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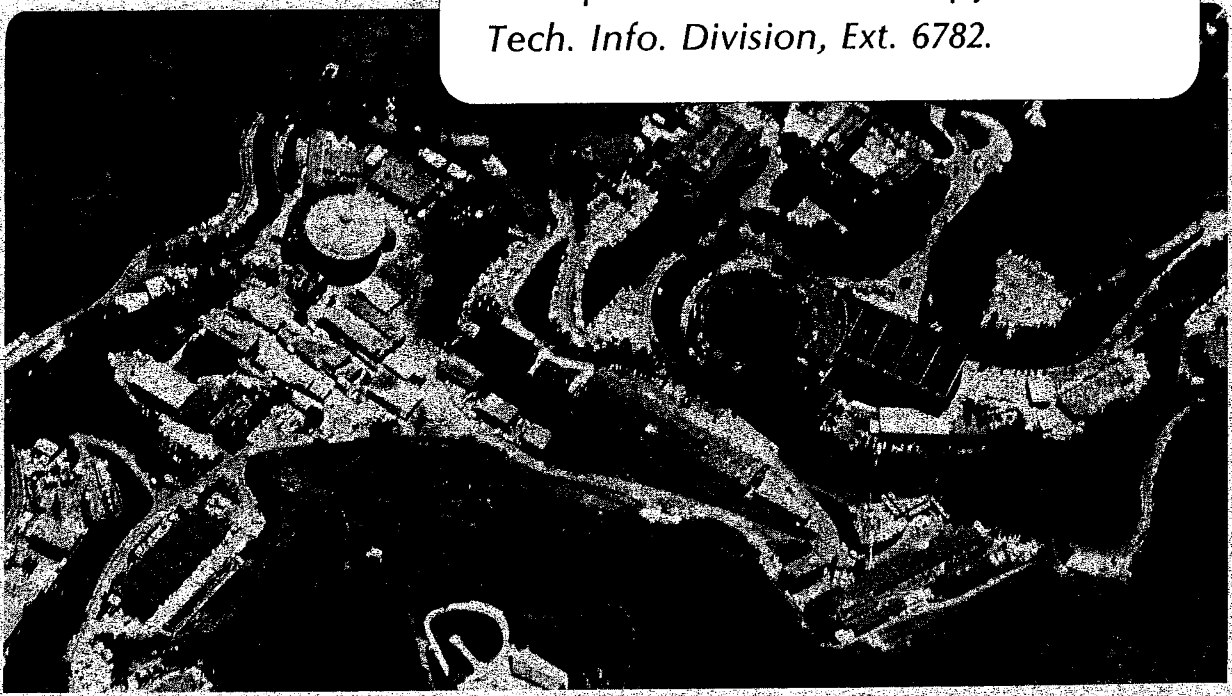

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MEASUREMENTS OF THE COSMIC BACKGROUND RADIATION TEMPERATURE AT 3.3 AND 9.1 MM

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Abstract - We report the results of measurements of the cosmic background radiation temperature at wavelengths of 9.1 and 3.3 mm. The 9.1 mm result, $T_{CBR} = 2.87 \pm 0.21$ K, is in good agreement with previous results and those obtained at longer wavelengths during the same experiment. The 3.3 mm result, $T_{CBR} = 2.4 \pm 1.0$ K, is consistent with previous measurements, but has a large error due to uncertainty in the atmospheric correction.

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All previous ground-based measurements of the cosmic background radiation (CBR) temperature date from at least twelve years ago[1]. Advances in microwave components now permit a more precise determination of the CBR spectrum, which contains important information about the events and processes in the early universe[2].

We measured the temperature of the CBR at wavelengths of 3.3 and 9.1 mm (90 and 33 GHz, respectively) on 5 and 6 July 1982 U.T. at White Mountain, California (altitude 3800 meters) as part of a systematic program to obtain accurate, consistent measurements of the CBR temperature at five wavelengths (0.33, 0.91, 3.0, 6.3 and 12 cm). A companion paper[3] provides an overview of the project and discusses the results.

We determine the temperature of the CBR according to the formula:

$$T_{A,CBR} = (T_{ZENITH} - T_{CL}) + T_{CL} - T_{ATM} \qquad (1)$$

by comparing the sky directly overhead with a liquid-helium-cooled load whose antenna temperature[4] is known to high accuracy. Each radiometer performs the comparison directly, using two antennas pointed in opposite directions. One antenna views the cold load below while the other observes the zenith above in order to measure the difference in their antenna temperatures. We add the antenna temperature of the cold load to the measured temperature difference to obtain the antenna temperature of the sky at the zenith, T_{ZENITH}.

The important components of T_{ZENITH} are the CBR antenna temperature $T_{A,CBR}$ and the atmosphere's contribution to the zenith temperature, T_{ATM}. T_{ATM}, which is large and variable due to water-vapor fluctuations, was determined by measuring the change in the sky's antenna temperature with zenith angle (and hence with atmospheric column density) and then fitting to an atmospheric model[5].

T_{ZENITH} also contains contributions from astronomical objects (the Sun, Moon, and galactic sources), and from any emissive object in the sidelobes of the antenna. Low-sidelobe antennas and careful shielding reduce the sidelobe contributions to a negligible level. The Sun and Moon do not contribute significantly for measurements made at night with the Moon more than 15 degrees from the antenna beam axis. Galactic emission can be neglected at these wavelengths.

Figure 1 shows a schematic diagram of the 9.1 mm radiometer. The 3.3 mm system is smaller, but similar in all important characteristics. The corrugated-horn antennas used in the two radiometers are geometrically scaled versions of one another. The two oppositely directed antennas (7.5^{o} HPBW) provide inputs to a Dicke superheterodyne radiometer, switched at 100 Hz. The instrument produces an output voltage proportional to the two-second average of the difference in antenna temperature between the objects viewed by the two antennas. The antennas and the receiver are rigidly mounted and temperature controlled to provide mechanical and thermal stability. Operating characteristics are shown in Table I.

Each radiometer is mounted on bearings which allow the antennas to point either vertically or horizontally. The vertical orientation is used to measure the temperature difference between the sky and the cold load. The horizontal orientation, used for measurements of the atmosphere, directs the antenna beams at two flat reflectors made of foamed plastic panels faced with aluminum sheet. They pivot to redirect the beams upward at specified zenith angles.

The microwave absorber in the cold load has a physical temperature of 3.77 ± 0.01 K (the corresponding antenna temperatures are 2.01 ± 0.01 K at 3.3 mm and 3.03 ± 0.01 K at 9.1 mm). The cold load has cylindrical aluminum walls and two thin (18 micron) polyethylene windows over the top. The walls and windows add 0.10 ± 0.04 K at 3.3 mm and 0.06 ± 0.03 K at 9.1 mm, so the antenna temperature T_{CL} of the cold load is 2.11 ± 0.04 K at 3.3 mm and 3.09 ± 0.03 K at 9.1 mm.

Each radiometer also uses an ambient-temperature blackbody load for gain calibrations. These loads are made of ferrite-loaded plastic, cast into an array of cones and embedded in foam insulation. They have a reflection coefficient less than 2×10^{-3}.

The sequence of measurements used to determine $T_{A,CBR}$ lasted 4 minutes with the 3.3 mm radiometer and 5 minutes with the 9.1 mm radiometer. The sequences were repeated for runs of 40 to 60 minutes, twice per night. Each sequence evaluated three quantities: 1) the temperature difference between the zenith and the cold load, 2) the temperature difference between the ambient-temperature load and the cold load (to calibrate the radiometer gain), and 3) the temperature difference between the zenith and the sky at one or more zenith angles (to measure the atmospheric contribution). Offsets in the radiometers were measured by interchanging the loads viewed by each antenna. The radiometer output, calibrator temperatures, and system housekeeping data were recorded on magnetic cassette tape and by hand.

Each sequence is analyzed individually, using Equation (1). Radiometer output voltages are averaged over each measurement and constant offsets are removed. The radiometer gain is calculated from measurements of the cold and ambient loads. A 7 ± 1 % correction is made for gain saturation in the 9.1 mm radiometer; no correction is needed for the 3.3 mm radiometer. The temperature difference ($T_{ZENITH} - T_{CL}$) is determined from the sky/cold-load measurements and the measured gain.

The atmospheric model used to compute T_{ATM} from measurements at different zenith angles is approximately a secant law but also includes the effects of atmospheric self-absorption, curvature, and antenna beamwidth (the difference between the model and a pure secant law is 90 mK at 9.1 mm and 330 mK at 3.3 mm). We also correct for the variation in the emissivity of the aluminum reflectors with the angle of incidence (up to 130 mK).

Typical results of our atmospheric measurements are:

$$T_{ATM} = 5.00 \pm 0.14 \text{ K} \quad \text{at} \quad 9.1 \text{ mm}$$

$$T_{ATM} = 12.3 \pm 0.8 \text{ K} \quad \text{at} \quad 3.3 \text{ mm}$$

where the quoted errors are the uncertainties in the values from an individual measurement sequence. The 9.1 mm value is larger than our theoretical estimate based on measurements at other wavelengths[5], but still in marginal agreement with it. It falls between the values previously obtained at the same location in the 9 mm range (4.62 K, Ewing et al.[6] ; 6.6 K, Wilkinson[7]). Our 3.3 mm atmospheric measurement is in good agreement with previous ones.

Statistical errors are caused by radiometer noise and by fluctuations in the radiometric temperature of the atmosphere. The RMS variation in $T_{A,CBR}$ is approximately 130 mK at 9.1 mm and 250 mK at 3.3 mm. Radiometer noise causes a 40 to 50 mK uncertainty; the rest is due to atmospheric fluctuations (Figure 2).

Systematic errors come from uncertainties in the correction terms [Table II]. The most important one results from uncertainties in the zenith angles used in atmospheric measurements, due to antenna misalignment or inaccurate reflector positions. For instance, a 10 arcminute error in the zenith angle causes T_{ATM} to be in error by 50 mK at 9.1 mm and 120 mK at 3.3 mm. Sunlight shining on the 3.3 mm radiometer warped its reflectors by approximately 1.5 degrees, causing a large uncertainty in T_{ATM}. The 9.1 mm radiometer experienced a similar problem, causing an anomalously large spread (>500 mK) in the atmospheric temperatures measured at different zenith angles on 6 July. Therefore the 9.1 mm data from that night are not included in this analysis.

Another systematic error results from flip offsets - changes in the radiometer offset with its orientation due to the earth´s magnetic field or to mechanically induced stresses on the waveguide components. Tests indicate that the magnetically-induced offset in both radiometers is less than 2 mK/Gauss. Measurements indicate that the offsets change by less then 30 mK when the horizontally pointed radiometers are rotated by 180 degrees. Analysis of the 9.1 mm sky/cold-load measurements suggests the presence of a vertical flip offset of up to 80 mK; 3.3 mm data show evidence of a similar offset of up to 300 mK. These uncertainties are included in the analysis as a part of the systematic error.

Systematic errors also result from drifts in the switch offset and radiometer gain during a measurement sequence, from errors in the various correction terms, and from emission from objects in the sidelobes of the antenna. None of these smaller uncertainties is estimated to be greater than 40 mK (see Table II).

The average of $T_{A,CBR}$ resulting from all the measurement sequences is converted to a thermodynamic temperature T_{CBR} to give the final result:

$$T_{CBR} = 2.87 \pm 0.21 \text{ K} \quad \text{at} \quad 9.1 \text{ mm}$$

$$T_{CBR} = 2.4 \pm 1.0 \text{ K} \quad \text{at} \quad 3.3 \text{ mm}$$

where the quoted errors are the statistical and systematic errors summed in quadrature. At 9.1 mm the statistical error contributes more than half of the total error. At 3.3 mm the error is almost entirely due to pointing uncertainty.

Our value of T_{CBR} at 9.1 mm is in good agreement with the published results in this wavelength range[6,7,8]. It is also intermediate between the temperature measured by Woody and Richards[9] at shorter wavelengths and the average of all the previous ground-based measurements[3], and falls within one standard deviation of both. At 3.3 mm, our results are consistent with previous measurements, but pointing uncertainties prevent us from concluding anything more definite.

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[3] Smoot, G. et al., companion paper (1983).

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TABLE I - Operating characteristics of the 3.3 and 9.1 mm radiometers

Wavelength	3.3 mm	9.1 mm
Bandwidth	2 GHz	1 GHz
System noise	1600 K	800 K
Sensitivity	110 mK/Hz$^{1/2}$	80 mK/Hz$^{1/2}$
Gain stability	0.2 % / night	0.6 % / night
Radiometer offset	6.8 K	3.1 K
Antenna HPBW	7.5°	7.5°
Reflector size	122 x 91 cm	152 x 122 cm
Angles from zenith for atmospheric scans	0, 40 S, 50 S (S refl.) 0, 40 N, 50 N (N refl.)	0, 30 N/S, 40 N/S for each reflector

TABLE II - Correction terms and systematic errors

Radiometer wavelength	3.3 mm	9.1 mm
Cold-load temperature:		
LHe antenna temperature	2.01 ± 0.01 K	3.03 ± 0.01 K
Wall emission	0.03 ± 0.03 K	0.04 ± 0.03 K
Window emission	0.07 ± 0.03 K	0.016 ± 0.003 K
Reflection from load	< 0.001 K	< 0.009 K
Total:	2.11 ± 0.04 K	3.09 ± 0.03 K
Gain saturation	0.00 ± 0.02 K	0.07 ± 0.01 K
Vertical atmosphere:		
Uncertainties:		
Zenith-scan pointing	< 600 mK	< 80 mK
Horizontal antenna sidelobes	< 10 mK	< 10 mK
Emission from Moon and galaxy	< 1 mK	< 3 mK
Diffraction over reflector's edge	< 8 mK	< 8 mK
RMS of an individual sequence	200 mK	110 mK
Total:	800 mK	140 mK
Typical values:	12.3 ± 0.8 K	5.00 ± 0.14 K
Vertical flip offset	< 300 mK	< 80 mK
Horizontal flip offset	< 30 mK	< 15 mK
Magnetic field offset	< 1.5 mK/Gauss	< 1 mK/Gauss
Sidelobes from vertical antenna	< 1 mK	< 1 mK

FIGURE CAPTIONS

Figure 1 -- Schematic diagram of the 9.1 mm radiometer. The instrument can be pointed horizontally for atmospheric measurements or vertically for measurements of T_{ZENITH}. The reflectors can be tilted to various angles to measure T_{ATM}.

Figure 2 -- Histograms of the results at 9.1 mm obtained during the night of 5 July 1982 (U.T.)

a) Antenna temperature of the CBR, $T_{A,CBR}$ - the mean value is 2.18 K and the RMS variation of the 38 data points is 0.13 K.

b) Atmospheric antenna temperature, T_{ATM} - the mean value is 5.00 K and the RMS variation for 157 observations is 0.37 K.

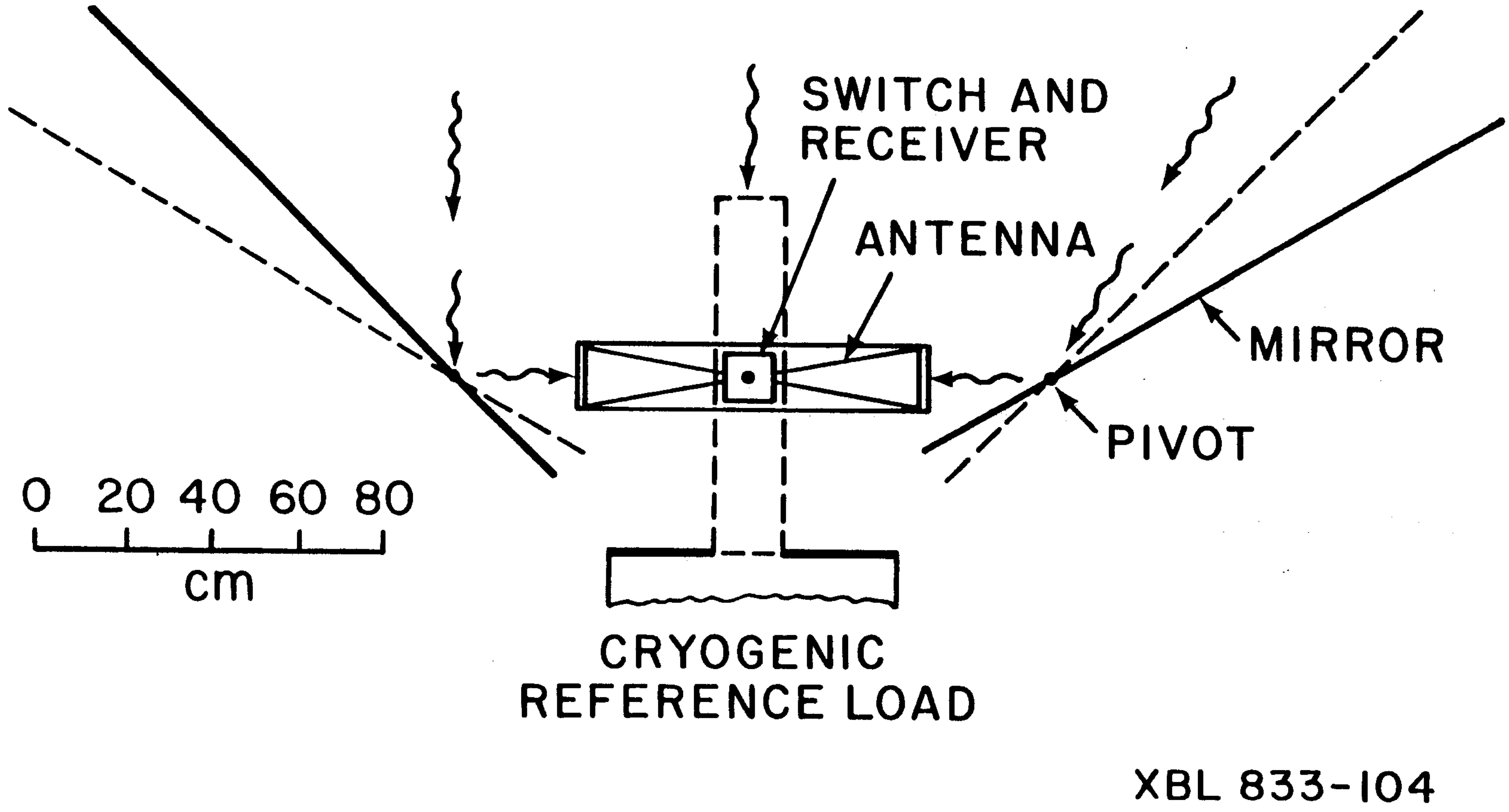
SWITCH AND RECEIVER
ANTENNA
MIRROR
PIVOT
0 20 40 60 80
cm
CRYOGENIC REFERENCE LOAD
XBL 833-104

Fig. 1

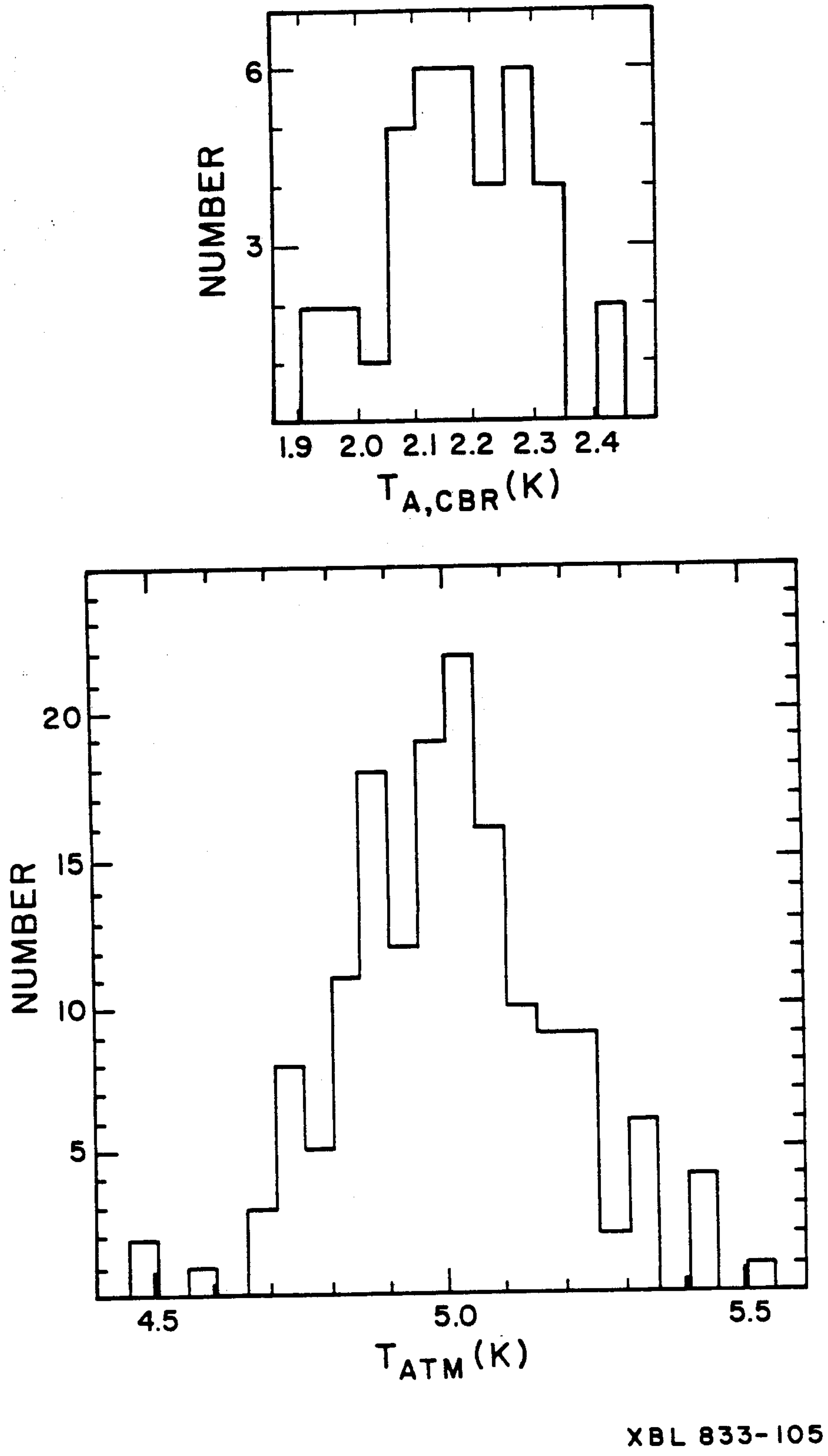

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Fig. 2