LBL--28024

DE90 011589

Low-Frequency Measurements of the CMB Spectrum

A. Kogut, M. Bensadoun, G. De Amici, S. Levin, M. Limon, G. Smoot,
Lawrence Berkeley Laboratory and
Space Sciences Laboratory
University of California
Berkeley, CA 94720

G. Sironi,
Physics Department
University of Milano
Milano

M. Bersanelli, and G. Bonelli
IFCTR/CNR
Milano

October 1989

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 No. DE-AC03-76SF00098, and by the National Science Foundation under Grant DPP-8716548.

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DISCLAIMER

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A. Kogut, M. Bensadoun, G. De Amici, S. Levin, M. Limon, and G. Smoot
U.C. Berkeley, Lawrence Berkeley Laboratory, and Space Sciences Laboratory

G. Sironi
Physics Department — University of Milano

M. Bersanelli and G. Bonelli
IFCTR/CNR — Milano

ABSTRACT

As part of an extended program to characterize the spectrum of the cosmic microwave background (CMB) at low frequencies, we have performed multiple measurements from a high-altitude site in California. On average, these measurements suggest a CMB temperature slightly lower than measurements at higher frequencies. Atmospheric conditions and the encroachment of civilization are now significant limitations from our present observing site. In November 1989, we will make new measurements from the South Pole Amundsen-Scott Station at frequencies 0.82, 1.5, 2.5, 3.8, 7.5, and 90 GHz. We discuss recent measurements and indicate improvements possible from a polar observing site.

INTRODUCTION

The spectrum of the cosmic microwave background (CMB) preserves a record of the interactions between the evolving matter and radiation fields in the early universe. The Rayleigh-Jeans portion of the spectrum is particularly sensitive to energy releases occurring at redshifts between approximately 2×10^6 and 4×10^4, where inverse Compton scattering and bremsstrahlung can produce spectral features[1,2]. The Rayleigh-Jeans spectrum can also distinguish between such models of the apparent sub-mm CMB distortion as dust emission and Compton scattering, which predict different spectral behaviour below 90 GHz[3]. Starting in 1982, an international collaboration from Italy and the U.S. has measured the Rayleigh-Jeans portion of the CMB spectrum[4,5]. Our present results indicate a slightly lower CMB temperature below 30 GHz than do measurements at higher frequencies. In an effort to reduce the magnitude and variability of non-cosmological foregrounds, we plan new measurements in November 1989 from the South Pole.

MEASUREMENT TECHNIQUES

The measurement at each frequency compares the output voltage of a radiometer as it alternately views a cryogenic reference target and the zenith sky. The 0.82, 2.5, and 90 GHz radiometers are Dicke-switched, while the others are total-power. The antenna temperature of the zenith is

$$T_{A,zenith} = T_{A,load} + G(V_{zenith} - V_{load}), \qquad (1)$$

where $T_{A,zenith}$ and $T_{A,load}$ are the antenna temperatures of the zenith sky and the reference target, G is the calibration coefficient of the radiometer, and V_{zenith} and V_{load} are the output voltages viewing the zenith or the reference load. We then measure and subtract all non-cosmological foregrounds (principally atmospheric and galactic emission) to arrive at the CMB antenna temperature:

$$T_{A,CMB} = T_{A,load} + G(V_{zenith} - V_{load}) - T_{A,Atm} - T_{A,Galaxy} - T_{A,ground} - T_{A,RFI} - \Delta T_{Offset}. \quad (2)$$

Here $T_{A,Atm}$, $T_{A,Galaxy}$, $T_{A,ground}$, and $T_{A,RFI}$ are the antenna temperatures of the atmosphere, galaxy, the earth seen in the antenna sidelobes, and man-made radio interference. ΔT_{Offset} refers to possible changes in radiometer performance correlated with radiometer position.

The measurements depend critically upon the cryogenic reference target used. The target used above 1 GHz from 1982 through 1987 has been described elsewhere[5]. To allow calibration down to 1 GHz, and to reduce potential systematic uncertainties, we built a new target before the measurements in 1988 (Figure 1).

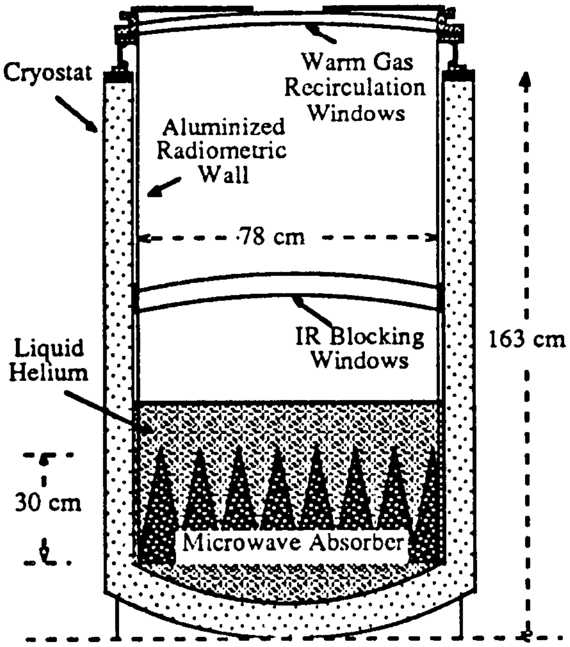

Figure 1: The cold load used in 1988.

The new cold load consisted of a microwave absorber immersed in liquid helium (LHe) within a large, open-mouthed cryostat. An aluminum-coated fiberglass cylinder surrounded the absorber and acted as an oversized multi-mode waveguide, preventing excessive radiation from warm portions of the cryostat from reaching the antenna aperture. Thin (25 µm) polyethylene windows at the top of the cryostat prevented air from condensing on the radiometric surfaces. There were two principal changes in the new cold load. Two IR-blocking windows replaced the old shutter system, which eliminated gaps in the radiometric wall and allowed easier operation with a much lower heat leak to the LHe. In addition, the absorber in the new cold load was more than 50% thicker to ensure low reflection at low frequencies. The antenna temperature of the target could be calculated from the temperature of the absorber (equal to the boiling point of helium at ambient pressure), with small contributions from emission or reflection from the windows and walls. The Teflon-impregnated glass cloth windows (76 and 150 µm thick) introduced new sources of reflection and emission, which we measured carefully. Total corrections were small (<50 mK between 1.5 and 10 GHz). The 0.82 GHz radiometer will use a separate LHe-temperature coaxial cold load[6].

Atmospheric and galactic emission define a natural observing window for ground-based CMB measurements between 1 and 20 GHz. We have measured atmospheric emission above 2.5 GHz by tipping the radiometers and comparing the signals from the zenith and the scan angle (typically 30° or 40°), and correlating the signal with the airmass in the beam. We estimated galactic synchrotron and HII emission by scaling maps at lower frequencies[7]. We have checked the galactic model by performing differential drift scans, comparing the signal difference between two points separated by ~30° in right ascension as the Earth's rotation moves the galaxy through the beams. The limiting uncertainty in the CMB determination typically has been the atmosphere for measurements above 2.5 GHz, and the galaxy below 2.5 GHz.

CURRENT STATUS

The current status of CMB spectrum measurements is summarized in Figure 2. There is an apparent spectral distortion at high frequencies[8] and a possible disagreement between the low-frequency ground-based measurements and results at higher frequencies. Measurements in this field are subject to a range of systematic errors. To assess these uncertainties, is highly desirable to measure the CMB spectrum under a variety of different conditions using different experimental techniques.

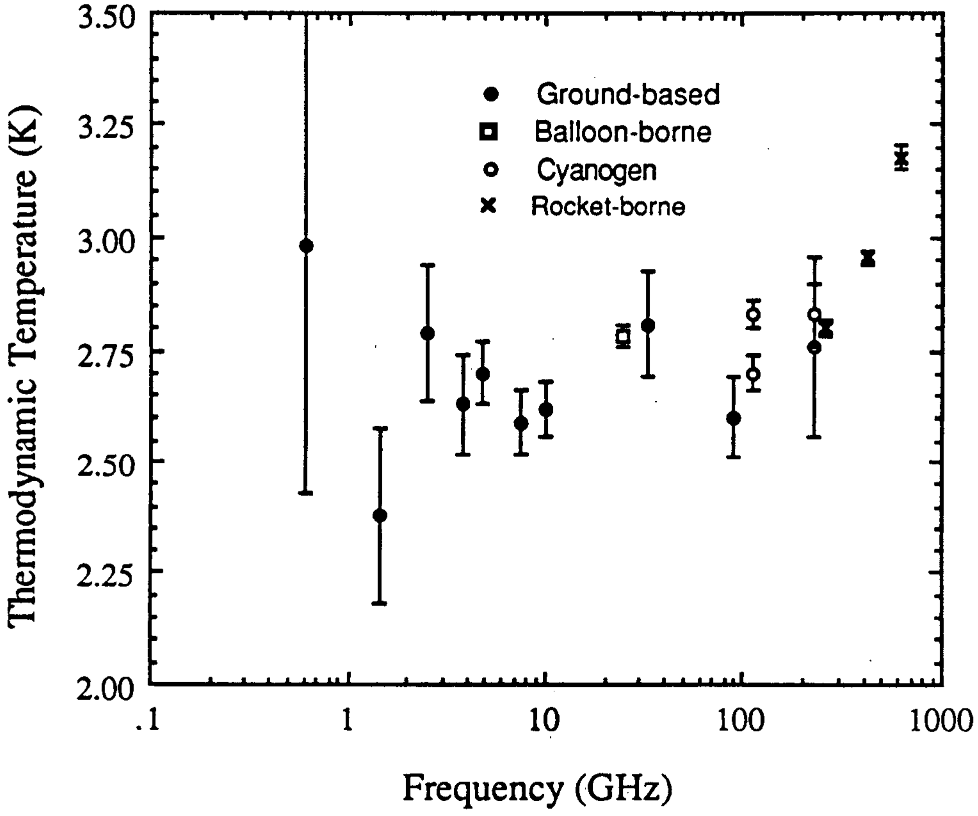

Figure 2: Recent precise CMB measurements

FUTURE WORK

Systematics are the bane of precise CMB measurements. Since 1982, we have changed many observing parameters as a cross check on the measurements. Such changes include changes in radiometer design, measuring technique for atmospheric and galactic scans, and an entirely new reference target. In November 1989 we plan to change the observing site by making measurements at 0.82, 1.5, 2.5, 3.8, 7.5, and 90 GHz from a site near the South Pole. The polar site allows a reduction in the magnitude and variability of various foreground signals.

Atmospheric emission of order 1 K is a foreground common to all of our measurements, and the only one without large frequency dependence; as such, it is a candidate for systematics in the ground-based set of measurements. A small error in the tip scans (e.g., larger than suspected ground pickup) could result in an overestimate of $T_{A,Atm}$ and an underestimate of $T_{A,CMB}$. We have tested extensively for such an effect; it is unlikely for our estimates of $T_{A,ground}$ to be in error by the same amount over more than a decade of frequency and a variety of radiometer designs. The importance of the low-frequency results, however, demands an additional check.

The measured $T_{A,Atm}$ tends to be both larger and more variable than predicted by models based on the oxygen and water vapor content of the atmosphere[9,10,11]. Although the data are probably better understood than the models, a cross-check is desirable. The low water vapor content of the polar atmosphere will reduce the magnitude of the atmospheric emission and eliminate essentially all variability, providing a convenient test for systematics in the determination of $T_{A,Atm}$. We will also attempt an atmospheric measurement at 1.5 GHz.

Interference from man-made radio transmitters has been a significant problem at several of our observing frequencies. We anticipate that RFI at the South Pole will be both smaller (perhaps negligible) and better understood. Nearly simultaneous observations from the same site at 6 frequencies will reduce the possibility of undetected systematics. The planned measurements will provide a precise determination of the low-frequency CMB spectrum from an ideal site. The reduction in foreground signals, and consequent improvement in the understanding of related systematics, will significantly improve our understanding of the low-frequency CMB spectrum.

ACKNOWLEDGEMENTS

This work is 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 No. DE-AC03-76SF00098, and by the National Science Foundation under Grant DPP-8716548.

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