Cosmic Background*

D. P. Woody, J. C. Mather,† N. S. Nishioka, and P. L. Richards
Department of Physics, University of California, Berkeley, California 94720, and Inorganic Materials Research Division, Lawrence Berkeley Laboratory, Berkeley, California 94720
(Received 24 February 1975)

The spectrum of the night sky has been measured in the frequency range from 3 to 40 cm^{-1} using a fully calibrated liquid-helium–cooled balloon-borne spectrophotometer at an elevation of 39 km. A model based on the known molecular parameters was used to subtract the atmospheric emission. In the frequency range from 4 to 17 cm^{-1}, the spectrum of the background radiation is that of a blackbody with a temperature of $2.99^{+0.07}_{-0.14}$ K.

Direct microwave measurements[1] have established the spectrum of the cosmic background radiation at seven frequencies from 0.02 to 3 cm^{-1}, and indirect optical measurements[1,2] provide points at 3.8 and 7.6 cm^{-1}. Existing direct measurements from balloon[3] and rocket[4,5] platforms provide limits on the broad-band energy flux in various bands between 1 and 20 cm^{-1}. All of these measurements are consistent with a blackbody spectrum with a temperature of ≈ 3 K. These measurements do not, however, establish the spectral shape of the background radiation beyond the peak of the blackbody curve at ≈ 6 cm^{-1}. We report in this Letter a direct measurement of this spectrum over the frequency range from 4 to 17 cm^{-1}.

A description of the apparatus used for this measurement has been published elsewhere.[6,7] The radiation was collected by a liquid-helium–cooled conical antenna with an apodizing horn[3] at the input to minimize diffraction side lobes. The geometrical beam had a full width of 7.6° and the antenna pattern was measured out to 70° off axis. A liquid-helium–cooled polarizing interferometer[8] was used as a Fourier spectrometer to measure the spectrum of the collected radiation. The detector was a germanium bolometer illuminated with germanium "immersion optics."[6,7] The cryostat was vented to the atmosphere and reached a temperature of 1.65 K at float elevation.

The spectral flux responsivity of the apparatus was calibrated both in the laboratory and during the flight. The flight calibration obtained from a movable, ambient-temperature blackbody which filled 17% of the beam is shown in Fig. 1(a). This calibration agreed with laboratory calibrations to within a few percent.

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 2008 CDT on 24 July 1974. The gondola was suspended 0.6 km below the 3.3 $\times 10^5$-m^3 balloon and was free to rotate about the vertical axis. 4 h of the data were obtained at a float altitude of ~39 km.

Figure 1(b) shows the night-sky spectrum measured by observation at a zenith angle of 24° with no window over the optics. The flow of helium boil-off gas from the cryostat was vented through the antenna. This was sufficient to prevent condensation of atmospheric gases into the cooled optics. 23 interferograms with an (unapodized) resolution of 1.4 cm^{-1} were obtained during 69 min of observing, as well as 2 interferograms with a resolution of 0.28 cm^{-1} during 24 min of

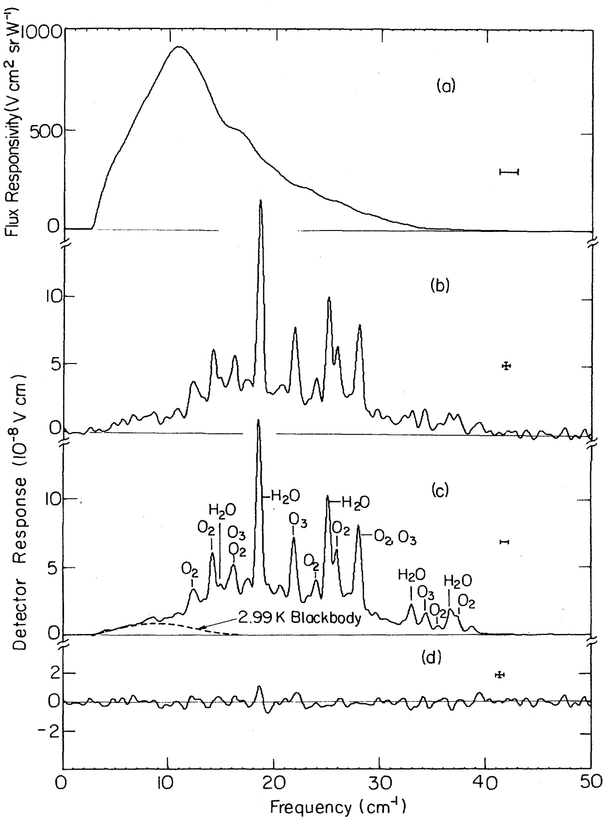

FIG. 1. (a) Instrumental flux responsivity as a function of frequency. (b) Observed instrumental response to the night sky. (c) The fitted-model spectrum. The origins of some of the stronger atmospheric emission lines are shown. (d) The difference between the curves of (b) and (c).

observing. These data were averaged together, apodized, and Fourier transformed with linear phase correction to obtain the spectrum shown in Fig. 1(b). The spectral power can be obtained from it by dividing out the instrumental flux responsivity and adding a correction for the spectrometer temperature. The noise level shown is the rms detector noise for the high-resolution interferograms alone.

These data were analyzed by fitting them with a model which contained four adjustable parameters. The cosmic background radiation was modeled by a blackbody spectrum with adjustable temperature. The model used for the atmospheric emission was based on tabulated line parameters for water, ozone, and oxygen.[9,10] The spectrum was computed by assuming an isothermal atmosphere; an exponential pressure profile; altitude-dependent, pressure-broadened, Lorentzian line shapes; and a constant mixing ratio for the three gases. The pressure at float altitude varied from 3.2 to 3.4 mbar. The ambient temperature measured during the flight was 215 ± 10 K. The column densities of water, ozone, and oxygen were treated as adjustable parameters. The measured interferogram was fitted by the Fourier transform of the product of the model spectrum and the responsivity of the apparatus. In this way, the experimental resolution was included correctly and problems with unresolved lines were avoided. In addition, the more precise data were automatically weighted more strongly in the fit.

The small, but finite, side-lobe response of the antenna meant that some earthshine could have contributed to the measured signal. An attempt was made to measure this earthshine directly by comparing spectra obtained at a zenith angle of 45° with those obtained at 24°. The column densities of atmospheric emitters computed from the 24° spectra were scaled as the secant of the zenith angle and used to subtract the atmospheric contribution from the data obtained at 45°. The residual was assumed to be earthshine and was scaled back to 24° using the measured angular dependence of the antenna pattern.[6,7] The spectrum of the residual thus obtained was less than the noise and no earthshine correction was included in the model.

Information about the radiation emitted by the warm portion of the optical system was obtained by varying its temperature during the flight. The junction between the cone and the horn was heated from 3.4 to 16 K. The emission of the antenna at the lower temperature was estimated from the increase in the observed signal to be substantially less than the detector noise, so no correction was made. No other warm parts of the apparatus are expected to contribute significantly to the collected radiation.

The calculated spectrum which gave the best fit to the observed data is shown in Fig. 1(c). The spectrum of a blackbody at the best-fit temperature of 2.99 K is shown as a dashed line. The values for the free parameters obtained from the fit are given in Table I. The fitted value for the column density of oxygen agrees with the value 1.54×10^{22} molecules/cm^2 computed from a mixing ratio of 21% and an altitude of 39 km. The values for all three gases are in good agreement with the results of other measurements at the same elevation.[3] To estimate the errors in our determination of the cosmic blackbody temperature the derivatives of the fitted blackbody tem-

TABLE I. Model parameters and errors.

	Value with 90% confidence limits	Error in blackbody temperature [a] (K)
Fixed parameters		
Atmospheric temperature	215^{+35}_{-10} K	+0.05, −0.02
Calibration factor [b]	$33.2^{+3.3}_{-3.3}$ K	+0.05, −0.06
Earthshine	$0^{+6}_{-0} \times 10^{-13} \nu^{1/2}$ W/cm^2 sr cm^{-1}	−0.13, +0.00
Fitted parameters		
H_2O vertical column density	$3.92^{+0.20}_{-0.20} \times 10^{17}$ molecules/cm^2	−0.001, +0.001
O_3 vertical column density	$3.50^{+0.18}_{-0.18} \times 10^{17}$ molecules/cm^2	−0.02, +0.02
O_2 vertical column density	$1.67^{+0.17}_{-0.17} \times 10^{22}$ molecules/cm^2	−0.01, +0.01
Blackbody temperature [c]	$2.99^{+0.07}_{-0.14}$ K	

[a] Error induced in fitted blackbody temperature by parameter errors quoted in column 2.

[b] Product of calibrator temperature and filling factor.

[c] Error determined by the rms sum of the detector noise plus the errors shown in column 3.

perature with respect to the most sensitive fixed and free parameters were calculated. The uncertainty in these parameters and the implied errors in the blackbody temperature are shown in Table I.

Figure 1(d) shows the difference between the observed spectrum in Fig. 1(b) and the calculated spectrum in Fig. 1(c). The magnitude of the noise can be estimated from the residual above 40 cm^{-1} where there is no optical signal. Since this residual is comparable in regions with and without optical signal it is dominated by random detector noise. No significant deviations between the model and the observed night-sky spectrum are apparent.

The spectrum of the cosmic background radiation is obtained by subtracting the atmospheric contribution from the measured night-sky spectrum. Figure 2 shows the measured spectrum of the cosmic background radiation compared with that of a 2.99-K blackbody. Both curves are plotted with a constant fractional resolution of 20%. The 2σ error limits were computed by assuming that the residual in Fig. 1(d) was entirely random noise. The dramatic reduction of the noise compared with Fig. 1 is due to the large amount of low-resolution data. This measurement establishes that the cosmic background radiation has a thermal spectrum from 4 to ~17 cm^{-1}, where the curve has fallen to ≈10% of its peak value.[11]

We have plotted our data for the thermodynamic temperature as a function of frequency in Fig. 3 along with selected narrow-band results of other experiments. A standard statistical analysis (χ^2 test) suggests that all the referenced measurements (plus ours) are consistent with the value 2.90 ± 0.08 K (2σ). The results from our experiment alone are $2.99^{+0.07}_{-0.14}$ K (90% confidence).

The authors are greatly indebted to many persons for assistance with this experiment. Pro-

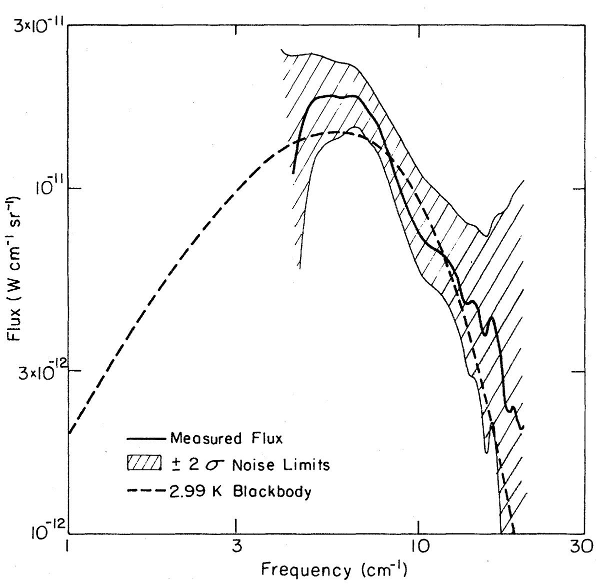

FIG. 2. The present measurement of the cosmic background radiation compared with a 2.99-K blackbody curve. Both curves are plotted with a constant fractional resolution of 20%.

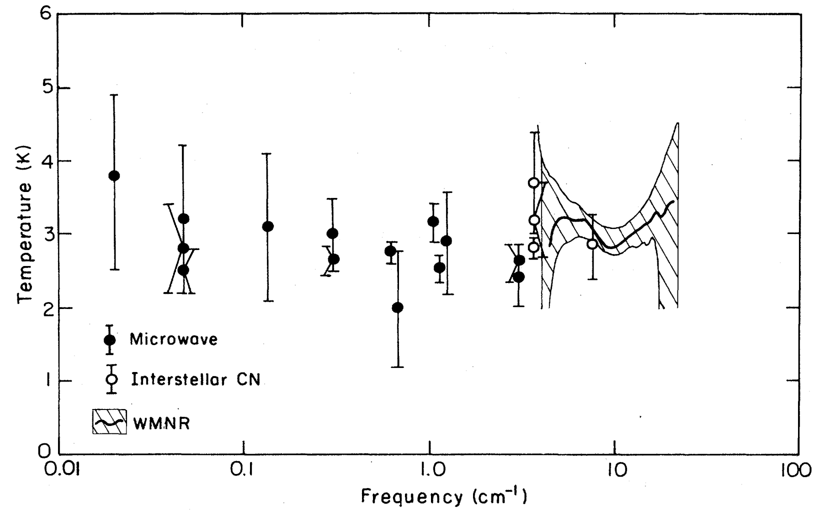

FIG. 3. The present measurement ($\pm 2\sigma$) of the thermodynamic temperature of the cosmic background radiation compared with selected results of other experiments. The data for frequencies $\leq 3\ \mathrm{cm}^{-1}$ were obtained using ground-based microwave radiometers (see Ref. 1). The data at 3.8 and 7.6 cm^{-1} were obtained from optical measurements of cyanogen (see Refs. 2 and 12).

fessor C. S. Bowyer suggested the project and provided a balloon for the first flight. Professor K. A. Anderson provided the gondola and a nearly ideal array of telemetry equipment. Mr. J. H. Primbsch gave invaluable assistance in all areas in the art of ballooning. Mr. B. W. Andrews helped with design calculations, and the NCAR staff at Palestine, Texas, provided us with two successful balloon flights.

*This work was supported in part by the U. S. Energy Research and Development Administration, and in part by the Space Sciences Laboratory, University of California, Berkeley, under National Aeronautical and Space Administration Grant No. NGL05-003-497.

†Present address: Goddard Institute for Space Studies, 2880 Broadway, New York, N. Y. 10025.

[1]P. J. E. Peebles, *Physical Cosmology* (Princeton Univ. Press, Princeton, N. J., 1971).

[2]D. J. Hegyi, W. A. Traub, and N. P. Carleton, Astrophys. J. 190, 543 (1974).

[3]D. J. Muehlner and R. Weiss, Phys. Rev. D 7, 326 (1973), and Phys. Rev. Lett. 30, 757 (1973).

[4]K. D. Williamson *et al.*, Nature (London), Phys. Sci. 241, 79 (1973).

[5]J. R. Houck, B. T. Soifer, and M. Harwit, Astrophys. J. 178, L29 (1972).

[6]J. C. Mather, P. L. Richards, and D. P. Woody, IEEE Trans. Microwave Theory Tech. 22, 1046 (1974).

[7]J. C. Mather, Ph.D. thesis, University of California, Berkeley, 1974 (unpublished).

[8]D. H. Martin and F. Puplett, Infrared Phys. 10, 105 (1969).

[9]R. A. McClatchey *et al.*, Air Force Cambridge Research Laboratory Atmospheric Absorption Line Parameters Compilation, AFCRL-TR-73-0096, Environmental Research Papers No. 434, 1973 (unpublished).

[10]H. A. Gebbie *et al.*, Proc. Roy. Soc., Ser. A 310, 579 (1969).

[11]No significant bias is introduced by assuming a blackbody background when fitting the atmospheric parameters. If we assume no background radiation in the fit, or if we assume that it has no sharp features and fit the atmospheric model to the data with large path difference, the estimate of the amount of O_2 is increased and the derived spectra fall below those in Fig. 2 (between 12 and 17 cm^{-1}), but within the error limit. The procedure used for Fig. 2 is preferable because the rms residual is smaller and the O_2 density agrees with the accurate value known from the pressure and the mixing ratio.

[12]P. Thaddeus, Annu. Rev. Astron. Astrophys. 10, 305 (1972).