Anisotropy measurements of the cosmic background radiation from the South Pole at 1 degree

PETER R. MEINHOLD,* PHILIP M. LUBIN, *and* ALFREDO O. CHINGCUANCO**

University of California
Santa Barbara, California 93106

DONALD E. MORRIS

Lawrence Berkeley Laboratories
Berkeley, California 94720

The search for structure in the spatial distribution of the cosmic background radiation is one of the few experimental tests of cosmological models. Currently no definitive detections of anisotropy have been made except for the dipole term, and upper limits of 20 to 200 parts per million have been established from 10 arc seconds to 90 degrees angular scale. In the region from 1 to 10 degrees, few experiments have been done with sufficient sensitivity seriously to constrain cosmological models, galaxy formation scenarios in particular. Two recent reports of detection in this region are suggestive but may suffer from systematic problems (Melchiorri et al. 1981; Davies et al. 1987).

For theoretical and experimental reasons, interest in experiments in the 1- to 10-degree range has risen in the past few years. The two primary systematic difficulties with doing sensitive experiments in this angular range are the atmosphere, which has time varying structure, and galactic contamination, which must be modeled and possibly subtracted.

We have chosen to work at 3 millimeters, where emission from the galaxy is low. While this choice of frequency reduces the problem of galactic contamination, problems with atmospheric emission are increased. It is evident from measurements and models of atmospheric emission that in order to work at 90 gigahertz, one requires either a very stable atmosphere or a high enough altitude that the emission lines are not saturated and the measurement can be done between molecular transitions. For example, at sea level, the atmospheric emission is more than 6 orders of magnitude higher than a desired sensitivity of $\Delta T/T = 10^{-5}$.

We have built a system to make measurements on 0.5- to 5-degree scales and have performed experiments at balloon altitude and at the South Pole Station. We chose the South Pole as a ground observation site because of the low water content and previously reported high stability of the atmosphere there. Figure 1 shows the measured atmospheric water vapor column density at the South Pole for the time we were there. Following is a brief description of the experiment and some of the results from the South Pole expedition.

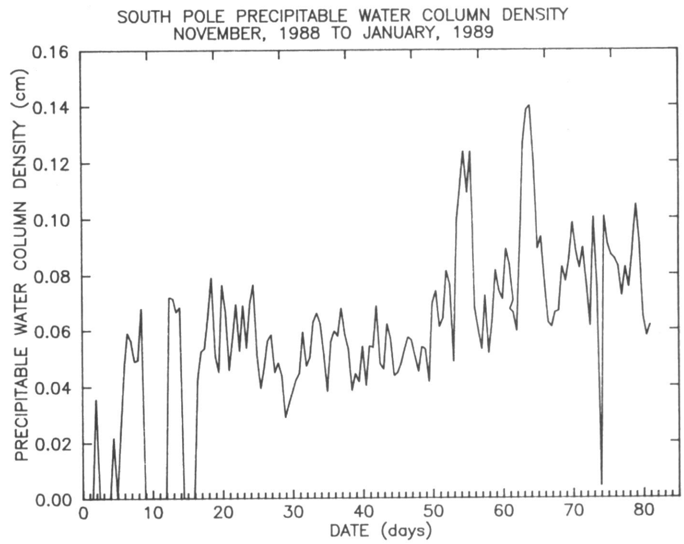

Figure 1. Precipitable water column density, South Pole Station, November, 1988, to January, 1989. (cm denotes centimeters.)

Our optical system is an off-axis Gregorian telescope, consisting of a 6.5 degree gaussian full width at half maximum power corrugated scalar feed, a 1-meter diameter, 1-meter focal length primary, and a confocal elliptical secondary mirror. The resulting beam can have a full width at half maximum power of 20 to 50 arc minutes, depending on the secondary mirror used (our results are for a full width at half maximum power of 36 arc minutes). Rotation of the secondary about the axis of the feed horn throws the beam in right ascension on the sky. We chop the beam by a physical angle of 1 degree on the sky at 10 hertz to make a first difference measurement of temperature fluctuations. With a gaussian full width at half maximum power of 36 arc minutes, the ratio of solid angle available for contamination to that in the beam puts stringent limits on the allowable sidelobe response. We measured our sidelobes down to −85 decibels, and attached a ground shield during data taking.

Our detector system is a Niobium SIS (Superconductor-Insulator-Superconductor) based coherent radiometer, operating at 90 gigahertz. Our mixer, HEMT IF amplifier (spot noise about 1 K), and cooled radio-frequency section enable us to achieve a system spot noise of about 33 kelvin at a mixer physical temperature of 3.5 kelvin. During data taking at the South Pole, our full band (0.6 gigahertz) noise was approximately 40 K, providing a theoretical system sensitivity (before chopping) of $\Delta T = 1.6\ mK/\sqrt{Hz}$.

From late November, 1988, to early January, 1989, we made measurements from the South Pole Station of cosmic background radiation fluctuations and galactic emission. Galactic dust emission is a possible background for us. By comparing data from two of our balloon experiments at 90 gigahertz to the IRAS data at 100 microns, we obtain a calibration of approximately $10[\mu K \div (M\ Jy \div Sr)]$ for the ratio of emission at 3 millimeters to IRAS 100-micron emission. Using this number, along with a galaxy scan taken at the South Pole, we can estimate the contribution of galactic emission to our data. We chose to measure in a region around RA = 21.5, DEC = −73, where the IRAS 100-micron map shows a total intensity minimum of about 4–10 MJy/Sr, and one degree differences only of order 1–2 MJy/Sr. This suggests that the galactic dust con-

* Peter R. Meinhold is also affiliated with the physics department, University of California at Berkeley 94720.

** Alfredo O. Chingcuanco is also affiliated with the mechanical engineering department, University of California at Berkeley 94720.

tribution is a small though not completely negligible correction at our sensitivity.

We observed nine points with 1-degree physical chop angle on the sky, in a strip, spaced so that one beam from each point coincided with one beam from the next point. Several strips were measured to different sensitivities. This gives us a powerful test for systematic errors, as well as providing information on a variety of angular scales, from the beam sigma of 15 arc minutes up to approximately 5 degrees. After time lost due to setting up, equipment problems, and bad weather, we obtained about 80 hours of data, which reduced to about 70 hours after editing out radio interference and bad sky data. Our scan system gave us an efficiency (time spent on the measurement points) of only 60 percent, reducing the real data further to about 43 hours. With a calculated chopped statistical system sensitivity of $3(mK \div \sqrt{Hz})$, or $4(mK \div \sqrt{Hz})$ with sky shot noise included, we measured approximately $6(mK \div \sqrt{Hz})$ (RMS) on the sky for short time scales. This number includes all sources of atmospheric noise at our scale.

Several runs were made of just atmospheric noise and are being investigated to help understand the nature of the sky noise at the South Pole. As an example, figure 2 shows the Fourier transform of a set of data taken with the azimuth fixed, so the instrument was measuring sky noise only. The X-axis is in millihertz, and the "1/f knee" occurs at approximately 0.5 millihertz, or approximately 2,000 seconds.

To work with the data, we have found it necessary to remove slow drifts in offset, which can be attributed to long-term sky variations, changing electrical offsets, and temperature gradients on the primary. Our observing technique allows a natural way to remove such nonintrinsic shifts. Since we scan from one side of the strip to the other and then back in a period of about 30 minutes, linear variations on time scales long compared to 30 minutes can be removed without removing cosmic background radiation structure. The results plotted in figure 3 are the summed data for each point, with statistical error bars, where the raw data have been edited and piecewise linear fit in time, over times of approximately 3 hours. The results for a truncated Fourier fit subtraction, constructed to fit only structure longer than three scans, as well as a Legendre polynomial fit, are consistent with the data presented. In addition, a linear fit in right ascension has been removed, as we presume it to be due to either systematic error or large-scale atmospheric variation. We are currently investigating the large-scale pressure variations over Antarctica during our measurement period in hopes of learning about this background. The error bars on this data set are consistent with the short-term RMS fluctuations.

This set with error bars shown has a reduced chi-square of 1.53, corresponding to approximately 20 percent probability of being consistent with the null hypothesis. We are currently analyzing the data to test various cosmological models, such as the cold dark matter galaxy formation model, scale invariant gaussian fluctuations, etc. These calculations will be presented in a forthcoming paper.

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References

Davies, R.D., A.N. Lasenby, R.A. Watson, E.J. Daintree, J. Hopkins, J. Beckman, J. Sanches-Almeida, and R. Rebolo. 1987. A sensitive measurement of fluctuations in the cosmic microwave background on scales of 5 degrees to 15 degrees. *Nature*, 326, 462.

Melchiorri, F., B.O. Melchiorri, C. Ceccarelli, and L. Pietranera. 1981. Fluctuations in the microwave background at intermediate angular scales. *AP. J.*, 250, L1.

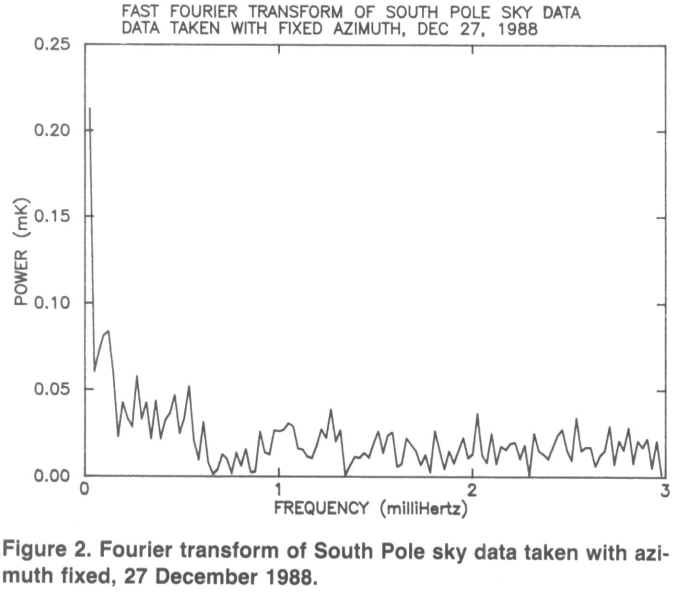

Figure 2. Fourier transform of South Pole sky data taken with azimuth fixed, 27 December 1988.

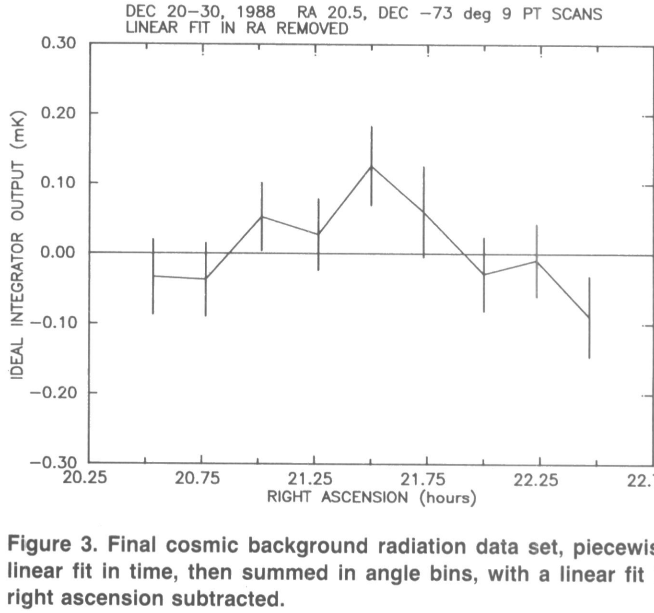

Figure 3. Final cosmic background radiation data set, piecewise linear fit in time, then summed in angle bins, with a linear fit in right ascension subtracted.