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SPECTRUM OF THE COSMIC BACKGROUND RADIATION

by

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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 residual atmospheric contributions to the spectrum measured at an altitude of 41 km were removed by fitting and subtracting a simple atmospheric model. 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.

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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 20 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 balloon borne Fourier spectrophotometer developed for our previous measurement of the near-millimeter CBR, which is described in references 2 and 3. The sensitivity was increased by an order of magnitude over that of our previous system by the use of a ^3He cooled composite bolometer.[4] Improvements were also made to the antenna by the use of a Winston concentrator[5] to define the $\approx 7°$ 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 1940 CDT 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. The mean pressure was nearly a factor two less than for our previous measurement because of our use of a larger balloon.

A total of 30 separate interferograms were measured: 15 at a zenith angle of 25°, 5 at 36°, 5 at 43° and 5 for characterizing the instrument. In order to optimize the signal-to-noise ratio on low resolution features, approximately 60% of the time was spent observing features wider than 1.0 cm^{-1} and 40% at resolutions between 0.13 and 1.0 cm^{-1}.

The individual interferograms were convolutionally phase corrected for linear and quadratic phase errors, averaged in groups according to zenith angle, and Fourier transformed to obtain spectra.

The spectrophotometer was calibrated after the flight using a low temperature blackbody source inserted approximately halfway down the antenna. Spectra were measured with calibrator temperatures of 5.44, 10.34, and 20.14 K. Spectra of the 300 K room measured before and after the flight agreed within 3% and, when corrected for detector saturation effects, were consistent with the cold blackbody calibrations. The zero level was determined both in the laboratory and during the flight by observing a cold blackbody immersed in the liquid helium bath. The instrumental responsivity obtained from these spectra is shown in Fig. 1(a). The low frequency response is limited by the waveguide cutoff from the 0.13 cm diameter exit aperture in the Winston concentrator, while the high frequency response is rolled off by a Fluorogold^{TM} filter. The features apparent at low frequencies are a result of mode structure in the antenna. The net estimated error for the calibration was ± 10% at $2cm^{-1}$ decreasing to +5 and -8% above 10 cm^{-1}. The sources of error included are calibrator temperature and emissivity, the effect of a varying liquid helium level in the optics, detector noise, and the stability of bolometer, preamp, and telemetry systems.

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 the earth and the antenna is less than 1% of the peak flux from a 3 K blackbody.[2]

The details of these measurements and the calibration procedure will be reported in a more extensive publication.

The response of the instrument to the emission of the night sky at a zenith angle of 25° is shown in Fig. 1(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 which dominates the spectrum above 12 cm^{-1}. 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 $2.76 \pm .16 \times 10^{17}$ H_2O/cm^2, $1.72 \pm .14 \times 10^{17}$ O_3/cm^2, and $1.09 \pm .15 \times 10^{22}$ 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 zero K reference temperature) which remains after subtracting 1(c) from 1(b) is shown at resolutions of 0.28 cm^{-1} and 1.79 cm^{-1} in Figs. 1(d) and 1(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 I(e) by I(a).

Figure 2 shows the $\pm 1\ \sigma$ error limits of the measured CBR flux for a triangular resolution function with $\sim 1\ cm^{-1}$ FWHM. The observed night sky emission before subtraction of the atmospheric contribution is also shown for comparison. Important sources of error include essentially random detector noise, nearly random atmospheric fitting errors and calibration errors which are strongly correlated over the spectral range. The error limits shown in Fig. 2 are rms sums of these three sources of error treated as if they were random. The present spectrum is consistent with our previous results[2,3] and with the work of Muehlner and Weiss[9] at the 90% confidence level.

The most striking feature of our data is the qualitative agreement with a simple Planck curve. The agreement covers nearly a decade in frequency and extends from the Rayleigh-Jeans 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.

The integrated flux of the CBR obtained from our measurement is equal to that from the $2.96^{+.04}_{-.06}$ K blackbody curve which is shown as a dashed line in Fig. 2. However when the fit is analyzed using a maximum likelihood method in which the correlations in the calibration errors are included, the measured spectrum deviates from the Planck curve by 5σ. It varies smoothly from $\approx$ 10% above the 2.96 K Planck spectrum at

6 cm^{-1} to 20% below it at 11 cm^{-1}.

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 $\sim$ 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, the earth, or galactic dust clouds. The spectra measured at different zenith angles and float pressures place an 85% confidence limit on the deviation not being atmospheric in origin. It could not arise from errors in the correction for known atmospheric constituents which is small 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]

In the limit of few scattering events the expected spectrum is a superposition of Planckian spectra which can be characterized by a Rayleigh-Jeans temperature T_{RJ} and the fractional energy transfer U from the matter to the CBR.[10] In the limit of many photon conserving scattering events the spectrum is characterized by a Bose-Einstein distribution with a finite chemical potential μ. 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. The above models do not fit the data as well as a simple Planck curve. The fit is degraded by 1σ for $U > .03$ or $\mu > 10^{-17}$ ergs. The result for U places a limit on the energy exchange between the photons and an optically thin hot plasma. This limit is 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 U given above.[13]

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. The existence of any such deviation is of cosmological significance. Further theoretical work and observations at both microwave and near millimeter wavelengths is 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 coauthors. Their earlier work 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 helped with the launch, and the NCAR staff at Palestine, Texas, provided us with a successful balloon flight.

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7. H. J. Liebe, G. S. Gimmestad and J. D. Hopponen, IEEE Trans. Antennas and Propagation AP-25, 327 (1977).

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

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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 $\hbar$.[12] 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.

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13. A weighted average of the microwave data gives a temperature of 2.65 ± 0.8 K (see ref. 1), but χ^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.

FIGURE CAPTIONS

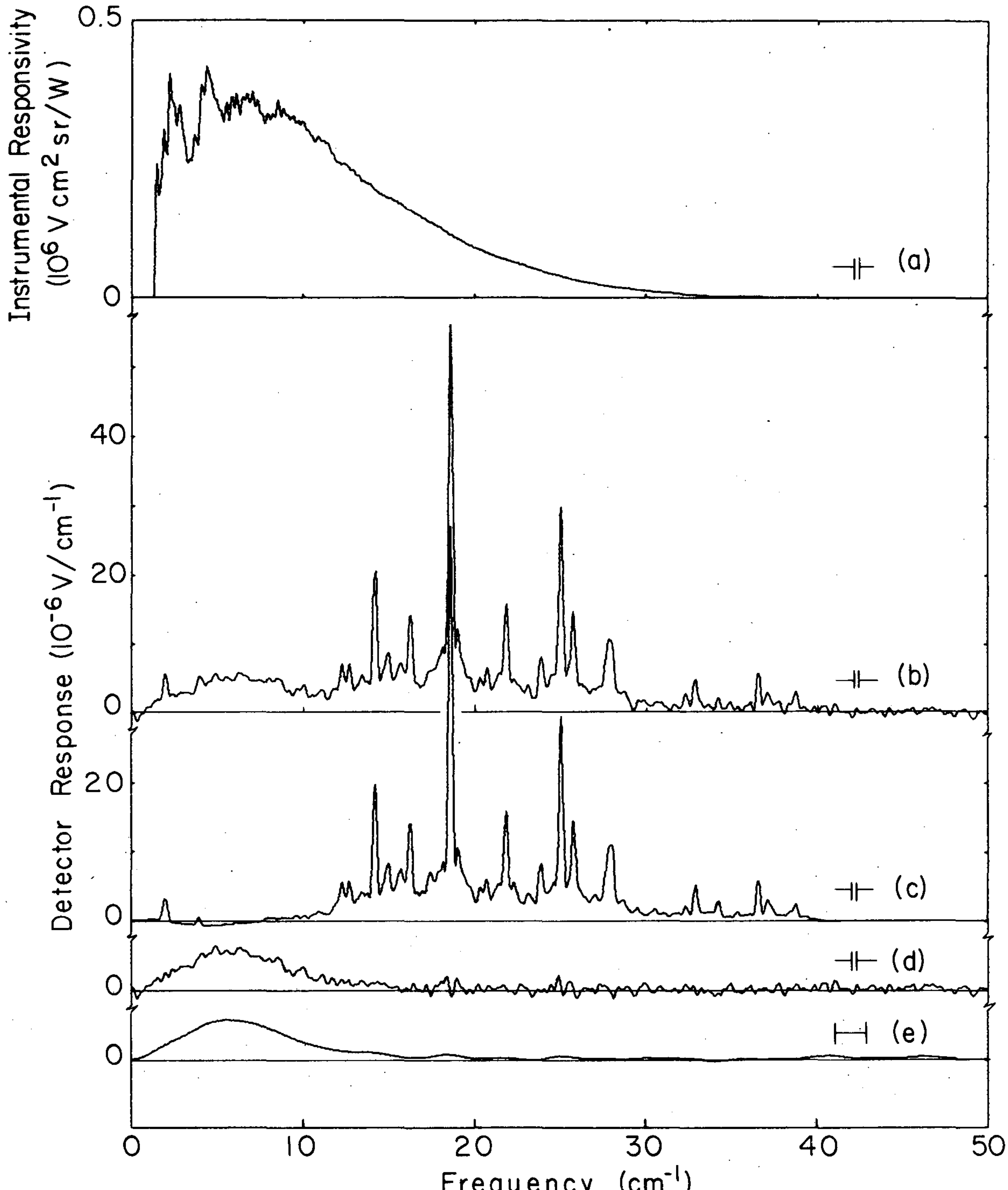
Fig. 1 (a) Calibration of the flux responsivity determined from the response of the instrument to a cold blackbody.

(b) Observed response to the night sky emission.

(c) Calculated response to the atmospheric emission, including the effect of the 1.67 K reference blackbody.

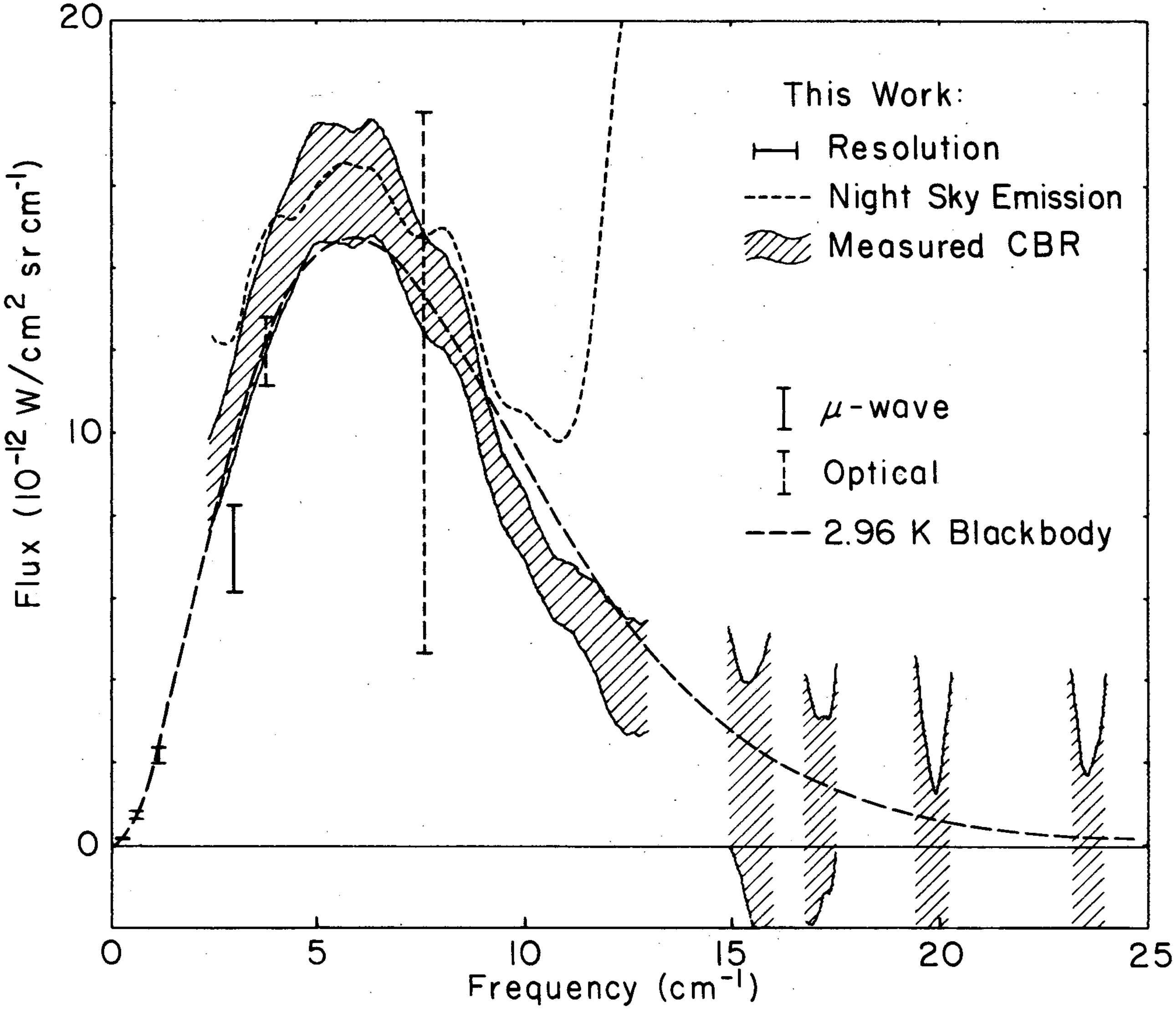
(d) and (e) Response to the CBR at two different spectral resolutions obtained by subtracting (c) from (b). The measured spectrum of the CBR shown in Fig. 2 is obtained by dividing the response data (e) by the flux calibration (a).

Fig. 2 Measured spectrum of the cosmic background radiation plotted as $\pm 1\ \sigma$ error limits assuming that all contributions to the error are random. There are gaps in the data at the frequencies of strong atmospheric emission lines where the errors become very large. For comparison we also show the raw emission spectrum of the night sky from an altitude of 41 Km without any correction for atmospheric emission, as well as the spectrum of the 2.96 K blackbody which fits the measured integrated flux, and selected microwave and optical measurements of the CBR. A significant portion of the error in the measured CBR arises from uncertainty in an essentially constant calibration factor, so is strongly correlated over the spectrum. A complete analysis which includes these correlations shows that there is a $5\ \sigma$ discrepancy between the measured curve and the best fit blackbody. The statistics of the fit are dominated by the frequency range $3 \leq \nu \leq 11 \mathrm{cm}^{-1}$ where the atmospheric correction is small.



Instrumental Responsivity
(10^6 V cm^2 sr/W)
0.5
0
(a)
Detector Response (10^-6 V/cm^-1)
40
20
0
(b)
20
0
(c)
0
(d)
0
(e)
0
10
20
30
40
50
Frequency (cm^-1)

XBL789-5875



20
10
0
Flux (10^{-12} W/cm^2 sr cm^{-1})
0
5
10
15
20
25
Frequency (cm^{-1})
This Work:
Resolution
Night Sky Emission
Measured CBR
μ-wave
Optical
2.96 K Blackbody

XBL 789-5876

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