MSAM1-94: Repeated Measurement of Medium-Scale Anisotropy in the Cosmic Microwave Background Radiation

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ABSTRACT

The second flight of the Medium Scale Anisotropy Measurement (MSAM1-94) observed the same field as the first flight (MSAM1-92) to confirm our earlier measurement of cosmic microwave background radiation (CMBR) anisotropy. This instrument chops a $30'$ beam in a 3 position pattern with a throw of $\pm 40'$, and simultaneously measures single and double differenced sky signals. We observe in four spectral channels centered at 5.6, 9.0, 16.5, and 22.5 cm^{-1}, providing sensitivity to the peak of the CMBR and to thermal emission from interstellar dust. The dust component correlates well with the *IRAS* 100 μm map. The CMBR observations in our double difference channel correlate well with the earlier observations, but the single difference channel shows some discrepancies. We obtain a detection of fluctuations in the MSAM1-94 dataset that match CMBR in our spectral bands of $\Delta T/T = 1.9^{+1.3}_{-0.7} \times 10^{-5}$ (90% confidence interval, including calibration uncertainty) for total rms Gaussian fluctuations with correlation angle $0\overset{\circ}{.}3$, using the double difference demodulation.

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1. Introduction

Observations of anisotropy in the Cosmic Microwave Background Radiation (CMBR) yield valuable clues about the formation of large-scale structure in the early universe. A particularly interesting angular scale for observing CMBR anisotropy is near $0\overset{\circ}{.}5$, where the first "Doppler peak" (or adiabatic peak) enhancement of the fluctuation power spectrum is expected to be observable (White, Scott, and Silk 1994). The Medium Scale Anisotropy Measurement (MSAM) is an experiment designed to measure CMBR anisotropy at this angular scale. This paper reports the initial results from the second flight of this experiment.

A number of detections of anisotropy at angular scales near $0\overset{\circ}{.}5$ have been reported recently. Observations by ARGO (de Bernardis *et al.* 1994), the Python experiment (Dragovan *et al.* 1994), the fourth flight of the MAX experiment (Devlin *et al.* 1994, Clapp *et al.* 1994), SK94 (Netterfield *et al.* 1995), and SP94 (Gundersen *et al.* 1995) all report detections of anisotropy near this angular scale.

Quantifying CMBR anisotropy at the level of these detections is an extremely challenging observational task (Wilkinson 1995). Many potential systematic errors cannot be unequivocally ruled out at the necessary levels, with the result that any single observation cannot prudently be accepted without an independent confirmation. The results in this paper are our attempt to confirm the results of our previous work. By observing the same region of the sky with a second balloon flight, we demonstrate the repeatability of our measurements in the presence of potential atmospheric noise and contamination from Earthshine.

We have reported earlier (Cheng *et al.* 1994, hereafter Paper I) our observations of anisotropy of the CMBR from the first flight of MSAM in 1992. Our results from those observations were 1) a positive detection of anisotropy, with the caveat that we could not rule out foreground contamination by bremsstrahlung; 2) the identification of two particular bright spots that were consistent with being unresolved sources. This paper reports our first results from the 1994 flight of MSAM, which observed an overlapping field.

2. Instrument Description

This instrument has been briefly described in Paper I; we give only an overview here. It has four spectral bands at 5.6, 9.0, 16.5, and 22.5 cm^{-1}, giving sensitivity to CMBR and Galactic dust. The off-axis Cassegrain telescope forms a $30'$ beam on the sky. The chopping secondary mirror moves this beam in a step motion $40'$ left and right of center. The beam moves center, left, center, right with a period of 0.5 s. The detectors are sampled at 32 Hz, synchronously with the chop.

The telescope is mounted on a stabilized balloon-borne platform. The absolute pointing reference is provided by a star camera; positions between camera fixes are interpolated using a gyroscope. The telescope is shielded with aluminized panels so that the dewar feed horn, the secondary and most of the primary have no direct view of the Earth.

The gondola superstructure was changed between the 1992 and 1994 flights. The previous superstructure as viewed from the telescope had a substantial cross-section of reflective material; in spite of our efforts to shield it we were concerned about the telescope being illuminated by reflected Earthshine. The new design is a cable suspension with considerably lower cross section above the telescope. Ground measurements indicate that rejection of signals from sources near the horizon is better than 75 dB in our longest wavelength channel.

3. Observations

The package was launched from Palestine, Texas at 00:59 UT 2 June 1994, and reached its float altitude of 39.5 km at about 03:25 UT. Science observations ended with sunrise on the package at 12:04 UT. During the flight we observed Jupiter to calibrate the instrument and map the telescope beam, scanned M31 (which will be reported in a future *Letter*), and integrated on the same CMBR field observed during the 1992 flight for 3.5 hours.

The CMBR observations were made as described in Paper I. The telescope observes near the meridian 8 above the north celestial pole, and scans in azimuth $\pm 45'$ with a period of 1 minute. The scan is initially centered on a point $21'$ to the east of meridian. We track to keep this point centered in our scan until it is $21'$ to the west of meridian, then jog $42'$ to the east. Each scan takes about 20 minutes, and half of each scan overlaps the preceding scan. We completed 4.5 such scans from 05:12 to 06:38 UT (we call this section 1 of the data), and completed an additional 7 scans from 07:22 to 09:43 UT (section 2). The observed field is two strips at declination $81.^\circ8 \pm 0.^\circ1$, from right ascension $15.^h27$ to $16.^h84$, and from $17.^h57$ to $19.^h71$ (all coordinates are J1994.5). Fig. 5. shows the fields observed in the 1992 and 1994 flights. The overlap between the fields is better than half a beamwidth throughout the flight. Our ability to observe exactly the same position on the sky is currently limited by the error in determining the position of the IR beam center during the initial in-flight calibration, i.e., our real-time determination of pointing is not as accurate as our post-flight determination.

4. Data Analysis

The signal from the detectors is contaminated by spikes induced by cosmic rays striking the detectors; we remove these spikes. The data are calibrated by our observation of Jupiter. The absolute pointing is determined from star camera images. The detector data are analyzed to provide measurements of brightness in our four spectral channels as a function of sky position. These are then fit to a spectral model to produce measurements of CMBR anisotropy and dust optical depth. These analyses and their results are described in the following sections.

4.1. Pointing

We determined the pointing by matching star camera images against a star catalog. This fixes the position of the camera frame at the time the exposure was taken. Between exposures, position is interpolated with the gyroscope outputs plus a small linear correction to make the gyroscope readings consistent with the camera fixes. This correction is typically $2'$ in 20 minutes. The relative orientation of the camera frame and the IR telescope beam is fixed by a simultaneous observation of Jupiter with the camera and the IR telescope. The resulting absolute pointing is accurate to $2.'5$, limited by the gyroscope drift correction. The pointing analysis was done in an identical way for the 1992 flight, and has similar accuracy.

4.2. Detector Data Reduction

The instrument is calibrated by in-flight observations of Jupiter. The brightness temperatures of Jupiter for our four spectral channels are 172, 170, 148, and 148 K, derived from the spectrum of Jupiter observed by Griffin *et al.* 1986. The apparent diameter of Jupiter during the 1994 flight is 42″. The uncertainty in the absolute calibration is 10%, dominated by uncertainty in the antenna temperature of Jupiter. The relative calibration uncertainty between the 1992 and 1994 flights is 5%, due to noise in the observations of Jupiter.

The detector signal contains spikes, at a rate of 0.25–0.5 s^{-1}, consistent with the hypothesis that they are due to cosmic rays striking the detectors (Charakhch'yan *et al.* 1978), and with the rate reported in Paper I. Cosmic rays deliver an unresolved energy impulse to the detector; we remove them by fitting the data to the impulse response function of the detector/amplifier/filter chain. We give here our results for the 5.6 cm^{-1} channel; the numbers for the other channels are similar. Candidate spike locations are identified using a $1.5\,\sigma$ threshold. The data within 1 s (5 detector time constants) are fit to a model of the response function. About 2% of the spikes require a second spike 2–10 samples separated from the first to be added to the fit. If the resulting spike amplitude has less than $3\,\sigma$ significance, the data is left as-is. If the fit is good, and the spike amplitude has more than $3\,\sigma$ significance, the spike template is subtracted. 5065 spikes are subtracted out of 504,000 time samples. (We allow either positive or negative amplitudes; 90% of the spikes have positive amplitude.) If the fit is poor, and the spike amplitude is significant, full data records (64 samples, or 2 sec) before and after the spike are deleted. 317 spikes were eliminated this way, removing a total of about 6% of the data.

We estimate the instrument noise by measuring the variance in the demodulated, deglitched data after removing a slow drift in time and the mean in each sky bin. This estimate is made for each 20 minute segment of data, and is then propagated throught the remaining processing. All χ^2 reported below are with respect to this error estimate.

We divide the sky into bins that are small compared to the beamsize. The bins are $0^{\rm h}\!\!.057$ in right ascension and $0\overset{\circ}{.}12$ in declination. Due to sky rotation, the data also need to be divided by angular orientation of the beam throw on the sky; the bin size for this coordinate is 10. The data are then fit to a signal in each sky bin plus a model of long-term drift formed from a cubic spline with knots every 12 minutes (2.5 minutes for the 16.5 cm^{-1} channel), plus terms for gondola inclination, roll, and air pressure. The simultaneous fit of long-term drift and sky signal ensures that this fit does not bias our observations of the sky. This fit is done separately on each channel and section of the flight. The resulting sky signals have bin-to-bin correlation, and we propagate a full covariance matrix through the remainder of the analysis. Sky bins containing less than 4 s of integration are deleted. So that our error estimate, described in the preceding paragraph, is unbiased by sky signal, we form the estimate from the residuals of this fit, and iterate to obtain a consistent solution.

The data are demodulated in two different ways. The double difference demodulation corresponds to summing the periods when the secondary is in the central position, and subtracting the periods when it is to either side.

This demodulation is least sensitive to atmospheric gradients and gondola swinging. The single difference demodulation is formed by differencing the period when the secondary is to the right from that when it is to the left, and ignoring the periods when the secondary is in the center. We use the scan over Jupiter to deduce optimal demodulations of the infrared signal.

The binned dataset contains 90% of all the data originally taken, with an achieved sensitivity in each of the four channels of 240, 150, 80, and 230 μK $\sqrt{\text{s}}$ Rayleigh-Jeans. For channels 1 and 2 this is 490 and 850 μK $\sqrt{\text{s}}$ CMBR. The offsets in the demodulated data for the different channels and demodulations range from 1 to 6 mK RJ, smaller than those reported in Paper I.

4.3. Spectral Decomposition

At each sky bin, we fit the four spectral channels to a model consisting of a CMBR anisotropy plus emission from warm Galactic dust. The results are not very sensitive to the parameters of the dust model; we use a dust temperature of 20 K and an emissivity index of 1.5 (consistent with Wright *et al.* 1991). The fit is done separately for the single and double difference demodulations. The χ^2/DOF for the fit is 408/430 (double difference) and 448/430 (single difference).

Fig. 5. shows the resulting fitted dust optical depth at 22.5 cm^{-1}. For clarity this figure has been binned more coarsely and does not distinguish between points at slightly different declination or chop orientation; our analyses, however, do not ignore these details. We have fit our observations to the *IRAS* Sky Survey Atlas at 100 μm (Wheelock *et al.* 1994) convolved with our beam patterns, with amplitude and offset as free parameters. The resulting fit is superimposed on Fig. 5.. The χ^2/DOF of this fit is 262/210 for the double difference demodulation and 310/210 for the single difference. The ratio of optical depths between IRAS and our data is consistent with an average dust emissivity spectral index between our bands and 100 μm of $\alpha = 1.40 \pm 0.16$ (still assuming a dust temperature of 20 K).

Our measurements of CMBR anisotropy are plotted in Fig. 5.. Superimposed are the measurements from 1992. As noted earlier, there is non-negligible correlation between the error bars on different sky bins. In making Fig. 5. we have fit out the two largest eigenmodes of the covariance matrix, and used error bars formed from the diagonal of the covariance matrix after removing the two largest eigenmodes; the result is that the error bars shown in the figure can be approximately treated as uncorrelated. (This procedure is similar to that used in Fixsen *et al.* 1994 for the *COBE*/FIRAS calibration.) The data have also been binned more coarsely, as in Fig. 5.. We stress that these steps are taken only for producing representative figures; in all quantitative analyses we use the full dataset and the full covariance matrix. We are in the process of calculating the correlation for the MSAM1-92 data; the 1992 data plotted here are identical to those in Paper I.

4.4. CMBR Anisotropy

To set limits on anisotropy in the CMBR, we assume Gaussian fluctuations with a Gaussian-shaped correlation function. We set 95% confidence level upper and lower bounds on the total rms fluctuation over the sky ($\sqrt{C_0}$), assuming this correlation function with a given correlation angle θ_c. The method used is described in Paper I, though we now use a full covariance matrix for the instrument noise on the observations. The upper and lower bounds from these observations for the single and double difference demodulations are shown in Fig. 5.. The bounds for the correlation angles at which the two demodulations are most sensitive are summarized in Table **??**, which also shows results for the two sections of the flight separately. The confidence intervals for both demodulations are consistent with those in Paper I.

5. Conclusions

We observed the same field in our 1992 and 1994 flights in order to determine if the detected signal was due to sidelobe pickup, atmospheric noise, or other systematic effects, or was in fact present in the sky. While we are still in the process of completing a detailed quantitative comparison of the two datasets, it is apparent that the double difference CMBR anisotropy features reproduce quite well. This encourages us to believe that the signal we see in the double difference is present on the sky, and that contamination from atmosphere or sidelobes is small compared to the sky signal. The single difference CMBR signal does not appear to reproduce as well. Pending the completion of the more thorough comparison, we cannot rule out contamination in the single difference channel.

In Paper I we pointed out that the anisotropy we observe could be due to diffuse Galactic bremsstrahlung. This possibility remains, and will be addressed by our MSAM2 experiment, which will observe the same fields in five bands over 65–170 GHz.

In Paper I we raised the possibility that the "sources" at R.A. 19 h and 15 h were either foreground sources of a previously unknown population, or non-Gaussian CMBR fluctuations. This speculation was prompted by our belief that such features were inconsistent with Gaussian statistics. More careful analysis by us and independently by Kogut, Hinshaw, and Bennett 1995 has indicated that features like these are in fact consistent with a variety of plausible correlation functions. Observations by Church *et al.* 1995 at 4.7 cm^{-1} rule out the source MSAM15+82 being more compact than $2'$. Therefore removal of these regions in studies of CMBR anisotropy, as we recommended in Paper I, are a biased edit of the data, and we no longer recommend it.

Our current conclusion is that the double difference, whole flight numbers in Table **??** are a reliable estimate of CMBR anisotropy in the observed regions. When we include the 10% uncertainty in the calibration, the resulting limits are $\Delta T/T = 1.9^{+1.3}_{-0.7} \times 10^{-5}$ (90% confidence interval) for total rms fluctuations. In the band power estimation of (Bond 1995), this is $\langle \mathcal{C}_l \rangle_B = 2.1^{+1.5}_{-0.9} \times 10^{-10}$ ($1\,\sigma$ limits), with $\langle l \rangle = 263$.

The CMBR anisotropy channel, Galactic dust channel, pointing, covariance matrices, and beammaps are publicly available. For more information, read `ftp://cobi.gsfc.nasa.gov/pub`

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The hatched circles show the sky coverage for the 1992 and 1994 flights as derived from the sky binning procedure. The beam size and chop spacing are indicated in the legend on the top of the plot. The region shown covers R. A. $14^{\rm h}.0$ to $20^{\rm h}.5$ and declination +80 to +84. The average declination difference between the two flights is $10'$.

Dust optical depth $\times 10^6$ at 22.5 cm^{-1}. The line is the brightness expected from *IRAS* 100 μm data, with the magnitude scaled to fit our observations. Scale at right is dust antenna temperature at 22.5 cm^{-1}. a) double difference, b) single difference.

Measured CMBR anisotropy. Points with diamonds are 1994 flight, crosses are 1992 flight. The telescope beam is superimposed. a) double difference, b) single difference.

Upper and lower limits on total rms $\Delta T/T$ as a function of correlation length for Gaussian-shaped correlation functions. Plotted are 95% CL upper limits for the double difference (solid), and single difference (long dashed); and 95% lower limits for the double difference (dashed) and single difference (dotted).