THE ASTROPHYSICAL JOURNAL, 370:L11–L14, 1991 March 20

A MEDIUM-SCALE MEASUREMENT OF THE COSMIC MICROWAVE BACKGROUND AT 3.3 MILLIMETERS

PETER MEINHOLD AND PHILIP LUBIN
Department of Physics, University of California, Santa Barbara CA 93106
Received 1990 March 5; accepted 1990 November 14

ABSTRACT

We have developed a system for making measurements of spatial fluctuations in the cosmic microwave background radiation, on an angular scale of 5′ to a few degrees. The system consists of an off-axis Gregorian telescope with a nearly Gaussian response with full width at half-maximum (FWHM) adjustable from 20′ to 50′, a superconductor-insulator-superconductor (SIS) coherent receiver operating at 3.3 mm, and a pointing system capable of better than 1′ RMS stabilization. We report on results from the system's first balloon flight in 1988 August, and ground-based measurements made from the South Pole in 1988 December. We use a portion of the South Pole data to place a 95% confidence level upper limit of $\Delta T/T < 3.5 \times 10^{-5}$ for Gaussian sky fluctuations in the background radiation at 20′ angular scale and a limit of $\Delta T/T < 3.3 \times 10^{-5}$ on overall excess intrinsic sky noise. We also estimate dust contamination in our cosmic background radiation data using measurements of the Galaxy from this flight and a previous one, along with the *IRAS* 100 μm map. These anisotropy results give the most stringent limits on cold dark matter theories to date.

Subject headings: cosmic background radiation — cosmology — early universe

1. INTRODUCTION

Searches for structure in the spatial distribution of the cosmic background radiation (CBR) are one of the few experimental tests of cosmological models. Currently no definitive detections of anisotropy have been made except for the dipole term, and limits of 20–200 parts per million have been established from 10″ to 90° angular scale. In the region from 10′ to a few degrees, few experiments have been done with sufficient sensitivity to seriously constrain cosmological models, galaxy formation scenarios in particular. Recent reports of detection at slightly larger scales are suggestive but may suffer from systematic and Galactic emission subtraction problems (Davies et al. 1987).

Measurements on very small angular scales (arcseconds to a few arcminutes) have been performed from large, ground-based, single-dish and synthesized aperture telescopes. For these scales, source confusion may soon become a significant problem at the $\Delta T/T \sim 5 \times 10^{-6}$ level (Franchesini et al. 1988). A recent result in this angular regime, where a discrete source needed to be taken into account, is that of Readhead et al. (1989). In addition, current ideas about the generation of structure in the CBR include smoothing on scales of order 10′ due to the finite thickness of the surface of last scattering. This tends to make measurements on small scales less critical as tests of theories of galaxy evolution.

The Sachs-Wolfe effect (Sachs and Wolfe 1967), gravitational Doppler shifting of photons evolving from the surface of last scattering, is one of the primary theoretical mechanisms for generating temperature fluctuations in the CBR. The most sensitive tests for theories of galaxy evolution are expected to be on scales of 10′ to 1°, above the scale where recombination and reheating effects are critical but still within the horizon. Many cold dark matter scenarios for galaxy formation predict fluctuations on these scales to be of larger amplitude than the Sachs-Wolfe fluctuations at larger angles (Vittorio et al. 1988; Bond and Efstathiou 1987). For these reasons, experiments in this range are of prime importance.

2. OUR EXPERIMENT

We have chosen to work at a wavelength of 3.3 mm, where large angular scale emission from our Galaxy is near minimum. This choice of wavelength requires going to either balloon altitudes or a high, dry ground site with a very stable atmosphere because of the large contribution of the atmospheric emission at 3.3 mm. For example, at sea level, the atmospheric emission is more than six orders of magnitude higher than a desired sensitivity of $\Delta T/T = 10^{-5}$.

We have built a system to make measurements on angular scales from 10′ to a few degrees and have carried out experiments at both balloon altitude and at the South Pole. The instrument flew at 30 km, where the precipitable water is approximately 3×10^{-4} mm. We chose the South Pole as a ground observation site because of the relatively low water content and previously reported atmospheric stability. We obtained data from South Pole radiosondes giving the precipitable water column density while we were observing. For several days during this time, the precipitable water vapor content was lower than 0.3 mm, while typical days were 0.4–0.5 mm, very low by ground-based standards, but still several orders of magnitude above what we achieve at balloon altitudes. As a comparison, dry days on Mauna Kea have closer to 1 mm precipitable water. Following is a brief description of the ballon payload, flight performance, and details of the South Pole expedition and results. For further details, see Lubin, Meinhold, & Chingcuanco (1990).

In order to get useful integration time, we need a balloon gondola capable of stabilizing to a fraction of the beamwidth. For our Gaussian beam, with FWHM = 30′, we require better than 3′ RMS stability.

Figure 1 is a diagram of our instrument, showing the major servo system components and optical elements. Our optical system consists of an off-axis Gregorian telescope, fed by a 6°.5 FWHM corrugated scalar horn, with a 1 m diameter, 1 m focal length primary, and a confocal ellipsoidal secondary mirror. The resulting beam can have a FWHM of 20′–50′, depending

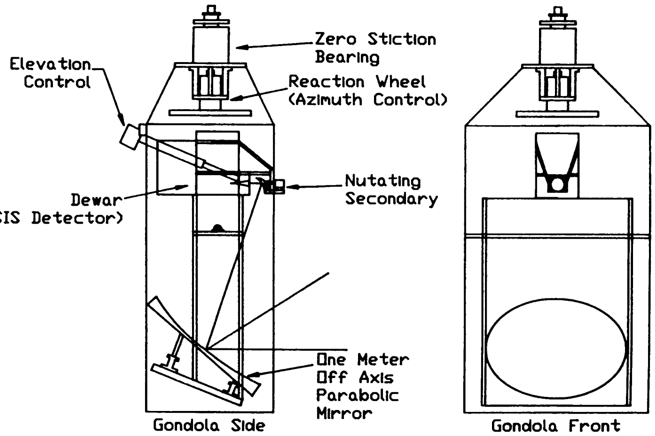

FIG. 1.—Schematic of telescope and pointing platform

on the secondary mirror used (our results are for a FWHM of 30′). Rotation of the secondary chops the beam horizontally on the sky. We chop the beam sinusoidally with an amplitude of 0°.7 on the sky of 8 Hz to make a first difference measurement of temperature fluctuations. The response is similar to a square wave chop of 1°, with a slightly reduced sensitivity. This effect is accounted for in arriving at the final limits below. Our primary reason for using this configuration is the very low sidelobe response of such an antenna. For the central lobe, the beam is well approximated by a Gaussian of $\sigma = 13'$: $P(\Omega) = e^{-\theta^2/2\sigma^2}$. The ratio of solid angle in the sidelobes to that in our narrow main lobe puts stringent limits on the allowable sidelobe response. We measured our sidelobes down to better than −85 dB at 40° from boresight (this is the noise floor for our test range), without ground shields. In addition, a ground shield was attached during data taken both during the balloon flight and at the South Pole. The main beam efficiency of the telescope is greater than 99%.

Our detector is an SIS (superconductor-insulator-superconductor)-based coherent radiometer, operating at 3.3 mm. Our mixer, HEMT IF amplifier (spot noise 1 K), and cooled RF section (all of which operate at liquid helium temperatures), enable us to achieve a narrow-band system noise of 33 K at a mixer physical temperature of 3.5 K. During data taking at the South Pole, our full band (0.55 GHz) noise was approximately 40 K, providing a theoretical system sensitivity (before chopping) of $\Delta T = 1.7$ mK/(Hz)$^{1/2}$.

3. DUST EMISSION

Since Galactic dust emission is a possible systematic error, we need to determine the scaling from short-wavelength data to 3.3 mm. Comparing a simple cosecant b fit to the *IRAS* 100 μm data to the cosecant amplitude for 3.3 mm from our earlier large-scale anisotropy flights (Lubin & Villela 1986), gives 17 μK (Rayleigh-Jeans at 3.3 mm) (MJy sr^{-1})$^{-1}$ at 100 μm (Hauser et al. 1984).

The first flight of the package was in 1988 August from the National Scientific Ballooning Facility in Palestine, Texas. We obtained 8 hr at an altitude of 30 km and achieved better than 1′ (RMS) pointing stability. Figure 2 shows a scan of the Galactic center, where the telescope was stepped among three positions near the Galactic center, remaining at each position for 1 minute. The trace shows four three-position scans, with a clear 20 mK signal from the Galaxy. The two most likely sources for this power are an H II region at R. A. = 17^h.712, decl. = −28°.8, near the estimated position of one of our beams, or emission from Galactic dust. If the emission is due to dust, then comparing this result to first differences of the *IRAS* 100 μm map in this region (1100 MJy sr^{-1}) gives 18 μK (Rayleigh-Jeans at 3.3 mm) (MJy sr^{-1})$^{-1}$ at 100 μm, in agreement with the 3.3 mm large-scale anisotropy data above. If the emission is indeed due to dust, then the data suggest an emissivity scaling index close to one, in disagreement with values close to two estimated from shorter wavelength measurements. In the next section, we estimate the contribution of dust emission to our data using this number. It should be emphasized that if the Galactic emission seen during our flight is due to H II emission, then this scaling of the *IRAS* 100 μm measurements overestimated dust emission at 3.3 mm, and actual dust emission of the Galactic plane should be lower. A more precise estimate will be possible when the *COBE* data become available.

4. SOUTH POLE RESULTS

From late November of 1988 to early January of 1989, we made ground-based measurements of CBR fluctuations from the South Pole Station, replacing the balloon azimuth stabilization system with a rotation table, while otherwise leaving the experiment in the same configuration as for the balloon flight.

We measured in a region around R.A. = 21^h.5, decl. = −73° ($l = -40°$, $b = -37°$), where the *IRAS* 100 μm map shows a total intensity minimum of about 4–10 MJy sr^{-1}, and first differences only of order 1–2 MJy sr^{-1}. Using the Galaxy data described above, this would be about 18–36 μK in our first difference data, which is small, though not negligible compared to our errors of 60 μK per data point, where we have made the assumption that the dust emissivity scaling is the same over the sky. Thus, even in the best parts of the sky, total dust emission at 3.3 mm wavelength is near the detection limit at our current sensitivity, and clearly of concern for future measurements. Measurements of an order of magnitude more sensitive will require Galactic subtraction, preferably by multiple wavelength measurements, which we are now undertaking.

We made first difference measurements of 10 patches of the sky at constant declination. The chop was sinusoidal with a 1°.4 peak-to-view throw, which gave a 1° effective chop angle. The patches were observed from nine positions of the telescope,

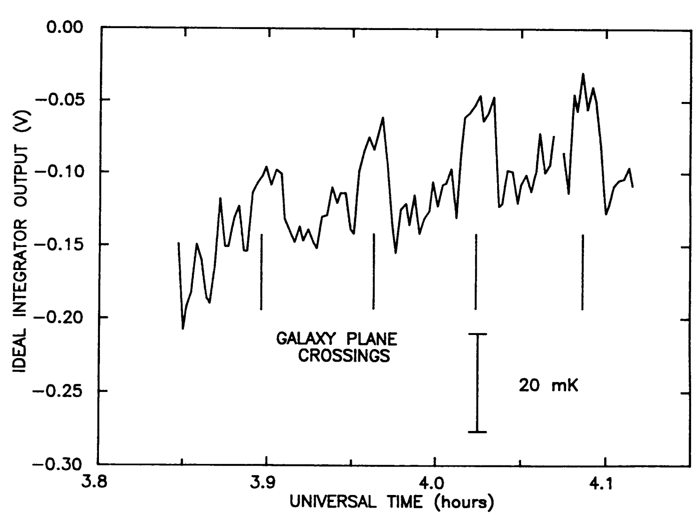

FIG. 2.—Scan of Galactic center from 1988 August flight. Four repetitions of our three-point scan are shown, with a clear 20 mK signal.

spaced so that one beam from each position coincided with the other beam from the next position. This scheme provides information on angular scales from the below the beam dispersion of 13′ up to approximately 5° and gives us a powerful test for systematic errors. Several strips were measured to different sensitivities. After time lost due to setting up, equipment problems, and bad weather, we obtained about 85 hr of data for the deepest nine position strip, which reduced to 72 hr after editing out radio interference and bad sky data. Our scan system gave us an efficiency (time spent on the measurement points) of 60%, reducing the final data set to 43 hr.

The calibration constant was detemined a minimum of once per day, using a warm load/blank sky technique, and was constant to $\pm 1.5\%$ during the measurement period. In addition, we calibrated using the Moon as a source and compared the results to a lunar regolith model at our wavelength (S. Keihm, private communication). The results of this are consistent with our warm load calibration. The calculated instantaneous chopped system sensitivity is 3.4 mK/(Hz)$^{1/2}$, or 4.3 mK/(Hz)$^{1/2}$ with atmospheric shot noise included, while we measured approximately 6.1 mK/(Hz)$^{1/2}$ (Rayleigh-Jeans, RMS) on the sky.

We have edited the raw data, removing sections showing abnormally large atmospheric or radio interference noise. We have also removed slow drifts in offset, which can be attributed to long-term sky variations, changing electrical offsets, and temperature gradients on the primary. The typical offset was a few mK, with drifts of less than 1 mK hr^{-1}. Our observing technique allows a natural way to remove such nonintrinsic shifts. Since we scan from one side of the strip to the other in 15 minutes, removal of a linear component from the data from each scan effectively removes long-term drifts which could increase the effective noise of the measurement. Removing this linear component changes our effective sensitivity to different types of intrinsic sky structure, and this is taken into account in the analysis which follows.

The results, with statistical (1 σ) error bars, are shown in Figure 3 and Table 1. These data have been corrected from antenna temperature to thermodynamic temperature, referenced to 2.74 K. The error bars on this data set are consistent with the short-term RMS fluctuations and give a χ^2 of 0.98 for 7 degrees of freedom. There is a probability of 45% of obtaining a χ^2 this large or larger from random data. In order to check that our data-fitting procedures are not correlating the points or removing structure, we have carefully tested them

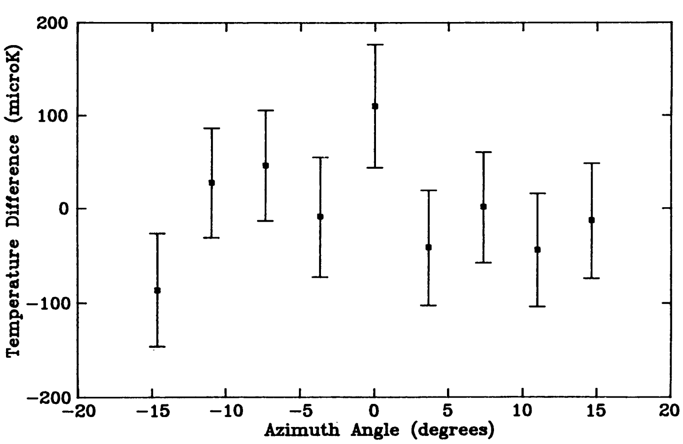

FIG. 3.—The nine data points with $\pm 1\ \sigma$ error bars. The data are the averaged results of several hundred scans, each with a linear fit in angle removed.

TABLE 1

FINAL DATA SET

Scan Position	Right Ascension	Bin Average (μK)	σ (μK)
1..............	22^{h}48	−86.4	59.9
2..............	22.23	27.6	58.7
3..............	21.99	46.1	59.5
4..............	21.74	−8.7	63.7
5..............	21.50	110.1	66.5
6..............	21.25	−41.7	60.9
7..............	21.01	1.4	58.9
8..............	20.77	−43.9	59.8
9..............	20.52	−12.7	61.1

with Monte Carlo data sets, simulating offset drifts in time, changing linear drifts with angle and Gaussian instrument noise. In all cases, the original intrinsic structure in the data set (less a linear component) is recovered after we perform our analysis.

We are investigating the net correlation of large-scale atmospheric phenomena in right ascension during the measurement period as a possible contaminant. For instance, at the South Pole, the average barometric pressure is approximately 650 torr, and random day-to-day variations are of order 5 torr, implying a change in total sky emission at our wavelength of 1%, or 50–100 mK from oxygen. If this change correlated with hour angle, it could result in a large signal. Although we have tried to model this, there is not enough pressure data for the polar plateau to definitely show an effect.

This type of argument has implications for measurements from any other ground-based location, particularly those at larger angular scales. At latitudes near the equator, for instance, atmospheric tides give a Sun–synchronous pressure variation of about 1%. This number is smaller for higher latitudes, but the variations can appear to be correlated with hour angle. As is discussed above, this effect can be reduced in our data by ignoring linear trends, or by doing a second difference measurement. At larger scales, these techniques may not work, since some atmospheric phenomena may be similar in angular size to the target CBR fluctuations.

In order to understand what the data set tells us about intrinsic sky fluctuations, we compare our results to simulations for various models. We use the value of assumed sky noise $\theta_{\rm sky}$ at which the likelihood function

$$L \propto \prod_{i=1}^{9} [2\pi(\sigma_i^2 + \theta_{\rm sky}^2)]^{-1/2} \exp\left[\frac{-\Delta T_i^2}{2(\sigma_i^2 + \theta_{\rm sky}^2)}\right]$$

falls to 0.1 of its maximum as a test statistic. As one test, we have produced sky simulations with Gaussian correlation functions of various angular scales, which we sample the same way in which we take data on the sky, including the weighting effect of our sinusoidal chop. By changing the amplitude of the assumed fluctuations relative to the measurement noise, we can determine the value of sky signal consistent with our measurement. By requiring that 95% of the simulated data sets yield a value of the test statistic greater than that obtained from the data, we find an upper limit to the amplitude of Gaussian autocorrelation function fluctuations at 95% confidence. We obtain an upper limit of 95 μK RMS intrinsic sky fluctuation: $\Delta T/T < 3.5 \times 10^{-5}$, at our most sensitive angular scale (for this model) of 20′–30′, using $T_{\rm cbr} = 2.74$ K. This limit includes the 4% correction for atmospheric attenuation, the 99% correction for main beam efficiency, and the previously applied correction of antenna temperature to thermodynamic (referenced to 2.74 K). For comparison, the 95% confidence limit obtained by determining the excess sky noise required to produce our measured χ^2 is $\Delta T/T < 3.3 \times 10^{-5}$. The details of these calculations, along with some calculations for specific cold dark matter models, are contained in a forthcoming paper (Vittorio et al. 1990; Bond et al. 1990). For comparison, Readhead et al. (1989) give an upper limit of 1.9×10^{-5} for a Gaussian correlation function at 2′.6. It should be noted that most galaxy formation scenarios predict more fluctuations at 20′ than at smaller angular scales. For this reason, our limit actually puts tighter restrictions on the parameters of most CDM theories than does the Readhead et al. result. Another recent result is that of Davies et al. (1987), who place an upper limit of about 4×10^{-5} at 8°. As mentioned above, this measurement probes a different type of structure than ours and may be subject to galactic contamination.

This work was supported by the National Aeronautics and Space Administration, under grant NAGW-1062 and GSRP grant NGT-50192, the National Science Foundation Polar grant DPP878-15985, California Space Institute grant CS 35-85, the University of California, and the US Army. We also gratefully acknowledge the support of the NSF Center for Particle Astrophysics. We particularly want to thank Nancy Boggess for her vision of the viability of this research and for her continued support. This work would not have been possible without the support and encouragement of Donald Morris, Richard Muller, Fred Gillett, Buford Price, and John Lynch. We wish to thank Anthony Kerr and S. K. Pan of NRAO for supplying the exceptional SIS mixer. The Nb/Al-Al_2O_3/Nb junctions used were supplied by Hypres Corporation. Special thanks to Robert Wilson, Anthony Stark, Joe Stack, and Paul Moyer at Bell Labs for machining the primary and secondary mirrors. In particular we would like to thank Bill Coughran, and all of the South Pole ANS support staff for a highly successful 1988–1989 polar summer.

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