LBL-18073

CONF-8405155--3

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Materials & Molecular Research Division

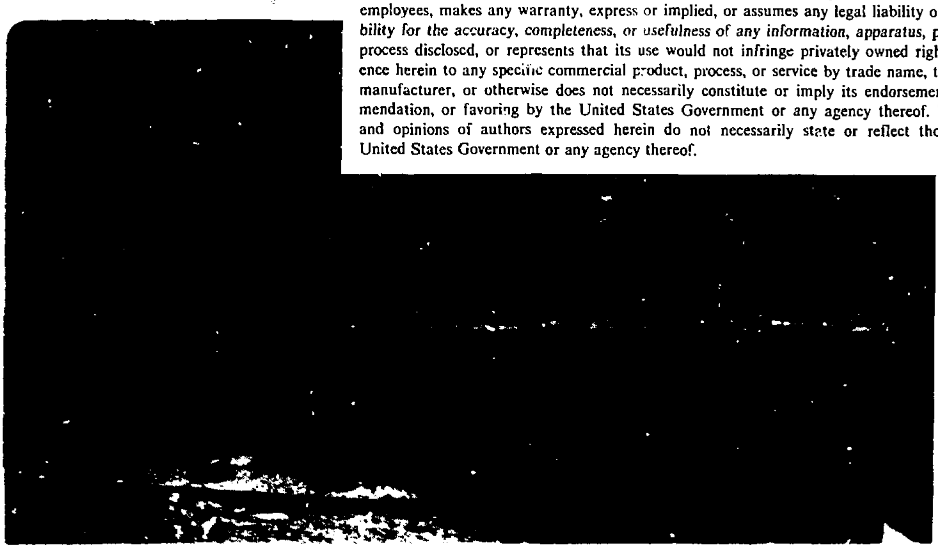
Presented at the Conference on Inner Space/Outer Space,
Fermi National Accelerator Laboratory,
Batavia, IL, May 2-5, 1984

NEW MEASUREMENTS OF THE SPECTRUM OF THE COSMIC MICROWAVE BACKGROUND

MASTER

J.B. Peterson, P.L. Richards, J.L. Bonomo,
and T. Timusk

June 1984



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

NEW MEASUREMENTS OF THE SPECTRUM OF THE COSMIC MICROWAVE BACKGROUND

J.B. Peterson, P.L. Richards, and J.L. Bonomo

Department of Physics
University of California
Berkeley, California 94720

and

T. Timusk

Department of Physics, McMaster University
Hamilton, Ontario, Canada L8S 4M1

Accurate measurements of the spectrum of the cosmic microwave background (CMB) can provide useful tests of cosmological theories. The data set existing in 1982 has been summarized on a number of occasions[1-3] and is shown in Fig. 1. To first approximation the CMB is characterized by a single temperature and thus has a blackbody spectrum over the frequency range from 0.02 to 24 cm^{-1}. The error limits given for these experiments are dominated by systematic errors and are often very subjective. Consequently, it is not clear how to analyze the data set in a valid way. The general impression, however, is of a scatter in the high frequency data that is somewhat larger than would be expected from the given error limits.

The infrared experiment of Woody and Richards[4] produced data over a significant spectral range as is shown in Fig. 2. When these data are tested for agreement with a best-fit blackbody curve, the fit is rather poor. If we make the doubtful assumption that the errors are statistical, there is only a 0.3 percent chance that the data are consistent with a 2.90 K blackbody. There is an excess of flux near the peak.

Deviations from the Planck curve are expected at some level, and their observation is of the highest importance for the refinement of cosmological models. Compton scattering of the CMB by hot electrons, radiation damping of turbulence, and the annihilation of residual anti-matter are some of the mechanisms which could lead to deviations from a blackbody spectrum.[5] 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.[4]

Models of the CMB which do not involve establishing complete thermodynamic equilibrium or which utilize frequency-dependent emission processes, are relatively unconstrained and can be made to fit the 1982 data set. Rowan-Robinson, Negroponte and Silk[6] have carried out calculations using the red-shifted dust features from a pre-galactic generation of stars to increase the CMB in the 3 to 8 cm^{-1} frequency range relative to that on either side of this range. They obtained a satisfactory fit to at least one plausible weighted average of the observations by this theory.

The fact that a fit can be obtained should not be interpreted as theoretical evidence for the suggested deviation. The question of the existence of a deviation must be answered experimentally.

New Microwave and Optical Experiments

An international collaboration involving groups from Berkeley and Haverford in the U.S.A. and Bologna, Milano, and Padova in Italy began in 1982 to carry out new microwave measurements of the CMB from White Mountain, California. The results announced thus far are generally consistent with previous microwave measurements and the error estimates are relatively small.[7] These results are plotted in Fig. 3. A group at U.C.L.A. has used measurements of the relative strengths of optical transitions[8] to deduce new values for the excitation temperature of cyanogen in the molecular cloud ζ Oph. Their results, shown in Fig. 3, give upper limits for the temperature of the CMB at two frequencies.

New Berkeley Infrared Experiment

We have designed a new apparatus to measure the spectrum of the CMB in the frequency range from 3 to 10 cm^{-1}. This range includes the peak of the measured spectrum and more than 80 percent of flux in the CMB. The new experiment is based on the balloon gondola of Woody and Richards. To avoid the possibility of repeating undetected systematic errors in that experiment, however, the new experiment has been changed in most important respects.

Although there is no specific reason to expect that the spectroscopy of the Woody-Richards experiment introduced significant errors, the Fourier transform spectrometer used by them has been replaced by a filter wheel with five band-pass filters. The fabrication of these filters and the measured filter bands have been described elsewhere.[9] Two of the filter bands lie below the peak of the CMB spectrum, one is at the peak and two lie above it. Although the change to filter spectroscopy permits us to do a relatively independent experiment, it introduces several potential problems. Resonant filters of the type used are subject to leakage at higher order resonant frequencies. Stray radiation from hot sources within the apparatus is somewhat more likely to be chopped in a filter-spectrometer than to be interference modulated in a Fourier spectrometer. Great care has been exercised in the design of the new experiment to avoid these difficulties.

Emission from the atmosphere is greatly reduced but not eliminated by measuring from balloon altitudes. In the Woody-Richards experiment, a 512 point spectrum of the sky emission was measured and compared with a theoretical calculation based on a simple atmospheric model and experimental parameters. The fit of the model spectrum to the measured sky spectrum was excellent in the frequency range beyond 12 cm^{-1} where they could be accurately compared. Below 12 cm^{-1} the atmospheric emission predicted from the model was a small fraction of the measured flux. Therefore, the model spectrum almost certainly provided an adequate correction for atmospheric emission in the frequency range where deviations from the blackbody curve were seen.

In the new experiment a detailed sky spectrum will not be available. The filter bands have been selected so as to minimize atmospheric emission. The amount of this emission has been estimated from the model to be negligible in the two lowest frequency bands and to be comparable to the CMB at the highest frequency. The contribution of the atmospheric emission to the measurement is evaluated by measuring the flux in each filter band as a function of the angle of the apparatus from the zenith.

One interesting feature of the Woody-Richards experiment is the fact that arbitrarily reducing the overall calibration factor by 30 percent brings the data into excellent agreement with a blackbody curve at the temperature of 2.77 K given by plausible averages of the microwave data.[4] If this change is made, then all of the data in

Fig. 1 are consistent with a single blackbody temperature. Although no reason for such a large error in calibration factor has been found, the suspicion has arisen that the calibration factor might have been different in flight from the value measured in the laboratory.[10]

Great care must be taken in the calibration of any new infrared measurement of the spectrum of the CMB. The ideal location for the calibrator is outside of the apparatus and filling the entire beam. Although a low temperature calibrator in this location is possible on satellite experiments, it is very difficult to provide in the balloon environment. Radiation from warm objects must be prevented from reflecting or scattering from the calibrator surface and entering the throughput of the photometer. The ambient pressure air must be prevented from freezing on the cold calibrator surface. If a window is used for this purpose, then reflections from it cause additional problems.

These considerations have led us to employ a variable temperature blackbody inside of our cryostat which can be used to calibrate the instrument during the flight. In principle this calibrator removes the effects of unwanted signals which arise from locations between the calibrator and the detector. Care must then be used to avoid signals which could arise between the calibrator and the sky.

Experimental Apparatus

The liquid helium cooled spectrophotometer used by Woody and Richards has been redesigned to include the features discussed in the preceding section. The entrance to the apparatus is surrounded by a large earthshine shield. The beam enters the top-looking cryostat through a removable window and an apodizing horn. The beam on the sky is defined by a long Winston[11] light concentrator. These portions of the apparatus were used previously and are described fully elsewhere.[4] Fig. 4 shows the lower portion of the apparatus which is enclosed in a copper box that is kept filled with superfluid liquid helium throughout the flight. A combination of a shortened Winston concentrator and a lens is used to collimate the beam arriving from the sky. This collimated beam is then shifted to the left by reflection from two diagonal mirrors. The beam is then refocused by a lens-and-cone combination onto a glass low-pass filter, an oscillating chopper, a filter wheel with five band-pass filters, and a ^{3}He-temperature composite bolometric detector. The filters[9] and the detector[12] have been described fully elsewhere. The chopper and the filters, along with their drive mechanisms, are immersed in superfluid helium and are carefully baffled with absorber to minimize the possibility that radiation from the warm upper parts of the cryostat can be chopped and reach the detector.

A portion of the apparatus including the lens and the first diagonal mirror rotates by 180° around a horizontal axis so that the detector can look either up to the sky, as is shown in Fig. 4, or down into a reference blackbody. The throughput to the calibrator is determined by the lens and a back-to-back pair of Winston concentrators. The dimensions of these concentrators are matched as closely as possible to the pair of back-to-back concentrators leading to the sky. The lowest concentrator has been truncated so as to permit the installation of a conical black absorbing surface.

The calibration system also includes two designs of variable temperature laboratory calibrator which can be inserted into the upper Winston concentrator. The purpose of these laboratory calibrators is to measure any asymmetry in the throughput or transmission between the sky and the internal cold calibrator.

Calibration

The first step in the calibration of our apparatus is carried out in the laboratory by measuring the detector signal as a function of the temperature of the internal flight calibrator and of the two laboratory calibrators which are placed in the throat of the Winston cone antenna. These two laboratory calibrators provide the primary calibration standard. Comparisons between the signals from them confirm that their design is adequate. A full description of the design and testing of these calibrators will be published elsewhere. The flight calibrator is used as a transfer standard. Signals from it differ by 2 percent from those coming from the laboratory calibrators. This up-down asymmetry is ascribed to the machining tolerances of the apertures which define the throughput up and down, and is assumed to be the same during flight as in the laboratory.

As a test of our understanding of the performance of the apparatus, we have plotted in Fig. 5 the measured signal as a function of the signal calculated from the blackbody temperature, the filter function, and the Planck spectrum. The data fit a straight line to ~1%. This experiment can be interpreted as the most accurate test ever made of the Planck function.

The intercept in Fig. 5 is very close to zero, indicating very little leakage of warm radiation. Some previous measurements of the CMB have had large values of this intercept.[13] The danger then exists that the leakage radiation causing the intercept will be different in flight from the value determined in the laboratory.

Except for the measurement of the small up-down asymmetry mentioned above, the calibration of our instrument is carried out in flight. Signals from the sky are compared to signals from the flight calibrator which is maintained at 3.1 K. Tests are made for spurious radiation from the upper part of the antenna by heating it in flight.

Tests for earthshine are made by measuring the sky signal as a function of zenith angle close to the horizon and comparing it with the sec θ dependence expected from a horizontally stratified atmosphere.

New Infrared Measurement

Our apparatus was successfully flown from the National Scientific Balloon Launch Facility in Palestine, Texas on November 16, 1984. The data were telemetered to the ground and recorded on magnetic tape. The gondola was recovered undamaged.

The first step in data analysis was the removal of glitches caused by cosmic rays hitting the bolometer. The noise in the deglitched data wa comparable to that seen in the laboratory. The calibration was very stable in time.

Data for each frequency channel were plotted as a function of air mass. Such data were measured both at fixed zenith angle as the balloon approached float altitude, and also by varying the zenith angle while the balloon was at (approximately) constant altitude. Because of extreme uncertainty about the anticipated duration of the flight, the scenario used was not optimum. The dominant error in these data occurred as a result of changes in the atmospheric ozone during the flight. These changes can be modeled and corrected to some extent. A better procedure, which is permitted by the high sensitivity of the apparatus, is to make all measurements for one channel in a short time.

At present, the focus of the data analysis is on estimating the importance of systematic errors These estimates are nearly complete and will produce a set of new measurements of the spectrum of the CMB which will be more accurate than the Woody-Richards result.[4] Preliminary results of this flight are available for the two lowest frequency bands centered at 3 and 5 cm^{-1}. The measured temperatures of 2.80 ± 0.2 and 2.95 ± 0.15 K are shown as boxes in Fig. 3. It is anticipated that results for all five bands will be available during 1984. A reflight of the apparatus in late 1984 should lead to further improvements in the data.

Acknowledgments

This work was begun with support from the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098, and has been completed with support from the Office of Space Sciences of the National Aeronautics and Space Administration, and by the Natural Sciences and Engineering Research Council of Canada.

References

1. P.L. Richards, Phys. Scripta 21, 610 (1980).
2. P.L. Richards and D.P. Woody, IAU Symposium 92, Objects at High Redshifts, G. Abell and J. Peebles, eds.(Dordrecht, 1980) p. 283.
3. P.L. Richards, Phil. Trans. R. Soc. Lond. A307, 77 (1982).
4. D.P. Woody and P.L. Richards, Ap J. 248, 18 (1981).
5. Ya.B. Zel'dovich, A.F. Illarionov, and R.A. Sunyaev, Zh. Eksp. Theor. Fiz. 62, 1217 (1972) [English transl. in Soviet Phys.-JETP 35, 643 (1972)].
6. M. Rowan-Robinson, J. Negroponte, and J. Silk, Nature 281, 635 (1979).
7. G. Smoot et al. Phys. Rev. Lett. 51, 1099 (1983), and private communication.
8. D.M. Meyer and M. Jura, Astrophys. J. Lett. 276, L1-L3 (1984).
9. T.T. Timusk and P.L. Richards, Appl. Opt. 20, 1355 (1980).
10. R. Weiss, A. Rev. Astr. Astrophys. 18, 489 (1980).
11. R. Winston, J. Opt. Soc. Am. 60, 245 (1970).
12. N.S. Nishioka, P.L. Richards, and D.P. Woody, Appl. Opt. 17, 1562 (1978).
13. H.P. Gush, preprint.

Figure Captions

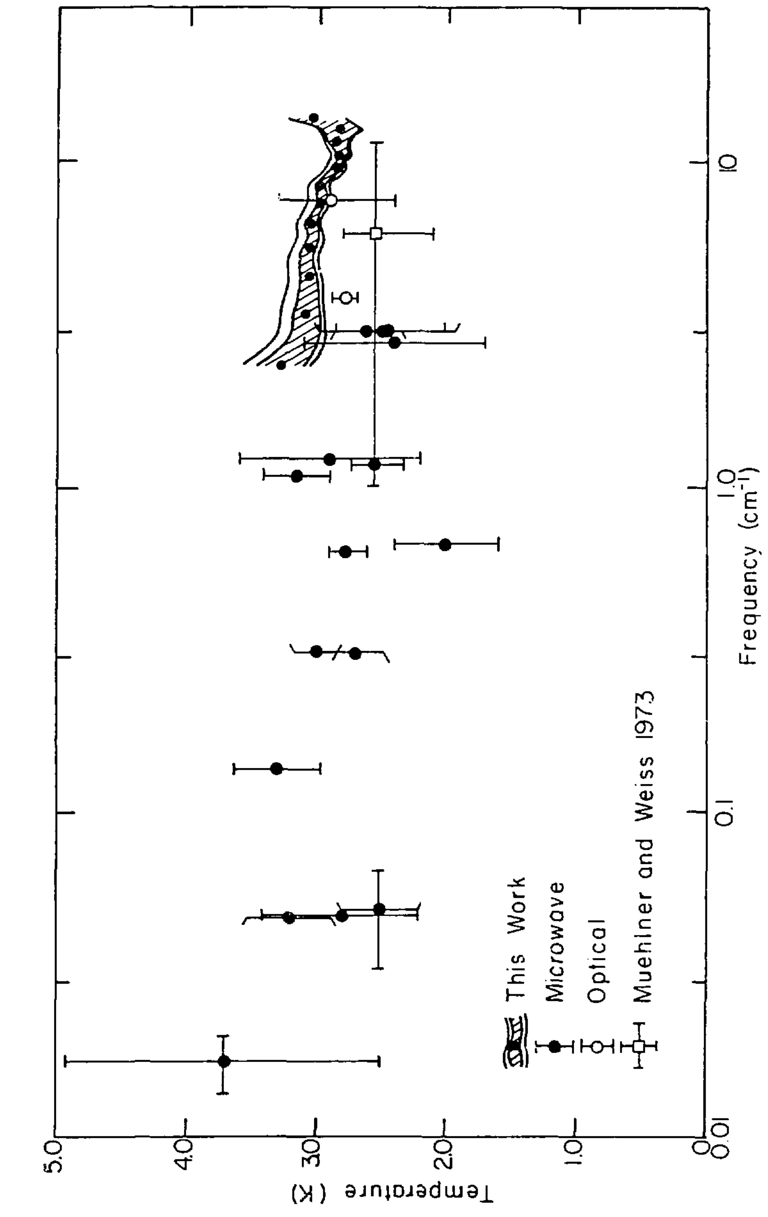
Fig. 1. Measurements of the CMB temperature available before 1982.

Fig. 2. CMB spectral flux measured by Woody and Richards compared with microwave and optical results available at that time.

Fig. 3. Recent microwave, optical and infrared measurements of the CMB temperature. The boxes, whose width represents the spectral band, are preliminary results of the new Berkeley experiment described here.

Fig. 4. Apparatus used for the new Berkeley balloon experiment.

Fig. 5. Comparison of the measured signal from the blackbody calibrator operated at various temperatures with the signal computed from the temperature, the filter transmittance and the Planck law.



XBL 805-5107

FIGURE 1

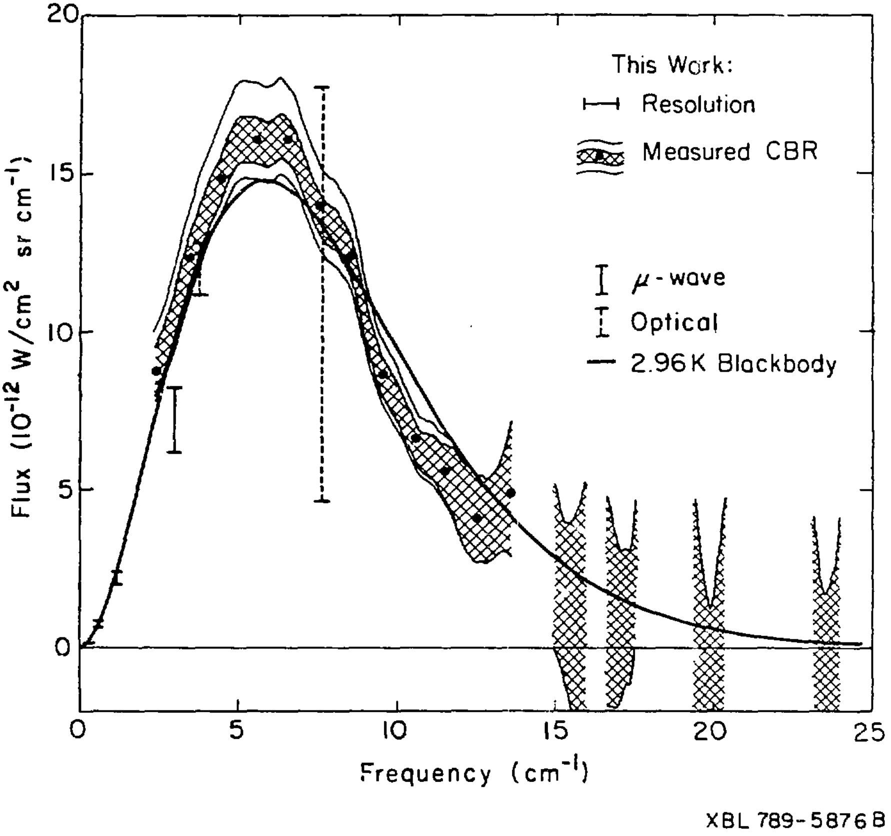
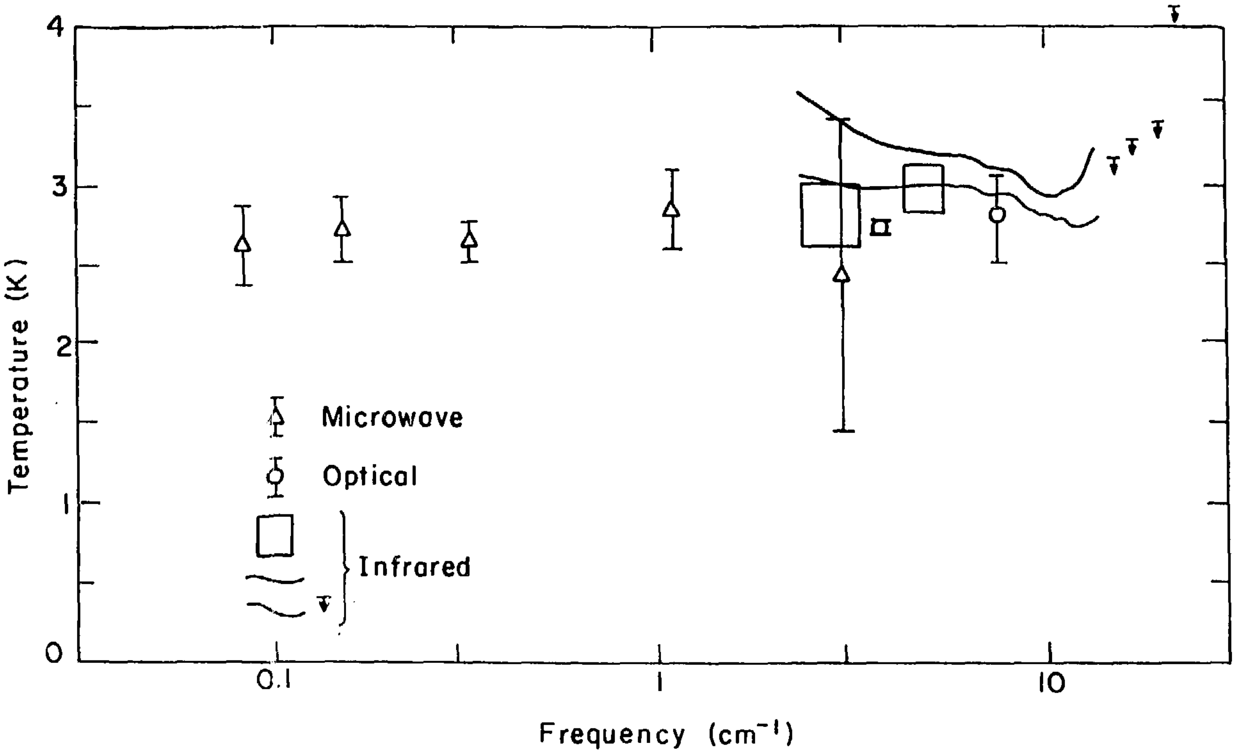
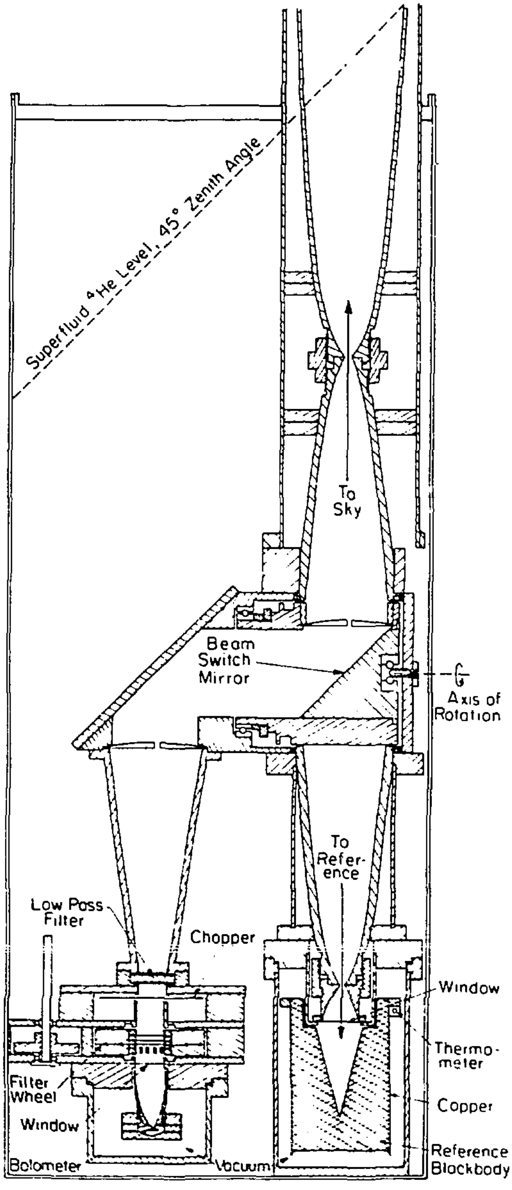

This Work:
Resolution
Measured CBR
μ-wave
Optical
2.96K Blackbody
Flux (10^{-12} W/cm^2 sr cm^{-1})
Frequency (cm^{-1})
0
5
10
15
20
25
XBL 789-5876 B

FIGURE 2



XBL 842-6620A

FIGURE 3



XBL 8110-6653C

FIGURE 4

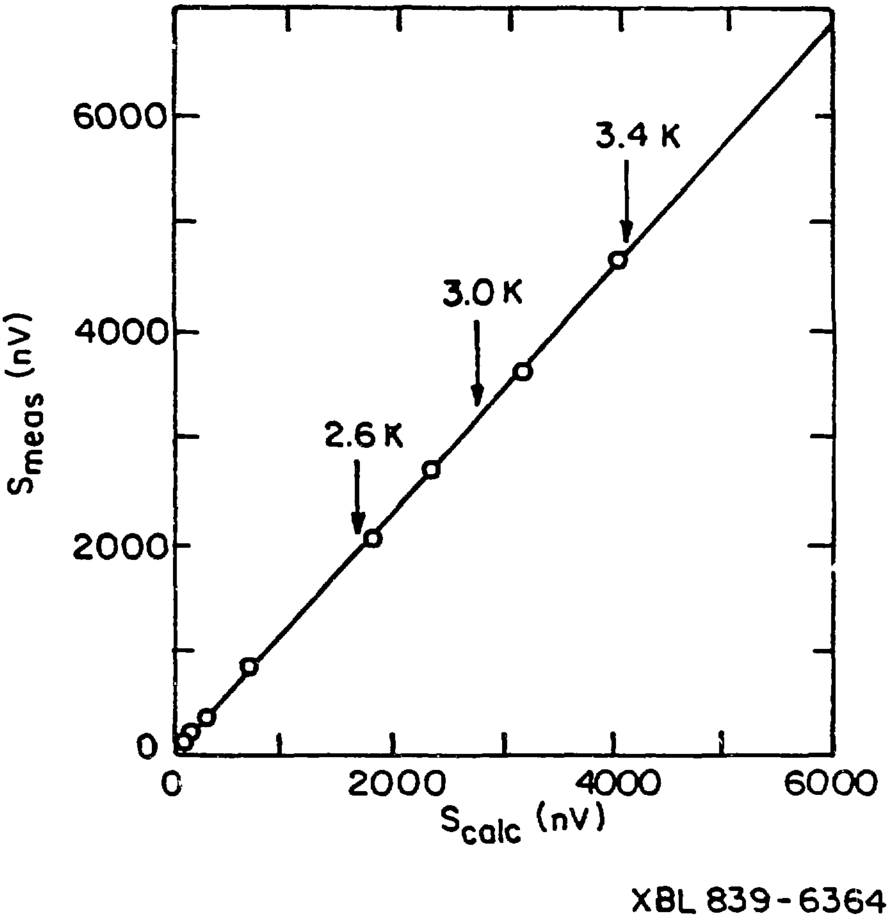

6000
4000
2000
0
S_{meas} (nV)
3.4 K
3.0 K
2.6 K
0
2000
4000
6000
S_{calc} (nV)
XBL 839-6364

FIGURE 5