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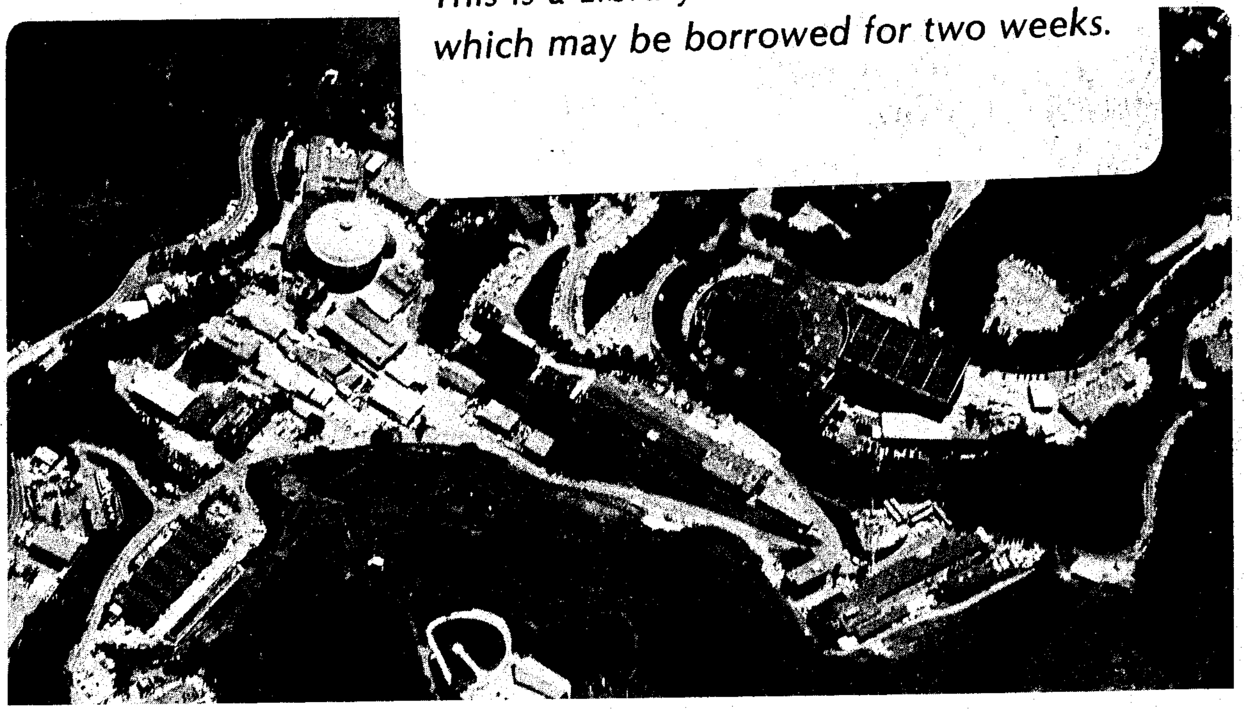

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LONG-WAVELENGTH MEASUREMENTS
OF THE COSMIC MICROWAVE BACKGROUND RADIATION SPECTRUM

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ABSTRACT

We have measured the temperature of the cosmic microwave background radiation at wavelengths of 0.33, 3.0, 8.2 and 21.3 cm. These measurements represent a continuation of the work reported by Smoot *et al.* (1985). The new results have a weighted average of 2.70 ± 0.05 K and are consistent with past measurements. They limit the possible distortion of the cosmic microwave background radiation spectrum to less than 6%. The results of all measurements to date are consistent with a Planckian spectrum with temperature 2.74 ± 0.02 K spanning a wavelength range of 0.1 to 21 cm.

Subject heading: cosmic microwave background radiation

I. INTRODUCTION

Precise measurements of the cosmic microwave background radiation (CMBR) spectrum may be the most powerful probe of the history of the universe in the period before galaxies and clusters of galaxies formed. In particular, the spectrum of the CMBR contains information about the energy-releasing processes in the early universe, since energy release would have distorted the CMBR spectrum from its initial blackbody distribution through Compton scattering and free-free emission (Danese and De Zotti 1977, 1978, and 1982). There are potentially a number of cosmologically revealing spectral distortions, some of which are very likely while others are highly speculative.

Recognizing that the previous long-wavelength measurements, all made in the late 1960's, were not very precise, an international collaboration (Smoot *et al.* 1986) conducted a program in the early 1980's to measure the long wavelength CMBR spectrum. This paper reports upon further progress we have made extending the work of the collaboration.

II. CONCEPTS, BACKGROUNDS, AND SYSTEMATIC ERRORS

The intensity of the CMBR is measured at each of four wavelengths by a radiometer, a device whose output is proportional to the power intercepted by its antenna. Each radiometer is calibrated in units of antenna temperature, T_A, which is proportional to the input power P and is related to the thermodynamic temperature T of a blackbody source covering the antenna aperture according to the formula

$$T_A = \frac{P}{kB} = \frac{T_\nu}{(e^{T_\nu/T} - 1)}, \tag{1}$$

where $T_\nu = h\nu/k$, h is Planck's constant, ν is frequency, k is Boltzmann's constant, and B is the radiometer bandwidth.

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

$$T_{A,zenith} = T_{A,load} + G(S_{zenith} - S_{load}), \tag{2}$$

where S_{zenith} and S_{load} are the output signals produced when the radiometer views the zenith and reference load respectively, and G is the calibration constant to convert the radiometer output signal to antenna temperature. We use a liquid-helium-cooled reference load since nearly equal reference-load and zenith antenna temperatures minimize the effect of calibration errors on the measured zenith temperature.

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 radiometer design includes stiffening members and other features to keep these effects at a low level. We also do special tests to measure the signal change from moving the radiometer. The corrections and uncertainties due to these changes from observing the cold load to the zenith are listed in Table 2 in the column labeled ΔT_{offset}.

Radiation reaching a zenith-pointing radiometer comes from a number of sources; neglecting (for this discussion but not in the data analysis) the small attenuation of incoming radiation by the atmosphere, $T_{A,zenith}$ is approximately:

$$T_{A,zenith} = T_{A,CMBR} + T_{galaxy} + T_{ground} + T_{atmosphere} \tag{3}$$

where $T_{A,CMBR}$ is the antenna temperature of the cosmic microwave 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. Subtraction of these sources from $T_{A,zenith}$ leaves the antenna temperature of the cosmic microwave 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. Atmospheric emission is the largest background source in the experiment. For that reason we have attempted to measure it very accurately. Atmospheric emission is determined by correlating the radiometer output with the air mass observed at different angles from the zenith. The radiometers were constructed to have good pointing accuracy during zenith-angle scans and to scan quickly at multiple zenith angles. Effort has been made to obtain a large number of atmospheric measurements with some made simultaneously to the CMBR observations. In determining the zenith 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. We have also included the effects and uncertainties of radiometer output change due to movement for those radiometers which were moved in the measurement of atmospheric emission.

The galactic background is minimized by avoiding the galactic plane and is estimated by scans and modeling. Values of T_{galaxy} are based upon measurements from the 21-cm, 12-cm, 8-cm, and 6.3-cm radiometers and published data (e.g. Haslam *et al.*, 1982). The data from the 21-cm, 12-cm, 8-cm, and 6.3-cm radiometers are in good agreement with the published data and empirical frequency-scaling relations ($\nu^{-2.75}$). The corrections were 0.7 and 0.07 K for the 21-cm and 8-cm results respectively.

Limits on ground emission and RF interference 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.

III. DESIGN OF EXPERIMENT AND MODIFICATIONS FROM PREVIOUS WORK

The 3-cm and 0.3-cm wavelength radiometers are described in previous papers (Friedman, *et al.* 1984; Smoot *et al.* 1986; and Witebsky *et al.* 1986). The primary change in the 3-cm radiometer since 1984 is the improvement in the ground screens.

Wavelength (cm)	Eccosorb	Windows and Gas	Walls	Reflection Power	Reflection Amplitude	Total Load
21.3	3748 ± 4	3 ± 2	19 ± 19	30 ± 30	0 ± 600	3800 ± 600
8.2	3695 ± 4	3 ± 2	7 ± 6	30 ± 15	0 ± 55	3737 ± 57
3.0	3547 ± 4	5 ± 2	9 ± 5	7 ± 4	0 ± 10	3568 ± 10
0.33	2024 ± 4	18 ± 3	10 ± 10	35 ± 35	0 ± 20	2087 ± 37

Table 1: Sources of emission from cold load expressed as antenna temperature in milliKelvin. The Eccosorb physical temperature is 3.782 ± 0.004 K.

Two new radiometers operating at 21-cm and 8-cm wavelengths made their first measurements during this phase of the experiment. Both of these are direct RF-gain total power radiometers. They have single corrugated-horn antennas for low sidelobes and were alternately pointed at the zenith, cold load, and an ambient temperature load. The 21-cm corrugated-horn antenna described elsewhere (Witebsky *et al.* 1987) is a large (2 m long by 1.5 m wide) rectangular horn with corrugations in the E-plane walls only. It is separable with only a smaller section viewing the cold load and ambient temperature calibrator. The antenna used in the 8-cm wavelength radiometer was loaned to us and is described by Mandolesi *et al.* (1986).

The absolute reference cold load is an ambient-pressure liquid-helium-cooled target in a large (0.7-m diameter) 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 489 ± 2 mm Hg, (slightly higher than previous years), which corresponds to a liquid helium boiling temperature of 3.782 ± 0.004 K. We calculate the emission from the absolute reference cold load by converting this target temperature to antenna temperature and adding the emission from the windows and walls and the radiation broadcast by the radiometer and reflected by the cold load. The reflection coefficient of the cold load is very small, typically 10^{-3} or less, and the power from the radiometers is generally small, typically 20 to 100 K, so that the reflected power is small. These effects are summarized in Table 1.

In our effort to make a radiometer tunable from 2 to 8 GHz we discovered that the reflection effects were worse than expected from a simple power reflection. The 2-8 GHz radiometer emitted a power of about 260 K, since we did not have an isolator or ferrite switch with sufficiently broad bandwidth. As a result the signal broadcast to the absolute reference cold load was produced mainly by the first amplifier instead of being produced mainly by the sky and the isolator/switch. We believe that the effect we were seeing was the result of the radiometer broadcast power interfering with itself in a coherent way, so that the effect of reflection did not depend upon the power reflection coefficient but upon amplitude reflection coefficients and effective isolation. If the power reflection coefficient is 10^{-4}, the amplitude reflection coefficient will be 10^{-2}. For coherent reflection effects one must take into account the reflection phases as well as amplitudes. This makes the effect more difficult to measure and estimate as it depends also upon the distance between the reflection and the point where the reflected signal recombines coherently and upon the effective radiometer bandwidth.

We have estimated the coherent reflection effect based upon our measurements of relevant parameters and included it in the next to last column of Table 1. The 90 GHz radiometer, due to a large bandwidth (2 GHz), has a characteristic coherence length of 15 cm, so its only important amplitude reflections originate near the end of the antennas. We have measured the effect directly in combination with the power reflection and limited the total of reflection effects to less than 35 mK. In this case we estimate that the amplitude effects are less than 20 mK and that the power reflected from the windows is slightly larger than this. For the other radiometers we could only estimate upper limits for this effect as we did not have a relatively straightforward way to vary the effect directly with sufficient accuracy. The 21-cm radiometer, besides its long wavelength, narrow bandwidth (25 MHz), and the coupling to the cold load, has in addition the coupling of the separable antenna parts. The relevant quantity is the change in signal caused by the difference between the two couplings.

IV. OBSERVATIONS AND DATA REDUCTION

Observations were made from the high (3800 m), dry (< 0.5 cm H_2O) site of the University of California White Mountain Research Station. This site reduced atmospheric emission by approximately a factor of three compared to sea level. Observations with liquid helium in the cold load were made on the nights of 5 and 6 July 1982; 4, 5, and 6 September 1983; 24 and 25 August 1984; and 8 and 9 August 1986 UT. Observations with liquid nitrogen in the cold load were made on 4 and 7 July 1982; on 30 August and 1, 2, and 7 September 1983; 17, 18, and 23 August 1984; and 6 and 7 August 1986 UT for practice and to crosscheck radiometer performance. The results from all the measurements prior to 1986 have been reported elsewhere (see for example Smoot *et al.* 1986, Partridge *et al.* 1985).

Typical values for the various years are listed in Table 2. Some values, especially those of atmospheric and galactic emission, vary from observation to observation; mean values are shown. The errors represent 68% confidence level uncertainties. Estimates of systematic uncertainties are added in quadrature with the statistical error.

The 3.0-cm result for 1982 has been reanalyzed in light of recent atmospheric measurements. The zenith - load difference at 3.0 cm consists largely of a constant CMBR term and a variable atmospheric term. The difference measured in 1982 is comparable to that measured in later years and correlates well with the atmosphere as measured at 0.33 cm. The measured 1982 3.0-cm atmospheric temperature of 0.93 ± 0.16 K is anomalously low and does not correlate with results from other radiometers and other years (Table 2). Based on our correlation of the 3.0-cm and 0.33-cm atmospheric results over the full four years at White Mountain, we believe that the atmospheric temperature in 1982 was 1.19 ± 0.11 K. This change, and the addition of another year's data, have decreased our estimate of T_{CBR} at 3.0 cm by more than the previously estimated error.

V. RESULTS, COMPARISON TO OTHER MEASUREMENTS AND INTERPRETATION

The measured CMBR thermodynamic temperatures are listed in Table 3 and shown in Figure 1 along with other recently published measurements . The results of this experiment agree well with previous measurements (Weiss 1980). The weighted average of our measurements is 2.70 ± 0.05 K, compared with 2.74 ± 0.09 K for the previous data. The weighted average of all recent data (Table 3) is 2.743 ± 0.017 with a Chi-squared of 22 for 17 degrees of freedom. Our data alone or with all the Rayleigh-Jeans measurements and other recent data are consistent with a blackbody spectrum. If we fit all the recent data to a blackbody spectrum plus a small Compton distortion, we find that our data and all the data are inconsistent with any distortion characterized by a chemical potential larger than 10^{-2} or a Comptonization parameter larger than 10^{-2}. Such a distortion would deviate from blackbody spectrum by less than 6% in the most extreme model (Danese and De Zotti 1982) over the wavelength range 0.2 to 20 cm.

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Wavelength (cm)	Year	$T_{A,Load}$	$G(S_{zenith} -S_{load})$	ΔT_{offset}	T_{ground}	$T_{atmosphere}$	T_{galaxy}
21.3	1986	3800 ± 600	-60 ± 30	± 90	9 ± 8	850 ± 50	707 ± 150
12.0	1982	4999 ± 212	-1401 ± 100	$* \pm *$	12 ± 10	950 ± 50	148 ± 30
	1983	5518 ± 130	-1557 ± 58	$* \pm *$	6 ± 10	950 ± 50	200 ± 30
8.2	1986	3735 ± 57	-314 ± 16	-35 ± 20	30 ± 7	860 ± 122	66 ± 30
6.3	1982	3716 ± 31	940 ± 80	960 ± 160	30 ± 10	1000 ± 100	40 ± 30
	1983	3682 ± 10	-45 ± 13	0 ± 20	20 ± 20	997 ± 70	35 ± 25
3.2	1982				30 ± 10	1030 ± 70	$< 30 \pm 10$
	1983				8 ± 5	1050 ± 70	$< 10 \pm 5$
3.0	1982	3562 ± 10	61 ± 5	0 ± 40	0 ± 3	1190 ± 110	3 ± 3
	1983		43 ± 7	0 ± 30	0 ± 3	1200 ± 130	4 ± 2
	1984		-17 ± 8	0 ± 30	0 ± 3	1122 ± 120	4 ± 2
	1986	3568 ± 10	-13 ± 47	6 ± 17	0 ± 3	1222 ± 65	8 ± 4
0.91	1982	3068 ± 9	3780 ± 40	-100 ± 50	1 ± 1	4850 ± 140	1 ± 1
	1983		3520 ± 30	-30 ± 30	1 ± 1	4530 ± 90	1 ± 1
	1984		3330 ± 30	-30 ± 30	1 ± 1	4340 ± 90	1 ± 1
0.33	1982	2083 ± 37	11520 ± 60	0 ± 50	1 ± 1	12600 ± 570	0 ± 1
	1983		8780 ± 40	10 ± 9	12 ± 15	9870 ± 90	0 ± 1
	1984		10220 ± 50	13 ± 5	12 ± 15	11300 ± 130	0 ± 1
	1986	2087 ± 37	14010 ± 50	-8 ± 4	12 ± 15	15020 ± 100	0 ± 1

Table 2: Representative measurements and calculated/estimated values expressed as antenna temperatures in milliKelvin.

References	Wavelength (cm)	ν (GHz)	T_{CBR} (K)
Sironi *et al.* 1986	50.0	0.6	2.45 ± 0.7
Levin (Smoot *et al.* 1987)	21.2	1.41	2.2 ± 0.6
Sironi (Smoot *et al.* 1985*b*)	12.0	2.5	2.78 ± 0.13
De Amici (Smoot *et al.* 1987)	8.2	3.66	2.59 ± 0.14
Mandolesi *et al.* 1986	6.3	4.75	2.70 ± 0.07
Kogut (Smoot *et al.* 1987)	3.0	10.0	2.60 ± 0.06
Johnson and Wilkinson 1986	1.2	24.8	2.783 ± 0.025
De Amici (Smoot *et al.* 1985*b*)	0.909	33.0	2.81 ± 0.12
Bersanelli (Smoot *et al.* 1987)	0.333	90.0	2.60 ± 0.10
Meyer & Jura 1985	0.264	113.6	2.70 ± 0.04
Meyer & Jura 1985	0.132	227.3	2.76 ± 0.20
Crane *et al.* 1986	0.264	113.6	2.74 ± 0.05
Crane *et al.* 1986	0.132	227.3	$2.75^{+0.24}_{-0.29}$
Peterson, Richards, & Timusk 1985	0.351	85.5	2.80 ± 0.16
	0.198	151	$2.95^{+0.11}_{-0.12}$
	0.148	203	2.92 ± 0.10
	0.114	264	$2.65^{+0.09}_{-0.10}$
	0.100	299	$2.55^{+0.14}_{-0.18}$

Table 3: Recent Measurements of the Cosmic Background Radiation Temperature

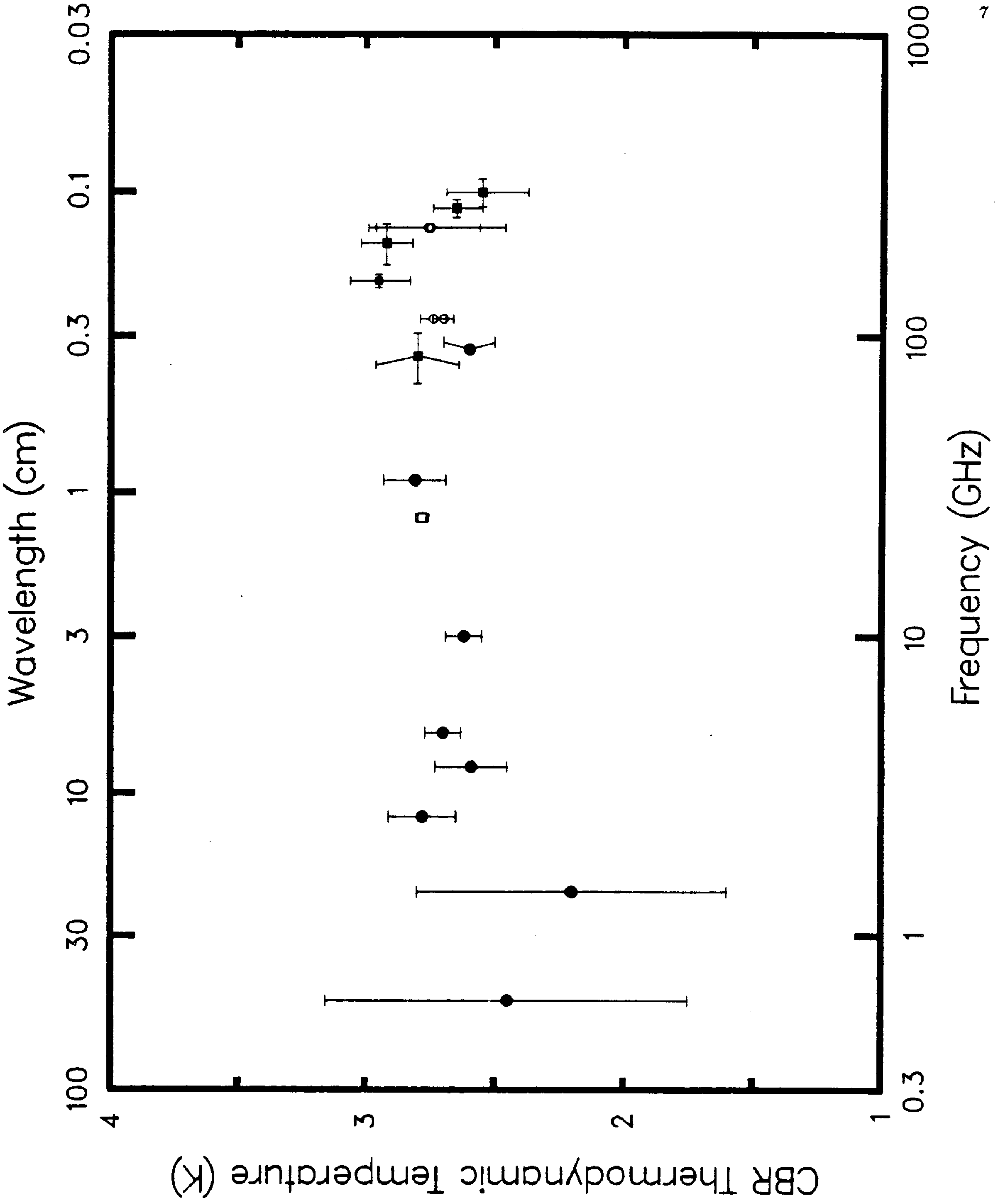

Figure 1: Plot of the these and other recent measurements of the thermodynamic temperature of the cosmic microwave background radiation.

loan of their corrugated horn antenna. This research was supported in part by National Science Foundation Grant No. AST 8406187, by the Department of Energy under Contract DE-AC03-76SF00098. M. Bersanelli thanks ISTRA (Istituto Studi per la Transizione) Milano and Fondazione A. Gini of Padova for fellowship support.

REFERENCES

Crane, P., Heygi, D. J., Mandolesi, N., and Danks, A. C. 1986, *Ap. J.*, **309**, 822.
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.
De Amici, G., Witebsky, C., Smoot, G. F., and Friedman, S. D. 1984, *Phys. Rev. D*, **29**, 2673.
De Amici, G., Smoot, G. F., Friedman, S. D., and Witebsky, C. 1985, *Ap. J.*, **298**, 710.
Friedman, S. D., Smoot, G. F., De Amici, G., and Witebsky, C. 1984, *Phys. Rev. D*, **29**, 2677.
Johnson, D.G., and Wilkinson, D.T., 1986, *Ap J. Lett.* **320?**, L1–L3.
Mandolesi, N., Calzolari, P., Cortiglioni, S., and Morigi, G. 1984, *Phys. Rev. D*, **29**, 2680.
Mandolesi, N., Calzolari, P., Cortiglioni, S., Morigi, G., Danese, L., and De Zotti, G. 1986, *Ap. J.* **310**, 561.
Mather, J.C. 1982, *Optical Eng.*, **21**, 769.
Meyer, D.M., and Jura, M. 1984, *Ap J. Lett.* **276**, L1–L3.
Meyer, D.M., and Jura, M. 1985, *Ap J.*, **297**, 119.
Partridge, R. B., *et al.* 1984, *Phys. Rev. D*, **29**, 2683.
Partridge, R. B., *et al.* 1985, *Societa Italiana di Fisica* Conference Proceedings, **1**, 7.
Peterson, J.B., Richards P.L., and Timusk T. 1985, *Phys Rev Lett.*, **55**, 332.
Silk, J. and Stebbins, A., 1983, *Ap J.*, **269**, 1.
Sironi, G., Inzani, P., and Ferrari, A. *Phys. Rev. D*, 1984, **29**, 2686.
Sironi, G., *et al.* 1987, *13th Texas Symposium on Relativistic Astrophysics*, ??, ?.
Smoot, G. *et al.* 1983, *Phys. Rev. Lett.*, **51**, 1099.
Smoot, G. *et al.* 1985*a*, *Ap. J. Lett.*, **291**, L23–L27.
Smoot, G. *et al.* 1985*b*, *Societa Italiana di Fisica* Conference Proceedings, **1**, 27.
Smoot, G. *et al.* 1986, *Highlights of Astronomy*, Reidel IAU Conference Proceedings, **7**, 297-305.
Weiss R., Annual Rev. Astron. Astropys. 18, 489 (1980)
Witebsky, C., Smoot, G. F., De Amici, G., and Friedman, S. D., 1986, *Ap J.*, **310**, 1.
Witebsky, C., Smoot, G. F., Levin, S., and Bensadoun, M., 1987, *submitted to IEEE Antennas and Propagation*, ??, ?.