Observational Cosmology
ASP Conference Series, Vol. 51, 1993
G. Chincarini, A. Iovino, T. Maccacaro, and D. Maccagni (eds.)

COSMIC MICROWAVE BACKGROUND ANISOTROPY AT ONE DEGREE- ACME HEMT 1990-91 SOUTH POLE RESULTS

T.C. GAIER, J.A. SCHUSTER, J.O. GUNDERSEN, P.R. MEINHOLD AND P.M.LUBIN
Physics Department,University of California, Santa Barbara, CA 93106

ABSTRACT We report on an experiment to measure the anisotropy of the cosmic microwave background at an angular scale of one degree. The measurement was performed at the Amundsen- Scott South Pole Station during the austral summer of 1990-91. The instrument used was the UCSB ACME telescope with a four channel HEMT receiver installed. The instrument operates from 25-35 GHz and has a 1.5°beam. 120 hours of data representing repeated scans of one elevation have been fully analyzed and are presented here. This scan can be used to set a 95% confidence level upper limit to CMB fluctuations of $\frac{\Delta T}{T} \leq 1.4 \times 10^{-5}$ at 1.2°. Also presented are preliminary results of a scan of an adjacent elevation.

INTRODUCTION

Anisotropy measurements of the cosmic microwave background (CMB) serve as a critical test of cosmological theories. While the recently reported detection of anisotropy by the COBE-DMR experiment (Smoot et. al,1992) may be due to primordial fluctuations in the universe, measurements at scales less than a few degrees are pertinant to the formation of large scale structures in the universe.

At ten degrees and larger, CMB signals are larger than the horizon size at decoupling. Therefore no microphysical processes contribute to these signals and such signals are considered primordial. At scales smaller than the horizon, structure formation is expected to leave its own imprint on the CMB. By measuring anisotropy at all angular scales, one can constrain theories of structure formation and thermal history using the detected anisotropy at 10° as a normalizing amplitude.

At scales much smaller than the horizon (a few arcminutes), anisotropies are expected to be damped via Thompson scattering due to the finite thickness of the surface of last scattering. Therefore measurements at scales of 10 arcminutes to a few degrees may provide the strongest test of cosmological theories.

Previous upper limits to anisotropy at 1° were about $\frac{\Delta T}{T} \leq 1 \times 10^{-4}$ with no significant detections reported. At this sensitivity, care must be taken to veto any possible spurious signals which may result in false detections. As such, multifrequency measurements are required to detect anisotropy with certainty.

We have performed a multifrequency measurement of CMB anisotropy at 1°using a four channel system operating between 25 and 35 GHz.

THE INSTRUMENT

This measurement made use of the UCSB Advanced Cosmic Microwave Explorer (ACME) telescope. This telescope has been used for both balloon borne and ground based measurements at frequencies ranging 25-360 GHz. For telescope details see Meinhold et.al, 1993.

The optical arrangement of the telescope is off-axis Gregorian with a one meter diameter primary and a chopping ellipsoidal secondary. The scalar feed horn of the detector is cooled cryogenically and placed at the focus of the secondary. A cryogenic amplifier using High Electron Mobility Transistors (HEMT) (Pospieszalski et. al.,1990) amplifies the signals. The amplifier has a bandpass from 25-35 GHz and a minimum noise temperature of 25 K. The integrated receiver noise is less than 30 K. Signals leave the dewar and are further amplified by a warm high gain amplifier. The signals then pass into a filter array splitting the band into four channels; 25-27.5 , 27.5-30, 30-32.5, and 32.5-35 GHz (Channels 1-4 respectively hereafter). Signals are detected by detector diodes and synchronously demodulated from the chopping secondary.

The optics result in an unchopped beam which has the characteristic Gaussian FWHM which varies as:

$$\theta_{FWHM}(\nu) = 1.4^{\circ} \pm 0.1 \times (\frac{27.7}{\nu_{GHz}})$$

The demodulated beam has a point source response which is antisymmetric with peaks separated by 2.1°. For further details of the sinusoidal chop and effective response refer to Meinhold et. al.,1993 and Gaier et al., 1992.

The system sensitivity is 1.4 $mK/\sqrt{Hz}$ in the lowest noise channel (Channel 2). The sensitivity after combining the channels is better than $1mK/\sqrt{Hz}$.

THE OBSERVATION SITE AND STRATEGY

Observations at 30 GHz requires atmospheric consideration. A high dry site is needed to minimize the effects of the atmospheric H_2O line at 22.2 GHz as well as the O_2 cluster at 60 GHz. The Amundsen-Scott South Pole Station is such a sight, with precipitable water content less than 1 mm, and a pressure altitude of 4.2 KM. We measured the atmospheric zenith temperature to be 2.5°K at 30 GHz, consistent with model predictions.

The sky at the South Pole is also exceptionally stable with an observed single chopped 1/f knee in excess of 1 hour. Our system sensitivity on the sky was as good as 1.6 $mK\sqrt{\sec}$ (Channel 2), but averaged greater than 2 $mK\sqrt{\sec}$ for useful data.

The South Pole is also geographically favorable as it allows tracking of a constant sky position without a change in elevation. This allows for long integrations without unnecessary atmospheric pickup or instability due to changing elevation. This dictated our scan strategy.

We opted for discrete step scans where the instrument is stepped in azimuth an angle corresponding to 2.1°on the sky. The instrument is stepped back and forth through N-points at constant elevation repeatedly to build up integration time. We performed 9-point scans at six adjacent elevations building a 2-d map. In addition a 15-point scan and a 13-point scan overlapping this region were performed. A map representation of the scan strategy is shown in Fig.1.

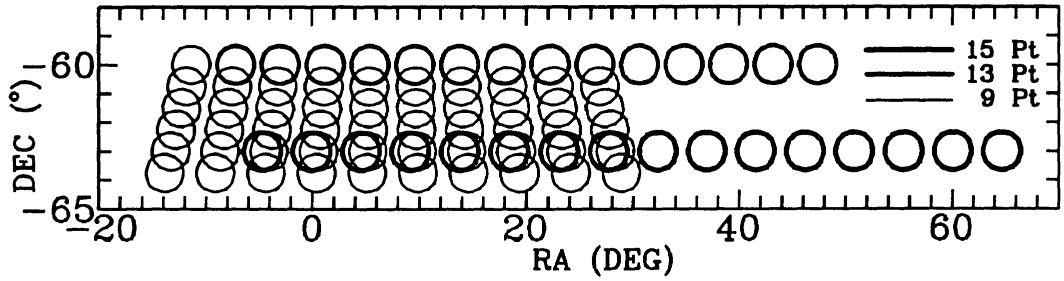

Fig. 1. Scan strategy. Displayed are the N+1 sampled points on the sky. The circles reflect the individual beam position, not the shape or symmetry.

The observed portion of the sky was selected by regions of low emission in the Haslam 408 MHz(Haslam et. al. 1982)and IRAS 100μ maps, subject to the requirements that the angle from the sun is large and elevation high enough to prevent ground pickup.

The system collected data from December 21, 1990 to January 12, 1991 for a total of 500 hours. A thorough analysis has been performed on the 9-point scan at $\delta = -62.25°$, the most sensitive of the 9-point scans. This result has been published (Gaier et. al., 1992) and will be discussed here. The 15-point scan also proved to be very sensitive. The preliminary results of this scan will also be discussed.

$\delta = -62.25°$ DATA REDUCTION

The instrument scanned a 9-point region centered on $\delta = -62.25°$, $\alpha = 0.5hr$, for a period of 1 week. For some of this time (two days), the weather was very poor and data were not collected (maintenance was performed). For some 120 hours, the weather was mixed and data were collected.

The analysis proceeds on this 120 hours as follows: First, gross single point outliers in the data are removed. These points are defined as deviating from nearby data (in a 20 second window) by more than 5σ. Less than 0.1% of the data are removed this way. At the same time, the offset angle of the chopping mirror is monitored, when it falls outside of some specified range, the data are removed.

The data are then divided into $\frac{1}{2}$-scans. A $\frac{1}{2}$-scan is defined as starting at position one and ending at position nine or vice versa. A best fit line is found for the data as a function of time for each $\frac{1}{2}$-scan, and removed from the data. The fit gradients were typically 250 μK growing as high as $800\mu K$ during bad weather. About 150 data points are used in each fit.

During periods of bad weather, the observed noise in the data was large. As stated earlier, under good seeing conditions, the noise in the data was about

1.6 $mK\sqrt{sec}$ (In channel two). During periods of poor weather, this noise could grow larger than 5 $mK\sqrt{sec}$. Our main concern with such data is that when the seeing conditions are poor, atmospheric structure can appear in the data.

Since we have no independent measure of the weather, we use the noise in the data as a measure of the quality of the seeing. The basic idea is to remove an entire $\frac{1}{2}$-scan when the RMS of the residuals of the fit (detailed above) is larger than some value s_c. Similar techniques have been used successfully in other experiments (Readhead et al,1989). The value we use for s_c is 3.2,2.8,3.6, and 3.4 mK for channels 1-4 respectively (Note the integration time is 1.2 s for each data point).

It is important to note that these values are well above the expected measured $\frac{1}{2}$-scan RMS's (about 2 mK with 150 degrees of freedom was expected on a "clear" day) . It is also important to note that the final data sets do not vary significantly with small changes in s_c. About 70% of the data from this scan were removed with these cuts, consistent with the weather being visually poor about 70 % of the observation period.

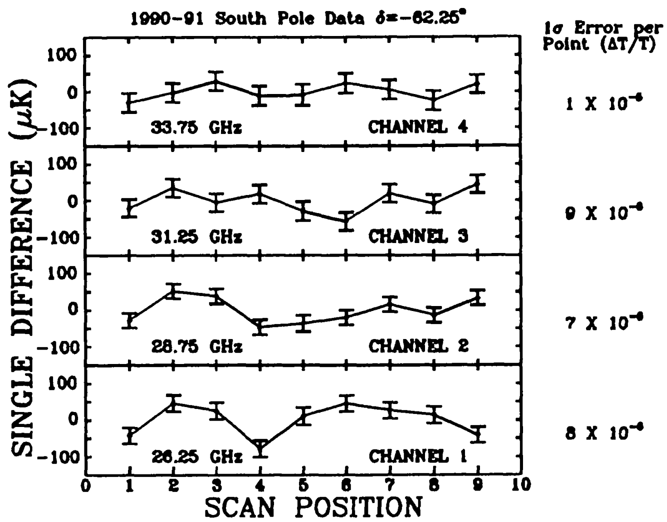

Fig. 2. Binned data from $\delta = -62.25^o$. Position 5 corresponds to $\alpha = 0.5$ hr. All gradients have been removed from scans contributing to this set. Positions are separated by 2.1^o on the sky. Units are μK thermodynamic for a 2.73 K blackbody. The errors shown are $\pm 1\sigma$.

The final binned data are shown in Fig. 2. These data sets represent the coadded data after removal of a line from individual $\frac{1}{2}$-scans. Only $\frac{1}{2}$-scans with RMS noise less than s_c are included, and all incomplete $\frac{1}{2}$-scans are removed. The final data sets cannot have a gradient, due to the fit.

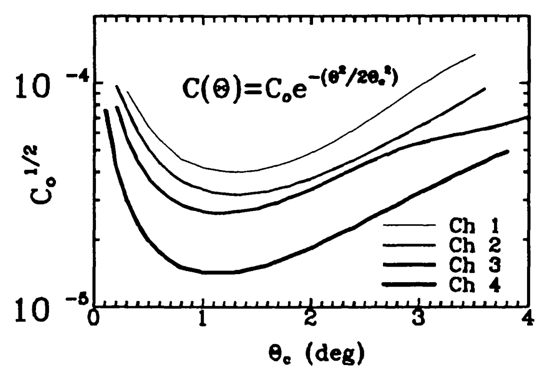

Fig. 3. 95% CL upper limits from the data in Fig 2. Limits are for a Gaussian ACF, and are calculated using a Bayesian analysis.

$\delta = -62.25°$ CMB LIMITS

The most obvious feature in the data in Fig.2 is the large signal in Channels 1 and 2. In Channels 3 and 4 there is no significant signal. Spectral analysis has been performed on these data to determine the origin of such a signal.

A model in which the most probable signal arises from CMB fluctuations is accepted with 2% probability. A model in which the most probable signal arises from extended synchrotron emission ($T_\nu \propto \nu^\alpha$, $\alpha = -2.85$) is accepted with 10% probability. The probability of the model increases with decreasing α. We conclude that the signals seen in Channels 1 and 2 do not arise from CMB fluctuations, and are from some foreground emission with a falling spectrum.

Since the two highest frequency channels have the least excess signal, we assume that the foreground source is not contributing significantly to the data. All channels and combinations of channels can be used to set upper limits to intrinsic CMB fluctuations. Channels 1 and 2 have 95% confidence level (CL) lower limits, but these are not used for CMB limits because of the spectrum. Since the two highest frequency channels have the least excess noise, they will provide the strictest CMB limits.

We calculate our upper limits using a Bayesian analysis with a uniform prior. We employ the generalized form of the likelihood function, including off diagonal terms in the correlation matrix (Gaier et.al.,1992). 95% CL upper limits are calculated for a Gaussian autocorrelation function (ACF) CMB for all four channels over a range of coherence angles. These limits are shown in Fig.3.

As expected, the strictest limits come from channel 4. The best limit set is $C_o^{1/2} \leq 1.4 \times 10^{-5}$ (39 μK) at 1.2° coherence angle. Combining channels 3 and 4 results in a comparable limit to channel 4 alone, $43\mu K$. Combining all four channels results in an upper limit of $52\mu K$.

The best limit set using this scan is a factor of 7 better than previous limits at 1.2°. This limit can be used in conjunction with the COBE detection to constrain the initial fluctuation power spectrum or evolutionary cosmological models. Work has also been done using this data setting limits on large scale bulk motions in the universe (Gorski, 1992).

$\delta = -63°$ 15-POINT SCAN

As stated earlier other scans were performed. Among these was a deep 15-point scan over a period of four days of good weather. The data have not been fully analyzed, but a preliminary work has been performed. Data reduction and analysis techniques are similar to those discussed for the 9-point scan. The reduced data are shown in Fig. 4.

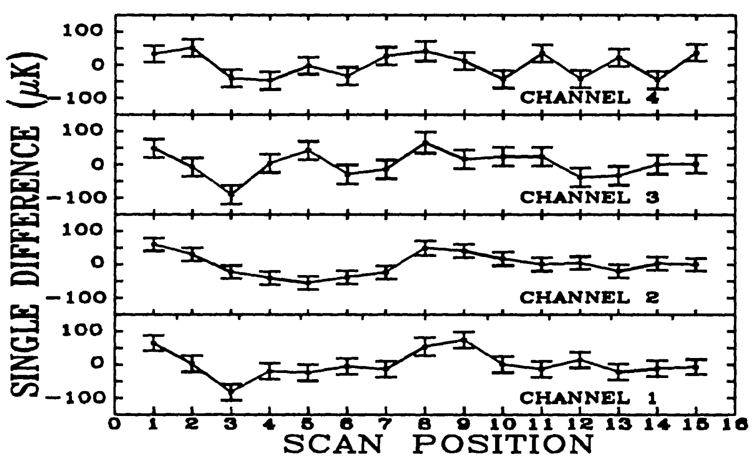

Fig. 4. Binned data from $\delta = -63°$. Position 8 corresponds to $\alpha = 2$ hr. The analysis and details of this 15-point data set are the same as for the 9-point scan shown earlier.

A signal is evident in all channels. The RMS of the most probable sky signal is approximately 25 μK, and below the 95 % limit set using the previous scan. No spectral analysis or systematic checks have been performed. In addition, potential foreground sources must be accounted for. It is too early to consider this a detection of CMB anisotropy, and work is in progress (Schuster et. al. in progress). This scan has a coadded one σ error of 11 μK per point.

CONCLUSION

We have measured the of anisotropy of the CMB at scales of 1°. This measurement is the most sensitive measurement to date at this scale. The signals detected by one scan of this measurement are spectrally inconsistent with CMB anisotropy. We use the data to set upper limits to CMB anisotropy. Our highest frequency channel, expected to be the least contaminated by foreground emission can be used to set a 95% CL upper limit CMB anisotropy of $\frac{\Delta T}{T} \leq 1.4 \times 10^{-5}$ for a Gaussian ACF with a coherence angle of 1.2°. We are currently analyzing additional scans which will provide greater sensitivity to CBR fluctuations.

ACKNOWLEDGEMENTS

This project was made possible by NASA grant NAGW-1062; NSF Polar Programs grant NSF DPP 89-20578, and a development grant from the NSF Center for Particle Astrophysics under grant UCB AST88-0916. The K_a band HEMT amplifiers are on loan from the NRAO CDL. We are grateful to Mike Balister, Marian Pospieszalski, and the staff of the NRAO CDL for their patience during numerous conversations on the subject of low-noise amplification. This work would not have been possible without the support and encouragement of John Lynch and Bernard Sadoulet.

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DISCUSSION:

Watson: This is more of a comment on your diagram showing comparisons of various experiments with the COBE results. The Gaussian ACF isn't really the most appropriate one as the COBE results fit an $n \simeq 1$ power spectrum, and this is where the apparent conflict occurs with our Tenerife result.

Gaier: I agree!