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Abstract

Direct Measurements of the Spectrum of the Near-Millimeter Cosmic Background
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The spectrum of the cosmic background radiation peaks at 6 cm^{-1} and falls rapidly at higher frequencies. The experimental determination of this simple but important fact has had a long and troubled history. It remained in doubt long after the nature of the Rayleigh-Jeans region of the spectrum was firmly established. In this review we describe the experimental difficulties which have plagued cosmic background measurements at and beyond the peak in the spectrum. A critical evaluation of the present status of the field will then be given.

1. Difficulty of the measurement

There are three primary reasons why direct measurements of the spectrum of the cosmic background radiation at and beyond the peak have proved troublesome:

(i) The background radiation must be measured in the presence of emission from nearby sources, including the atmosphere, the earth, and the apparatus. The ratio of the brightness of a 300 K blackbody to that of a 3 K blackbody is only 10^2 at low frequencies. Because of the exponential cutoff of the 3 K curve, however, this ratio is 5×10^2 at 6 cm^{-1} and 1.5×10^5 at 20 cm^{-1}. Avoidance of the emission from ambient temperature objects becomes extremely difficult. In practice, high frequency experiments must use low temperature apparatus.

(ii) The density and strength of emission lines in the earth's atmosphere increases rapidly with frequency. The combination of (i) and (ii) means that ground-based measurements can be made at 1 cm^{-1} with only a small atmospheric correction. By 12 cm^{-1}, however, large atmospheric corrections are required for measurements made from the highest available balloon altitudes.

(iii) The technology for high frequency cosmic background measurements was and is relatively undeveloped. In the Rayleigh-Jeans spectral region where adequate microwave technology was generally available, any investigator who seriously attacked the measurement problem had, in principle, an opportunity to do a measurement of good quality. At higher frequencies the early workers simply did not have the technology base required. Despite intensive and imaginative efforts, misleading results were sometimes announced. In retrospect, the value of many of these early experiments lay in their contributions to measurement technology. Our present knowledge of the cosmic background spectrum at and beyond the peak comes from recent experiments which could not have been done without making use of the antennas, spectrometers, and detectors that were invented during the past ten years.

2. Outline of technology development

This review will not provide a complete listing of all measurements of the spectrum of the cosmic background at high frequencies. Such listings have been given recently by Danese and Zotti [1] and also by Robson and Clegg [2]. Rather than repeating this information it seems more useful to summarize the development of the technology base on which current direct spectral measurements rely. Only those techniques which are likely to be used in the future will be included in this summary.

The early rocket experiments [3] of the Cornell, Naval Research Laboratory, and Los Alamos groups were pioneering efforts in a very real sense. It was very difficult to make any background measurements from sounding rockets at that time because the sensitivities of the available detectors were not sufficient to permit detailed diagnostic studies of instrumental performance to be made during the flight. There were also serious size and complexity limitations for rocket payloads. The conical antenna introduced by the Los Alamos group was of great value in later experiments.

The field was advanced considerably by the balloon experiments of the MIT group [4]. These experiments showed that balloon platforms did permit the required complexity of payload and long observing times, but with problems from the residual atmosphere at balloon altitude. A number of ideas and techniques were introduced which provided the basis for subsequent measurements. Probably the most important of these was the explicit recognition of the seriousness of diffraction of 300 K radiation from the horizon into the apparatus. The apodized antenna and ground shield were developed to reduce this problem. It was demonstrated that balloon experiments could be operated open port, thus avoiding the use of a warm emissive window. The MIT group also introduced the procedure of fitting their data to detailed atmospheric calculations. Since the MIT experiment used fairly broad spectral bands, the atmospheric signal contained contributions from both saturated and unsaturated emission lines. As a consequence, a multi-parameter fit to the zenith-angle dependence of their data was required which limited the accuracy of the experimental results.

The Florence group has reported [5] attempts to measure the spectrum of the cosmic background radiation from a mountain top using bolometric detectors and band-pass filters centered in atmospheric windows. This approach is a high frequency extension of the measurement philosophy used in the microwave region. Although such experiments appear possible in the neighborhood of the peak, they are in practice extremely difficult. Future progress in spectral measurements above 2 cm^{-1} is more likely to come from experiments done at higher altitudes.

The most recent generation of balloon measurements by the groups at Queen Mary College (QMC) [6] and Berkeley [7,8] have made use of Fourier transform infrared spectrometers to obtain the spectral resolution required to separate atmospheric lines from the background radiation. The Martin-Puplett polarizing interferometer invented at QMC has nearly ideal properties for measurements of this type and was used in both experiments.

The Berkeley experiments were accompanied by an extensive program of technology development. Innovations for the first Berkeley flight included the use of an unobstructed conical antenna in front of the beam defining aperture, the introduction of antenna pattern calculations using the geometrical theory of diffraction, and the invention of a method for measuring the antenna pattern [9] over a broad range of angles and spectral frequencies. Innovations introduced in the second Berkeley experiment [8] included the use of a Winston cone [10] for the primary antenna, and the use of a ^3He cooled composite bolometric detector [11].

A new generation of rocket experiments which employ a Fourier transform infrared spectrometer has been developed at the University of British Columbia (UBC). Improved detectors have reduced the importance of the limitations to observing time in rocket experiments. The results thus far do not appear to have exhausted the potential of this approach [12].

3. Status of spectral measurements

Because of the continuous technical progress, we will comment only on the QMC and Berkeley balloon experiments, which were similar in goal and concept. They both claim to have observed the long sought turn-down of the background spectrum at frequencies beyond 6 cm^{-1}. As has been pointed out, however, the QMC experiment and the Berkeley experiments are not compatible [2,13]. The QMC group reported weak atmospheric emission lines superimposed on a broad continuum. A dip in the continuum was reported between 12 and 15 cm^{-1} which was interpreted as evidence for the fall of the background spectrum beyond the peak. The data were analyzed by drawing line segments between the troughs of the spectrum, fitting the high frequency continuum to an estimate of the window emission, and ascribing the low frequency continuum to the background radiation [6].

Although the Berkeley experiment used similar spectral resolution and looked through a similar amount of atmosphere, the observed spectra were very different. Strong atmospheric emission lines were seen which are in quantitative agreement with simple atmospheric emission models.

No dip was seen in the raw data between 12 and 15 cm^{-1}. Model atmospheric spectra were fitted and subtracted from the measurements to obtain the spectrum of the background radiation, which did fall beyond the peak at 6 cm^{-1}. Although many persons [13] favored the Berkeley experiment because of the agreement with the expected atmospheric emission, others [2] felt that because of uncertainties in the molecular parameters of oxygen and in the concentration of ozone to be expected, no decision between the experiments could be made. It was clear, however, that both experiments could not be correct.

The Berkeley apparatus was subsequently improved by the use of a very much better detector [11], higher spectral resolution, higher flight altitude, and larger antenna. Results of the second Berkeley experiment [8] agree with the first Berkeley experiment and very precisely with the expectations of the standard atmospheric model. The conclusion now seems inescapable that the QMC experiment suffered a significant malfunction. The published description of the QMC experiment is so brief that an outsider has no chance to guess what actually happened. It seems clear, however, that information of cosmological significance can be obtained from this experiment only if the experimenters can provide a detailed analysis of the flight which accounts quantitatively for the distortions observed in the atmospheric spectrum.

4. Second Berkeley experiment

The results of the second Berkeley experiment can be summarized by reference to Figs. 1, and 2. Fig. 1(a) shows the response of the apparatus when the antenna is filled with frequency-independent incoherent radiation. This curve was obtained by measurements of laboratory blackbodies with temperatures between 5 and 300 K before and after the flight. The sharp onset of sensitivity at 3 cm^{-1} and the low frequency structure on this curve result from the propagation of individual electromagnetic modes through the small beam-defining aperture of the antenna. The instrumental response is cutoff at high frequencies with a filter. The complex features of this curve are entirely reproducible, and illustrate some of the inherent difficulties of doing measurements over a broad spectral band in a frequency region where the wavelength is comparable to important dimensions of the apparatus.

Fig. 1(b) shows the measured spectrum of the night sky from an altitude of 43 Km. Fig. 1(c) shows the predicted response of the apparatus to the atmospheric emission at the flight altitude, temperature, and pressure. This response was obtained by fitting a simple constant-temperature, constant mixing-ratio atmospheric model with adjustable column densities of oxygen, ozone, and water to the data of 1(b). The fit reproduces the known mixing ratio of atmospheric oxygen to within 7%. Curve 1(c) is negative at low frequencies because it represents the difference between the (small) emission from the sky and the (larger) emission from the apparatus which was at 1.67 K. The residual which remains when the atmospheric emission 1(c) is subtracted from the sky spectrum 1(b) is shown at two spectral resolutions in 1(d) and 1(e). None of the sharp features shown in 1(d) are statistically significant. The normalized measurement of the background radiation is obtained by dividing 1(e) by 1(a).

The primary conclusions of the second Berkeley experiment are shown as a plot of flux versus wavenumber at a spectral resolution of 1 cm^{-1} in Fig. 2. The two thin lines above and below the cross-hatched region indicate the ± 1 standard deviation limits of the measurement assuming that all known errors are random and can be added in quadrature. There are gaps in the data at the frequencies of strong atmospheric emission lines where the error limits become very large. The data clearly indicate that the spectrum of the background radiation peaks in the neighborhood of 6 cm^{-1} and falls rapidly at higher frequencies. The integrated flux is equal to that from a 2.96 K Planck curve which is shown for comparison. These new data are consistent with the first Berkeley experiment which was best fit by a 2.99 K Planck curve and also with the MIT results [4].

Because of the interest in possible deviations from a Planck curve the errors in this experiment have been analyzed carefully.

Significant sources of error have been summarized in the preliminary publication [8], and will be discussed in greater detail in a forthcoming paper. One type of error, which arises from sources such as amplifier gain, helium in the antenna, etc., has the effect of expanding or contracting the scale factor for the overall curve. Another type of error, which arises from sources such as detector noise and uncertainties in atmospheric line parameters, is essentially statistically uncorrelated from one spectral resolution element to the next. In Fig. 2 we plot the ± 1 standard deviation limits of these latter errors as a cross-hatched region. This region can be shifted up or down within the limits set by the thin solid lines in order to include the effects of uncertainties in the overall scale factor.

A statistical analysis which separates the effects of errors which are correlated across the spectrum from those which are uncorrelated between neighboring resolution elements shows that the data are 5 standard deviations away from the Planck curve with the same included flux. Possible spurious sources for these deviations have been carefully explored. They are unlikely to arise from the atmospheric correction which is small for frequencies below 12 cm^{-1}. A large (~ 25%) reduction in the overall scale factor would bring the data into agreement with a lower temperature Planck curve, but no cause for such an error has been identified. If it had occurred, the measured atmospheric spectrum would no longer be in agreement with the known mixing ratio of atmospheric oxygen.

The form of the deviation is difficult to understand in terms of any likely cosmological phenomena. If correct, it will therefore require some revisions in our thinking about the early universe. In order to understand the degree to which such revisions are imposed upon us by this experimental result it is necessary to consider the nature of physical measurements. In any difficult experiment it is impossible to be absolutely certain that all systematic errors have been identified and either eliminated or corrected. The degree of confidence in any one experiment obviously increases with evidence that the experiment has been carefully done. A high degree of confidence, however, is obtained only when several experiments give the same conclusion. It is preferable that these experiments be done using different techniques.

A number of new experiments are in various stages of development which should shed some additional light on the spectral shape of the background radiation. The UBC group has re-flown their rocket experiment but have not yet reported the results. A measurement of the spectrum at and beyond the peak is being planned as part of the COBE satellite. This experiment should provide an accurate independent measurement.

A new balloon experiment is being developed at Berkeley which is designed to be as different as possible from the previous Berkeley measurements so as to provide independent information. The Fourier transform spectrometer will be replaced by a set of 5 narrow-pass filters over the frequency range from 3 to 10.3 cm^{-1}. The center frequencies of the filters have been selected to avoid strong atmospheric lines. The residual atmospheric contribution at balloon altitude will range from 0.5 to 47% of the background signal and will arise almost entirely from unsaturated line emission. This contribution will be removed by measuring signals as a function of zenith angle and extrapolating to zero atmosphere. The instrument will be calibrated in flight with an ambient temperature calibrator that fills the entire antenna beam. The results of this new experiment should be available in one to two years.

Interest in the possibility of deviations from a Planck curve should not obscure the main conclusion of the Berkeley experiments. The spectrum of the background radiation has a peak at ~ 6 cm^{-1} and falls rapidly at higher frequencies. Despite the difficulties of high frequency measurements, the flux accuracy achieved is comparable to that of the better microwave measurements.

5. Criteria for useful measurements

There is significant astrophysical interest in improving the accuracy of background measurements by orders of magnitude at all frequencies. This goal will be reached only if further developments in measurement technology occur. Lessons can be learned from the history of high frequency measurements which will facilitate these on-going experiments. Most groups working seriously on a high frequency spectral measurement have had the experience that their initial design concepts were inadequate. Successful experiments were produced by the process of continuous revision and refinement which required many tens of man-years of effort. Unfortunately the publication policy of most groups working in the field has been such that this effort has gone unreported. Some publications are so incomplete that even the general experimental approach is unclear. Consequently, much of importance for the development of the field has been lost.

In the opinion of this reviewer, it is of highest importance for future progress that all investigations be reported in great detail. This point has also been emphasized by R. Weiss, who set an excellent example in the detailed publication of the MIT balloon experiments. Theses or technical reports can be a satisfactory substitute for long journal articles <u>if they are made generally available</u>.

In order to contribute meaningful information about the spectrum of the background radiation it is necessary to do very difficult absolute measurements where the answer (a ~ 3 K blackbody) is "known." Opportunities for unintentional bias of the results are enormous. Successful measurements require a high level of sophistication and rigorous intellectual honesty. The task of the reviewer in this field is to judge both the sophistication and the care exercised in each measurement. The primary source of information is the published account. There is a strong and justifiable tendency to be skeptical about experiments which are not reported fully. A list of items which should be discussed in quantitative detail in any serious report is included as Table I. Many of the items mentioned there are also relevant for a new generation of more precise measurements of the spectrum in the Rayleigh-Jeans region.

Insert Table I

6. Acknowledgments

The author is greatly indebted to his former students and colleagues, Dr. J. C. Mather and Dr. D. P. Woody, who participated actively in the two Berkeley experiments and who taught him many valuable lessons about how to do experimental physics. The third Berkeley experiment is being prepared with the collaboration of Professor T. Timusk and Mr. J. Bonomo.

Table I. As a bare minimum any new spectrum experiment must provide a detailed quantitative discussion of the following topics:

1. Antenna pattern measurements and calculations
2. The importance of radiation from the horizon
3. The temperature distribution in the apparatus
4. The subtraction of emission from the atmosphere and/or environmental contaminants, and from other near-field sources such as the antenna, the spectrometer, etc.
5. The temperature, blackness, and throughput of the calibration system
6. All corrections estimated whether or not considered significant
7. Consistency of results with calculated system parameters, atmospheric spectra, etc.

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Figure Captions

Fig. 1. Stages in the analysis of the data from the second Berkeley experiment:

(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 of oxygen, ozone, and water, 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).

Fig. 2. Second Berkeley spectrum plotted as $\pm 1\ \sigma$ error limits with a distinction made between two types of experimental error. The crosshatched region gives the error limits considering only those sources of error which are essentially statistically independent between one spectral resolution element and the next. When sources of error are included which affect the overall scale factor the crosshatched region can be shifted up or down within the limits indicated by the thin solid lines. For comparison we also show the spectrum of the 2.96 K blackbody which fits the measured integrated flux, and selected microwave and optical measurements of the cosmic background radiation.

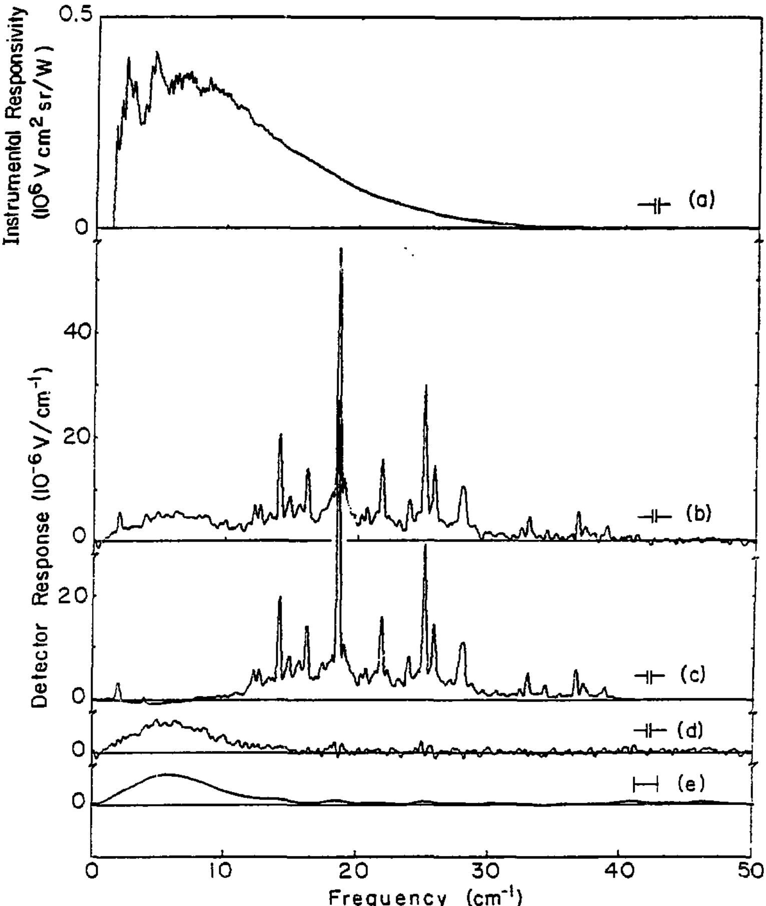

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Figure 1

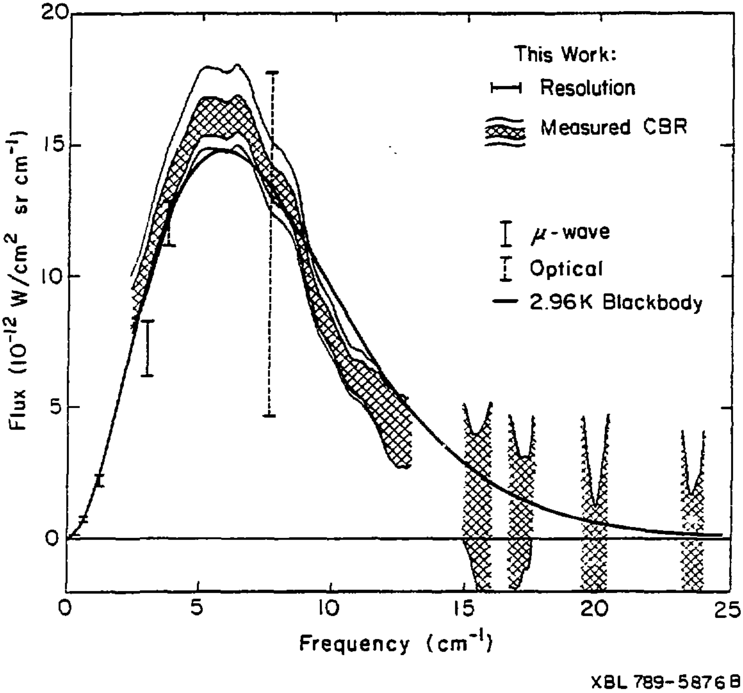
This Work:
Resolution
Measured CBR
μ-wave
Optical
2.96K Blackbody
Flux (10^{-12} W/cm^2 sr cm^{-1})
Frequency (cm^{-1})
0
5
10
15
20
25
XBL 789-5876B

Figure 2