THE SPECTRUM OF THE MICROWAVE BACKGROUND

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ABSTRACT

The spectrum of the microwave background radiation closely resembles that of a blackbody with a peak at 6 cm^{-1}. Many experimenters have contributed to the determination of this simple but important fact. In this review we describe the experimental difficulties which have plagued background measurements in the high frequency Wien region. An evaluation of the present status of our knowledge of the entire spectrum will be given and prospects for future experiments will be mentioned.

MEASUREMENTS IN THE RAYLEIGH-JEANS REGION

Spectral measurements at frequencies $\lesssim 3$ cm^{-1} have made use of ground based microwave antennas with well controlled sidelobe response and conventional heterodyne receivers. Atmospheric contributions were removed by measuring the sky temperature as a function of zenith angle. Calibration was accomplished with an ambient temperature (hot) load and a liquid He temperature (cold) load. The addition of the cold load to a relatively conventional radio telescope system made possible the original detection of the background radiation by Penzias and Wilson (1965). A second generation apparatus developed by the Princeton Group (Wilkenson 1967) was used for several experiments in the frequency range $0.3 < \nu < 3$ cm^{-1}. It employed a stationary downward looking receiver with an external cold load and a tiltable mirror to scan the zenith angle.

The data obtained using these microwave techniques have not changed appreciably in nearly 10 years. They provide a reasonably consistant picture in the Rayleigh-Jeans region over the frequency range from 0.01 to 3 cm^{-1}. The accuracy of the data was limited at the low frequency end by galactic synchrotron radiation and at the high frequency end by atmospheric emission. This review will not list all measurements of the spectrum of the microwave background. Such a list has been given recently by Danese and De Zotti (1977).

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MEASUREMENTS AT AND BEYOND THE PEAK

Direct measurements of the spectrum of the microwave background radiation at and beyond the peak have proved troublesome for three important reasons:

(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 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 thus becomes extremely difficult. In practice, high frequency experiments must use liquid He 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 a relatively 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, however, 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 microwave background spectrum at and beyond the peak comes from the most recent experiments which could not have been done without antennas, spectrometers, and detectors that were invented during the past ten years.

It seems useful to summarize the development of the technology on which current direct spectral measurements rely. A great variety of approaches has been used for the high frequency measurements. The early rocket experiments of the Cornell, Naval Research Laboratory, and Los Alamos groups using far infrared detectors and band-limiting filters 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 sensitivity of the available detectors was 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. References to this early work are given by Danese and De Zotti (1977).

The field was advanced considerably by the balloon experiments of the MIT group (Muehlner and Weiss 1973a, 1973b). Their 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. 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 multiparameter fit to the zenith-angle dependence of their data was required which limited the accuracy of the experimental results. This group explicitly recognized the seriousness of diffraction of 300 K radiation from the horizon into the apparatus and developed the apodized antenna and ground shield to reduce this problem. They 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.

The most recent generation of balloon measurements by the groups at Queen Mary College (Robson et al., 1974 and Robson 1976) and Berkeley (Woody, et al., 1975, Woody and Richards 1979)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 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 to define the beam on the sky, the introduction of antenna pattern calculations using the geometrical theory of diffraction, and the invention of a method for measuring the antenna pattern over a broad range of angles and spectral frequencies (Mather, et al., 1974). Innovations introduced in the second Berkeley experiment included the use of a Winston cone (Winston 1970) for the primary antenna, and the use of a ^{3}He cooled composite bolometric detector (Nishioka, et al., 1978).

Because of the continuous technical improvements in the higher frequency measurements only the results from the most recent Berkeley balloon experiment will be discussed. The primary conclusions of this experiment are shown as a plot of flux versus wavenumber at a spectral resolution of 1 cm^{-1} in Fig. 1. The two thin lines above and below the crosshatched 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.

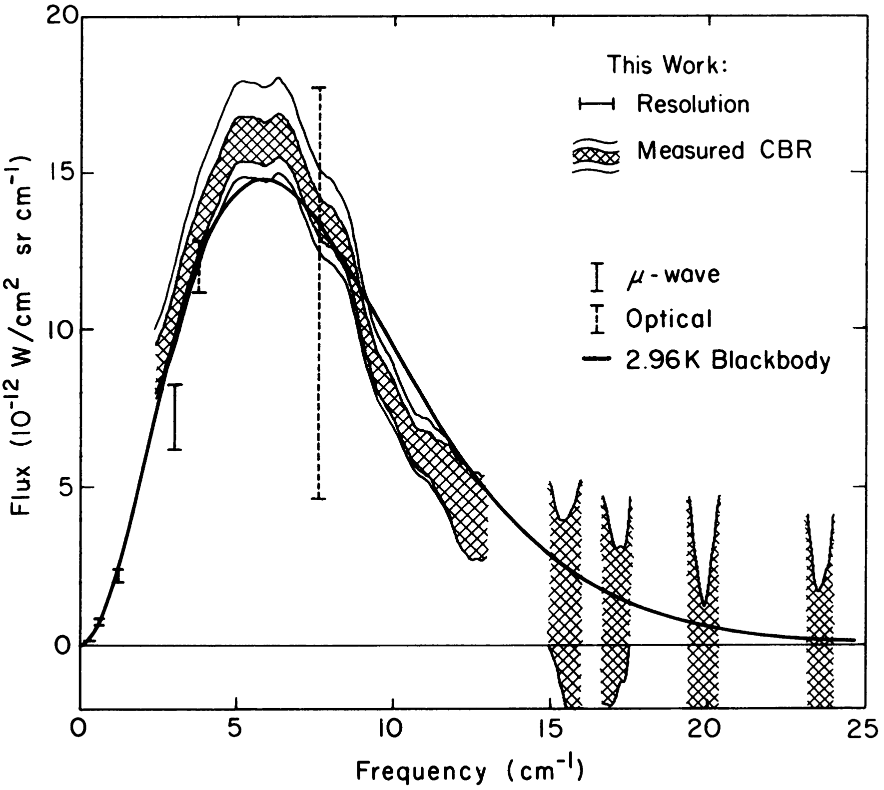

Figure 1. Second Berkeley spectrum plotted as ± 1 σ error limits with a distinction made between two types of experimental error. The cross-hatched region gives the error limits considering only those sources of error which are essentially statistically independent between one spectral resolution element 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, as well as selected microwave and optical measurements of the cosmic background radiation.

Because of the interest in possible deviations from a Planck curve the errors in this experiment have been analyzed carefully. 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. 1 the ± 1 standard deviation limits of these latter errors are plotted as a crosshatched 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 and the Planck curve with the same included flux are 5 standard deviations apart. Possible spurious sources for these discrepancies 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.

COLLECTED RESULTS

A comparison between the Berkeley data (full 1 σ error limits) and the microwave data is given in Fig. 2 in the form of a plot of temperature versus frequency. Measurements of the rotational temperature of interstellar CN molecules deduced from optical spectra are also shown at 3.8 and 7.6 cm^{-1}. The temperatures obtained in this way are relatively insensitive to systematic errors and should be thought of as hard upper limits. Corrections have been applied to the 3.8 cm^{-1} data to account for local excitation of the CN molecules. When this is done the temperature is reduced by about 0.1 K below the plotted point. (Thaddeus 1972).

There is a hint of a discrepancy in the data in the 3 cm^{-1} region where the highest frequency microwave points fall below the Berkeley data. It is interesting to note in this regard that the atmospheric contribution to these ground based measurements was more than 10 times the background signal. The atmospheric contribution to the balloon experiment by contrast, was small for frequencies $\lesssim$ 12 cm^{-1}.

In the presence of possible systematic errors the assignment of error limits is a subjective process. It is difficult therefore to compare error limits set by different investigators. Two rather extreme points of view will illustrate the problem:

(i) We can assume that differences in the errors assigned by different investigators are significant and weight each data point in accordance with its quoted error. If this point of view is accepted, then the data set is dominated by a few measurements which have narrow error limits.

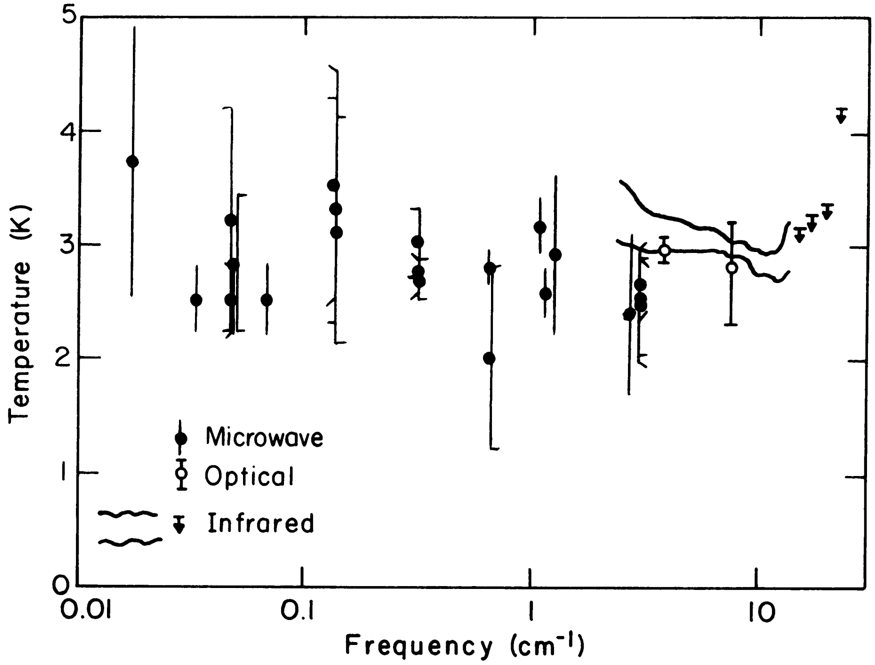

Figure 2. Collected microwave, interstellar CN and Berkeley results plotted as a frequency dependent thermodynamic temperature. The error limits are intended to be ± 1 σ.

(ii) We can assume that the differences in assigned error are primarily subjective and average only the measured values. From this point of view, a weighted average introduces a high degree of subjectivity into the conclusions. Because of the differences between these possible interpretations it is not clear to us how to correctly analyze the entire data set.

We will restrict our comments to the Berkeley data which are a consistent data set and which are not in agreement with a thermal spectrum. Some of the mechanisms which could lead to deviations from a blackbody spectrum are Compton scattering of the background photons by "hot" electrons, radiative damping of turbulence, and annihilation of matter and antimatter (Zeldovich, et al., 1972). 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, however, do not fit the data as well as a simple Planck curve. The fit is degraded by 1 σ for an energy exchange between the photons and an optically thin hot plasma equal to 3% of the energy in the microwave background at the time of interaction.

One idea which appears to account adequately for the shape of the Berkeley spectrum has been discussed by Rowan-Robinson, et al., (1979). They suggest that the microwave background could have been re-heated by interaction with dust which was created during an early period of star formation. If this occurred at $Z = 200$ then a silicate feature in the emissivity of the dust could account for the observed fall in thermodynamic temperatures with frequency beyond the peak.

If the deviation is correct, it will 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 these experimental results 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.

NEW EXPERIMENTS

A consensus appears to be developing in the interested community that improved measurements are both possible and desirable over the whole microwave frequency range. It has been suggested by Wilkinson (1979) that measurements of the rate of change of flux with frequency could have better accuracy than absolute flux measurements. Better experiments for frequencies above $\lesssim 1$ cm^{-1} would have to be done above the surface of the earth. At low frequencies large antennas would be required to accurately sift out the effects of galactic synchrotron radiation.

A measurement of the spectrum at and beyond the peak is being planned as part of the COBE satellite. The design is related to the Berkeley experiment reported above in that it makes use of bolometric detectors and a polarizing Fourier spectrometer. An accurate independent measurement should be available from this experiment in about 1984.

Also, 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 relatively independent information. The Fourier transform spectrometer will be replaced by a set of 5 band-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 in the filter bands at balloon altitude will range from 0.5% to 47% of the background signal. 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 about one year.

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DISCUSSION

Baum: Could you get a better fit to the observed microwave background radiation spectrum by assuming a spread of blackbody temperatures (and associated emissivities) instead of a single blackbody temperature?

Woody: The Compton scattering from hot electrons and many other reheating mechanisms can be analyzed as a superposition of different temperature blackbodies with emissivity less than one. Such models do not improve the fit to our data. An improvement can only be obtained if emissivities are allowed to exceed unity.

Epstein: Some of your graphs seem to show that the atmospheric emission is quite large compared to the deviations from the pure blackbody spectrum. I think some of us are confused and/or skeptical as to how you convinced yourselves that you had correctly removed the effects of the atmosphere. Would you please review this point for us?

Woody: Although the atmospheric emission is large at frequencies above 15 cm^{-1}, the atmospheric correction in the region where deviations are reported is small. At the peak in the CBR the atmospheric contribution is less than 1% of the observed night sky emission. It increases to ~ 40% at 11 cm^{-1}. We have found no reasonable alteration in the atmospheric emission model that would account for the deviations.

Segal: I wonder whether you know of any special reason to anticipate that the CBR does not have a substantial isotropic angular momentum.

Woody: We have no special information to contribute on this question.

J. Roberts: The atmospheric contribution which you subtract is negative in just the frequency range where you find an excess. Why is this?

Woody: Our instrument measures the differences between the sky temperature and the instrumental reference temperature of 1.7 K. The plot referred to is a theoretical prediction of the instrumental response to the atmospheric emission. It goes negative at low frequencies where the atmospheric temperature becomes less than 1.7 K.