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Physics Division

Submitted to The Astrophysical Journal,
Letters to the Editor

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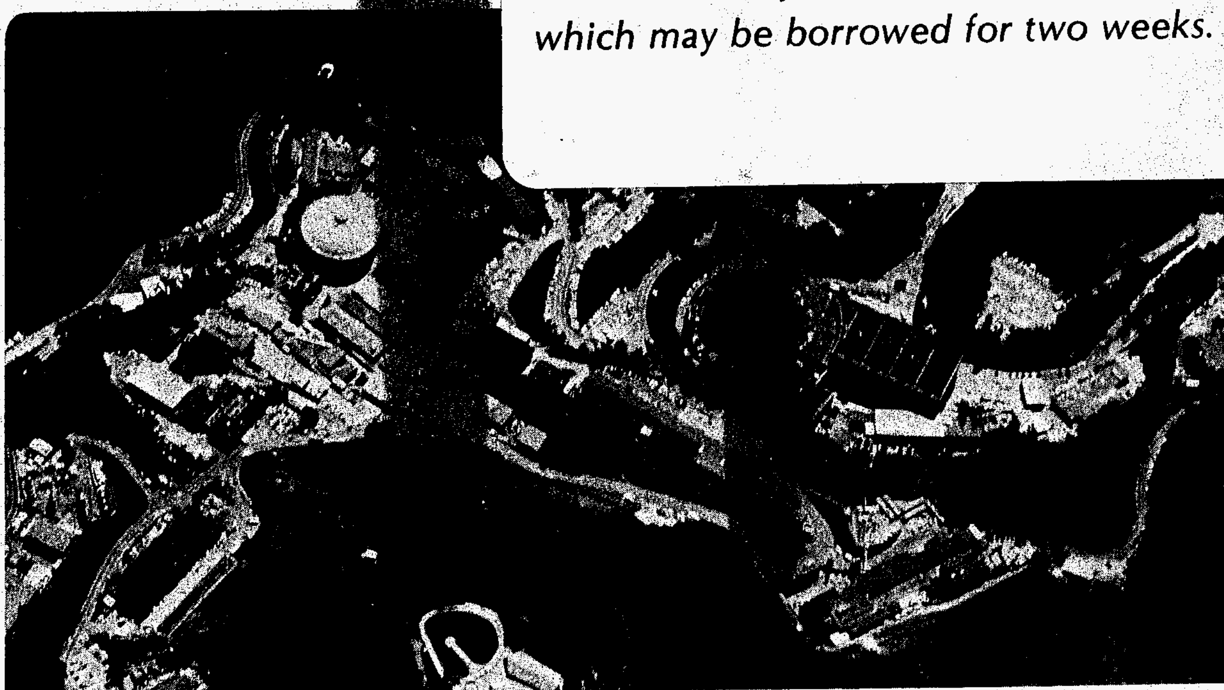
November 1984



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

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Received 1984 Nov 5; Accepted 1984 YYY yy

ABSTRACT

The long-wavelength spectrum of the cosmic background radiation has been measured at five wavelengths (0.33, 0.9, 3.0, 6.3, and 12.0 cm). These measurements represent a continuation of the work reported by Smoot *et al.* (1983). The combined results have a weighted average of 2.73 ± 0.05 K and are consistent with past measurements. They limit the possible Compton distortion of the Cosmic Background Radiation spectrum to less than 8%.

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

I. INTRODUCTION

Measurements of the Cosmic Background Radiation (CBR) are among the few observations that can provide information about the early universe. In particular, the spectrum of the CBR contains information about the energy-releasing processes in the early universe, since energy release would have distorted the CBR spectrum from its initial blackbody distribution through Compton scattering (Illarionov and Sunyaev 1975, Danese and De Zotti 1977, 1978, and 1982). The existence of spectral distortions would have important implications for cosmological theories.

Realizing that a significant (≈15%) distortion could have gone undetected, we began a program to remeasure the low-frequency spectrum of the CBR. Preliminary results have been reported by Smoot *et al.* (1983). This paper presents the results of a new set of observations which continue our previous work.

II. CONCEPTS AND REQUIREMENTS OF THE MEASUREMENT

The intensity of the CBR is measured at each of five wavelengths by a radiometer, a device whose output voltage is proportional to the power intercepted by its antenna. Each radiometer is calibrated in units of antenna temperature per voltage output.

The antenna temperature T_A is proportional to the input power P according to the relation

$$P = kT_A B \tag{1}$$

and is related to the thermodynamic temperature T of a blackbody source covering the antenna aperture by

$$T_A = \frac{x}{(e^x - 1)} T, \tag{2}$$

where $x = h\nu/kT$, h is Planck's constant, ν is frequency, k is Boltzmann's constant, and B is the radiometer bandwidth. At low frequencies ($x << 1$) the antenna temperature is nearly equal to the thermodynamic temperature.

Each measurement compares the antenna temperature of the zenith with that of an absolute-reference blackbody load of known temperature. The zenith temperature can be expressed as

$$T_{A,zenith} = T_{A,load} + G(V_{zenith} - V_{load}), \tag{3}$$

where V_{zenith} and V_{load} are the output voltages produced when the radiometer views the zenith and reference load respectively, and G is the gain calibration of the radiometer. We use a liquid-helium-cooled reference load because having nearly equal reference-load and zenith antenna temperatures minimizes the effect of gain-calibration errors on the measured zenith temperature.

Radiation reaching a radiometer pointing at the zenith comes from a number of sources; we can approximate $T_{A,zenith}$ as the sum:

$$T_{A,zenith} = T_{A,CBR} + T_{galaxy} + T_{ground} + T_{atmosphere.} \tag{4}$$

where $T_{A,CBR}$ is the antenna temperature of the cosmic background radiation, T_{galaxy} is the antenna temperature of radiation from the galaxy (due to synchrotron emission and thermal emission from H II regions), T_{ground} is the terrestrial thermal radiation intercepted by the antenna sidelobes, and $T_{atmosphere}$ is the vertical antenna temperature of the atmosphere less a small term (< 40 mK) resulting from the attenuation of the incoming CBR. (This is the quantity physically measured in zenith scans.) Subtraction of these sources from $T_{A,zenith}$ leaves the antenna temperature of the cosmic background radiation as the residual.

We have designed the experiment to minimize the extraneous sources of radiation entering the receivers. Some sources, such as the atmosphere and the galaxy, could not be reduced to negligible levels by equipment design. Instead, we have measured them with the same radiometers used to measure $T_{A,zenith}$ in order to minimize the effects of gain calibration errors. The atmospheric emission is determined by correlating the radiometer output with the amount of atmosphere observed at different angles from the zenith. Galactic emission is measured from drift scans we made at the longer wavelengths.

III. DESIGN OF EXPERIMENT AND MODIFICATIONS FROM 1982 WORK

a) Radiometers, mirrors, and ground screens

The five radiometers used to measure $T_{A,CBR}$ operate at 12.0-cm, 6.3-cm, 3.0-cm, 0.91-cm, and 0.33-cm wavelength. A sixth radiometer monitors atmospheric emission at 3.2-cm wavelength. All are superheterodyne receivers operated with Dicke switching, and all have low-sidelobe, corrugated horn antennas as inputs. Each radiometer is described in previous papers (Sironi *et al.* 1984; Mandolesi *et al.* 1984, Partridge *et al.* 1984; Friedman *et al.* 1984; and De Amici *et al.* 1984).

Since the July 1982 measurements, each of the radiometers has been modified to improve the quality of the CBR measurement and the ease of operation. The Dicke reference on the 12-cm wavelength radiometer, previously an antenna pointed at the north celestial pole, was replaced by a liquid nitrogen load. In addition, the radiometer mount was modified to allow atmospheric zenith-angle scans in any direction. The configuration of the 6.3-cm radiometer was modified to resemble that of the 3-cm radiometer in order to minimize the up-versus-down instrument offset and to permit rapid zenith-angle scans and zenith/cold-load measurements. The 3-cm radiometer was stiffened and the mirror and ground shields were extended to allow atmospheric scans to larger zenith angles. The 0.91-cm radiometer was improved with stiffer and flatter mirrors and more accurate pointing capability for zenith-angle scans. The configuration of the 0.33-cm radiometer was changed to provide a 60-degree opening angle between the two antennas, so that atmospheric zenith-angle scans could be made without mirrors. The zenith angles observed by the atmospheric monitor were decreased somewhat in order to reduce the signal contamination by ground radiation at the larger zenith angles. The ground shields on all the radiometers were improved to reduce the extraneous thermal radiation and RF interference entering the sidelobes of the antennas.

b) Absolute Reference Cold Load

The absolute reference cold load is an ambient-pressure liquid-helium-cooled target viewed through a large (0.7-m) open-mouth dewar covered by two windows of 23-micron-thick polyethylene film. The cold load has been described previously (Smoot *et al.* 1983) and has not been significantly modified. The pressure in the cold load was 487.5 ± 2.0 mm Hg, which corresponds to a liquid helium boiling temperature of 3.776 ± 0.004 K (Brickwedde *et al.*). Two Lakeshore Cryotronics sensors mounted in the target gave readings of 3.773 ± 0.020 K and 3.795 ± 0.020 K. We calculate the emission from the absolute reference cold load for each wavelength by converting this target temperature to antenna temperature and adding the emission from the windows and walls and the radiometer as reflected by the cold load (Table 1). The reflection coefficient of the load is small, typically 10^{-3} or less. The antennas of all radiometers except the 12-cm one have much smaller diameters than the mouth of the cold load, and hence viewed the cold load by essentially free propagation. The antenna of the 12-cm radiometer has the same diameter as the cold load mouth; consequently the interfacing and alignment of the antenna and cold load were more critical, and the walls and interface contributed additional power. In 1983, this extra source of antenna temperature was measured in each run (see Table 1).

Wavelength (cm)	Eccosorb	Windows and Gas	Walls	Reflection	Total Load
12.0	3716 ± 4	4 ± 2	1209 ± 210	70 ± 25	4999 ± 212
			1458 ± 120	340 ± 50	5518 ± 130
6.3	3663 ± 4	5 ± 2	8 ± 7	40 ± 30	3716 ± 31
				6 ± 4	3682 ± 10
3.0	3541 ± 4	5 ± 2	9 ± 5	7 ± 4	3562 ± 10
0.91	3039 ± 4	4 ± 2	5 ± 5	20 ± 6	3068 ± 9
0.33	2020 ± 4	18 ± 3	10 ± 10	35 ± 35	2083 ± 37

Table 1: Sources of emission from cold load expressed as antenna temperature in milliKelvin. The Eccosorb physical temperature is 3.776 ± 0.004 K. When there are two rows at a wavelength, the top row is for 1982 data and the bottom for 1983.

c) Observing site

Observations from the high (3800 m), dry (≤ 3 mm H_2O) site of the University of California White Mountain Research Station reduced atmospheric emission by approximately a factor of three compared to sea level. Its remote location reduced man-made RF interference to acceptably low levels.

d) Layout and Operations

The radiometers were mounted on carts and positioned on a 20-m length of rails. Each cart in turn was rolled into position above the reference cold load and each radiometer then made a rapid series of measurements viewing the cold load and the sky both toward the zenith and at various angles from the zenith. The 3.2-cm (9.4-GHz) radiometer (Partridge *et al.* 1984), located 10 meters south of the rail system, made an automated measurement of the atmospheric emission every 8 minutes. The zenith angles used in the 1983 atmospheric scans were 0°, 32.5°, 44°, 51°, and 55°, values chosen to give roughly equal steps in the quantity $(\sec z - 1)$. These measurements provided an important cross-check on the atmospheric observations made by the radiometers used to measure the CBR, and allowed us to monitor the behavior of the atmosphere on an ongoing basis.

IV. OBSERVATIONS AND DATA REDUCTION

Observations were made on the nights of 5 and 6 July 1982 and 4, 5, and 6 September 1983 UT with liquid helium in the cold load. Observations with liquid nitrogen in the cold load were made on 4 and 7 July 1982, and on 30 August and 1,2, and 7 September 1983 for practice and to crosscheck radiometer performance. The 1983 results are consistent with the 1982 results already reported (Smoot *et al.* 1983; De Amici *et al.* 1984; Friedman *et al.* 1984; Mandolesi *et al.* 1984; Sironi *et al.* 1984), but have smaller errors, particularly at 0.33-cm.

The measurements for both years are listed in Table 2. There are two rows for each

Wavelength (cm)	$T_{A,Load}$	$G(V_{zenith} - V_{load})$	ΔT_{offset}	T_{ground}	$T_{atmosphere}$	T_{galaxy}
12.0	4999 ± 212	-1401 ± 100	$* \pm *$	12 ± 10	950 ± 50	148 ± 30
	5518 ± 130	-1557 ± 58	$* \pm *$	6 ± 10	950 ± 50	200 ± 30
6.3	3716 ± 31	940 ± 80	960 ± 160	30 ± 10	1000 ± 100	40 ± 30
	3682 ± 10	-45 ± 13	0 ± 20	20 ± 20	997 ± 70	35 ± 25
3.2				30 ± 10	1030 ± 70	$< 30 \pm 10$
				8 ± 5	1050 ± 70	$< 10 \pm 5$
3.0	3562 ± 10	57 ± 4	0 ± 40	0 ± 3	930 ± 160	3 ± 3
		43 ± 7	0 ± 30	0 ± 3	1200 ± 130	4 ± 2
0.91	3068 ± 9	3780 ± 40	-100 ± 50	1 ± 1	4850 ± 140	1 ± 1
		3520 ± 30	-30 ± 30	1 ± 1	4530 ± 90	1 ± 1
0.33	2083 ± 37	11340 ± 60	0 ± 300	1 ± 1	12600 ± 590	0 ± 1
		8780 ± 60	10 ± 9	1 ± 1	9870 ± 90	0 ± 1

* Included in $T_{A,load}$

Table 2: Representative measurements and calculated/estimated values expressed as antenna temperatures in milliKelvin. The top row is for 1982 values, the bottom for 1983 values.

wavelength: the top row is for 1982, the bottom for 1983. The values in each column of the table are averaged over all the data for the year. Some values, especially for atmospheric and galactic emission, vary from observation to observation; mean values are shown. The errors represent the uncertainties of the yearly means. Estimates of systematic uncertainties are combined in quadrature with statistical errors.

V. SOURCES OF RADIATION AND SYSTEMATIC ERRORS

The galactic background is minimized by observations at high galactic latitudes and is estimated by scans and modeling. Values of T_{galaxy} are based upon measurements from the 12-cm and 6.3-cm radiometers and published data (e.g. Haslam et al, 1982). The data from the 12-cm, 6.3-cm, and 3.2-cm radiometers are in good agreement with the published data and simple frequency-scaling relations.

Limits on ground emission are estimated by numerical integration of the measured antenna beam patterns and verified by tests to determine the effect of additional shields. We looked for coherent RF interference using the radiometers and also using a spectrum analyzer. The only RF interference found was observed with the 3.2-cm radiometer two days before the liquid-helium runs in 1982.

Flip offsets, that is changes in radiometer output depending upon the direction of observation, are an important problem. They directly affect the measurement of the temperature difference between the zenith and the reference cold load because the radiometer must be moved during the measurement. The corrections and uncertainties due to flip offsets caused by rotation from observing the cold load to the zenith are listed in Table 2 in the column labeled ΔT_{offset}. Flip offsets can also cause errors in the measurement of atmospheric emission; these errors are included in the column $T_{atmosphere}$. The 12-cm, 6.3-cm, and 3-cm radiometers had to be rotated to measure the atmospheric emission, as did the 0.33-cm radiometer in 1983. The other radiometers accomplished their zenith-angle scans with moveable mirrors.

Atmospheric emission is the largest background source in the experiment. For that reason we have attempted to measure the atmospheric emission very accurately. The radiometers were modified to improve their pointing accuracy during zenith-angle scans and to permit them to scan more quickly. In addition, we changed our procedures to permit scans at multiple angles. Special effort was made to obtain a large number of atmospheric measurements and to make some simultaneously at all six wavelengths. These improvements gave us more accurate data with more cross-checks than in 1982. We were also fortunate that less water vapor was present during the September 1983 measurements than during those of July 1982, so the total atmospheric emission and variability were reduced. In determining the vertical atmospheric emission we have included terms for the self-attenuation of the atmosphere, its curvature, and convolution of atmospheric emission with the antenna beam pattern. These corrections are most significant at 0.33 and 0.91 cm.

The results for the 3.2-cm atmospheric monitor were corrected to account for radiation diffracted into the antenna by the top edge of the ground screens, as described by Partridge *et al.* (1984). Additional corrections were made for the non-linear gain of the radiometer, spill-over past the edge of the elliptical reflector, angle-dependent emission by the reflector, and emission from our Galaxy (Haslam *et al.* 1982; Witebsky, 1978). $T_{atmosphere}$ was calculated from temperatures measured at the various zenith angles, with greater weight given to the measurements at the larger zenith angles.

Measured values of $T_{atmosphere}$ at 3.2 cm varied between 0.85 K and 1.30 K, with 1.05 as a typical value. This value is consistent with our 1982 results, though slightly higher (probably because of a 1982 over-correction for diffraction of ground radiation). On the other hand, the 1983 value is $\sim$ 0.05 K smaller than expected from an atmospheric model consistent with our measurements at longer wavelengths (Danese *et al.* 1984).

VI. RESULTS, COMPARISON TO PREVIOUS MEASUREMENTS AND INTERPRETATION

The measured antenna and thermodynamic CBR temperatures are listed in Table 3. Some 1982 values differ slightly from those previously published (Smoot *et al.* 1983) because of further analysis. The final column in Table 3 gives the combined results of our two-year program. The values are the weighted averages of the 1982 and 1983 results. In the case of the 3.0 cm measurements, we were able to improve the accuracy of $T_{atmosphere}$ as follows. First, we extrapolated the independent measurements at 3.2 cm to 3.0 cm using our atmospheric model (an extrapolation of $\approx$ 30 mK). Then these values were averaged with the measurements at 3.0 cm, resulting in improved estimates of the atmospheric temperature and T_{CBR} and thus reducing their associated errors.

Our final results are shown in Figure 1 along with other published measurements (see the review by Weiss,1980; Meyer and Jura 1984). The results of this experiment agree well with previous measurements. The weighted average of our combined measurements is 2.73 ± 0.05 K, compared with 2.74 ± 0.09 K for the previous data. Our data and the data of Meyer and Jura (1984) are in conflict with those of Woody and Richards (1979). With the exception of the Woody and Richards data all of the measurements fit a Planckian spectrum of temperature 2.73 ± 0.04K with a Chi-squared of 9 for 22 degrees of freedom.

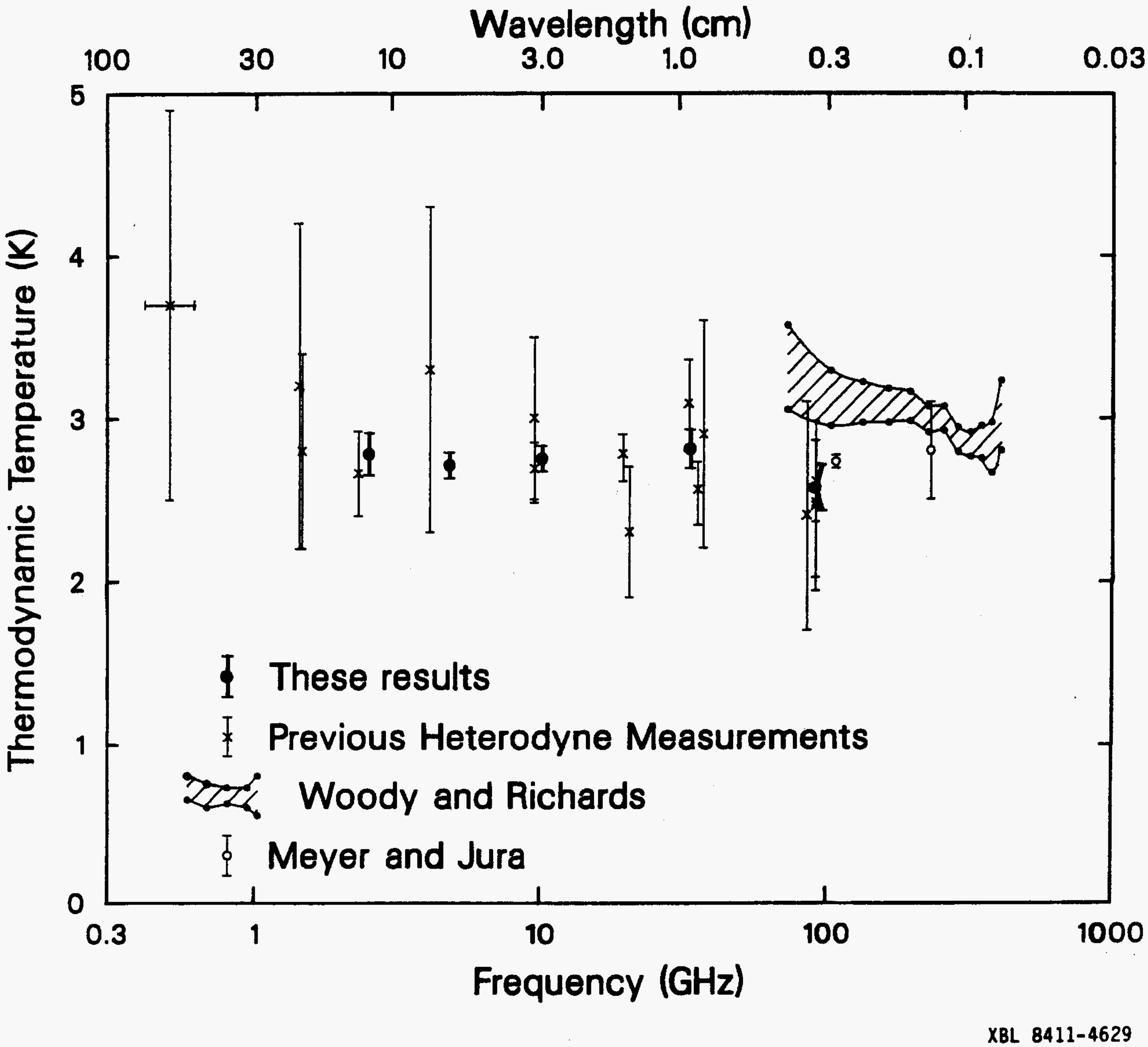

Figure 1: Plot of the present results together with previous measurements of the thermodynamic temperature of the cosmic background radiation.

Wavelength (cm)	Number of Observations	$T_{A,CBR}$	T_{CBR} Thermodynamic	Combined Results
12.0	6	2.49 ± 0.24	2.55 ± 0.24	
	18	2.82 ± 0.15	2.88 ± 0.16	2.78 ± 0.13
6.3	5	2.64 ± 0.21	2.74 ± 0.22	
	38	2.60 ± 0.08	2.71 ± 0.08	2.71 ± 0.08
3.0	82	2.68 ± 0.17	2.91 ± 0.17	
	59	2.41 ± 0.14	2.64 ± 0.14	2.75 ± 0.08
0.91	21	2.10 ± 0.20	2.82 ± 0.21	
	32	2.09 ± 0.13	2.81 ± 0.14	2.81 ± 0.12
0.33	29	0.86 ± 0.70	2.42 ± 1.00	
	49	0.99 ± 0.11	2.57 ± 0.14	2.57 ± 0.14

Table 3: Results of our measurements of the CBR expressed in Kelvins.

Our data alone, as well as with all the measurements in the Rayleigh-Jeans region, are consistent with a blackbody spectrum. If we fit the data to a blackbody spectrum plus a small Bose-Einstein distortion, we find our data separately and combined with previous results are inconsistent with any distortion characterized by a chemical potential larger than 10^{-2}. Such a distortion would deviate from blackbody spectrum by less than 8% in the most extreme model (Danese and De Zotti, 1982).

Acknowledgements: We thank the staff of the White Mountain Research Station and Alan Benner, Paulo Calzolari, Hank Donnelly, Hal Dougherty, John Gibson, Nancy Gusack, Steve Levin, Enrico Mattaini, Faye Mitschang, Ellen Rubinstein, and Emilio Santambrogio for their assistance.

This research was supported by National Science Foundation Grants No. PHY80-15694 and AST 800737, by the Department of Energy under Contract DE-AC03-76SF00098, and by Consiglio Nazionale delle Ricerche Fellowships No. 203.2.13 and 203.2.15, by Italian Ministero Della Pubblica Istruzione, and by NATO Grant 1871.

REFERENCES

Brickwedde, F. G., van Dijk, H., Durieux, M., Clement, J. R., and Logan, J. K. 1960, *Journal of Research of the National Bureau of Standards*, **64A**, 1.

De Amici, G., Witebsky, C., Smoot, G., and Friedman, S. 1984, *Phys. Rev. D* **29**, 2673.

Danese, L. and De Zotti G. 1977, *Riv. Nuovo Cimento* **7**, 277.

Danese, L. and De Zotti G. 1978, *Astron. Astrophys.* **68**, 157.

Danese, L. and De Zotti G. 1982, *Astron. Astrophys.* **107**, 39.

Danese, L. and Partridge, R. B. 1984, in preparation.

Friedman, S. D., Smoot, G. F., De Amici, G., and Witebsky, C. 1984, *Phys. Rev. D* **29**, 2677.

Haslam, C. G. T., Salter, C. J., Stoffel, H., and Wilson, W. E. 1982, *Astron. Astrophys. Supp. Series* **47**, 1.

Illarionov, A. F. and Sunyaev, R. A. 1975, *Sov Astron* **18**, 691.

Mandolesi, N., *et al.* 1984, *Phys. Rev. D* **29**, 2680.

Meyer, D. M. and Jura, M. 1984, Ap. J. Lett. **276**, L1.

Partridge, R. B., *et al.* 1984, *Phys. Rev. D* **29**, 2683.

Sironi, G., *et al.* 1984, *Phys. Rev. D* **29**, 2686.

Smoot, G. F., *et al.* 1983, *Phys. Rev. Lett.* **51**, 1099.

Weiss R. 1980, *Annual Rev. Astron. Astropys.* **18**, 489.

Witebsky, C. 1978, *COBE Report No.* 5013, unpublished.

Woody, D. P., and Richards, P. L. 1979, *Phys. Rev. Lett.* **42**, 925.

Woody, D. P., and Richards, P. L. 1981, *Ap. J.* **248**, 18.

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