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MEASUREMENTS OF ANISOTROPY IN THE COSMIC MICROWAVE BACKGROUND RADIATION AT DEGREE ANGULAR SCALES NEAR THE STARS SIGMA HERCULIS AND IOTA DRACONIS

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ABSTRACT

We present results from two four-frequency observations centered near the stars Sigma Herculis and Iota Draconis during the fourth flight of the Millimeter-wave Anisotropy eXperiment (MAX). The observations were made of 6° × 0°.6 strips of the sky with a 1°.4 peak to peak sinusoidal chop in all bands. The FWHM beam sizes were calculated 0°.55 ± 0°.05 at 3.5 cm^{-1} and a 0°.75 ± 0°.05, at 6, 9, and 14 cm^{-1}. Significant correlated structures were observed at 3.5, 6, and 9 cm^{-1}. The spectra of these signals are inconsistent with thermal emission from known interstellar dust populations. The extrapolated amplitudes of synchrotron and free-free emission are too small to account for the amplitude of the observed structures. If the observed structures are attributed to CMB anisotropy with a Gaussian autocorrelation function and a coherence angle of 25′, then the most probable values at $\Delta T/T_{\rm CMB} = 3.1^{+1.7}_{-1.3} \times 10^{-5}$ for the Sigma Herculis scan, and $\Delta T/T_{\rm CMB} = 3.3^{+1.1}_{-1.1} \times 10^{-5}$ for the Iota Draconis scan (95% confidence upper, lower limits).

Subject headings: cosmic microwave background — cosmology: observations

1. INTRODUCTION

Measurements of the anisotropy of the cosmic microwave background (CMB) provide an effective method for testing and constraining models of cosmic structure formation. The *Cosmic Background Explorer* (*COBE*) satellite has detected anisotropy at large angular scales (Smoot et al. 1992). Recently, there has been a concerted effort to measure medium-scale anisotropy (Schuster et al. 1993; Gaier et al. 1992; Wollack et al. 1993; Cheng et al. 1994). The results of CMB observations during the second, third, and fourth balloon flights of the Millimeter-wave Anisotropy eXperiment (MAX) are reported in Alsop et al. (1991), Gundersen et al. (1993), Meinhold et al. (1993a), and Devlin et al. (1994). We report here on two medium-scale CMB anisotropy observations made during MAX 4 in low dust emission regions near the stars Sigma Herculis and Iota Draconis.

2. MEASUREMENT

The instrument has been described in detail elsewhere (Fischer et al. 1992; Alsop et al. 1992; Meinhold et al. 1993b). It consists of an off-axis Gregorian telescope and a bolometric photometer mounted on an attitude-controlled balloon platform which makes measurements at an altitude of 36 km. The new single-pixel four-band bolometric receiver used for this flight features negligible sensitivity to radio frequency (RF) interference, an additional frequency band at 3.5 cm^{-1}, and an adiabatic demagnetization refrigerator to cool the photometer to 85 mK (Clapp et al. 1993). The underfilled optics provide a 0°.55 ± 0°.05 FWHM beam in the single-mode 3.5 cm^{-1} band and 0°.75 ± 0°.05 FWHM beams in the multimode 6, 9, and 14 cm^{-1} bands, with bandwidths $\delta\nu/\nu = 0.57$, 0.45, 0.35, and 0.25 FWHM. To convert antenna temperatures to 2.726 K thermodynamic temperatures, multiply by 1.54, 2.47, 6.18, and 34.08.

The observations consisted of constant velocity scans in azimuth of ±3°.0 on the sky while tracking the pointing stars Sigma Herculis $\alpha = 16^{\rm h}30^{\rm m}$, $\delta = 42°46′$ and Iota Draconis $\alpha = 15^{\rm h}25^{\rm m}$, $\delta = 59°36′$ (epoch 1993). A complete scan from 3° to −3° and back to 3° required 108 s. We chose these regions for low dust emission from the *IRAS* 100 μm map (Wheelock et al. 1991). The Sigma Herculis scan lasted from UT = 8.73 to UT = 9.44 hr. The Iota Draconis scan lasted from UT = 7.15 to UT = 7.60 hr, both on 1993 June 15. Calibrations were made before and after each observation using the membrane transfer standard described in Fischer et al. (1992). Scans of Jupiter were made between UT = 5.08 and 5.33 hr to confirm the calibration. The Jupiter calibration agrees with the membrane calibration to 10% in each band. Hence we assume a 10% error in the absolute calibration. The instrument is calibrated so that a chopped beam centered at the boundary between regions with temperatures T_1 and T_2, would yield $\Delta T = T_1 - T_2$.

3. DATA REDUCTION AND ANALYSIS

Transients due to cosmic rays were removed using an algorithm described in Alsop et al. (1992), which removed 15%–20% of the data. No RF interference was observed. The detector output was demodulated using the sinusoidal reference to produce antenna temperature differences, ΔT_A, on the sky. The measured variance in each sky bin of data from each chopper cycle, averaged over an observation, gives noise levels of 580, 545, 770, and 2660 μk s^{-1} in CMB thermodynamic units in the 3.5, 6, 9, and 14 cm^{-1} bands, respectively. Due to

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noise from a faulty JFET, only 30% of the 6 cm^{-1} data from the Sigma Herculis scan, and 37% of the 6 cm^{-1} data from the Iota Draconis scan, were usable.

Each of the bands has an instrumental offset, identified in previous flights as the algebraic sum of two effects. Chopped emissivity differences on the primary mirror give antenna temperatures that are independent of frequency, elevation angle, and nearly constant in time. Chopped atmospheric emission gives a signal whose amplitude increases with frequency, decreases with elevation angle, and varies slowly with time. The averages of the measured offsets in antenna temperature were 3.0, 1.2, 0.9, 0.7 mK at 3.5, 6, 9, and 14 cm^{-1} No offset drift was observed in the 3.5 cm^{-1} band. In the higher frequency bands the value of the offset drifted slowly as a function of time. Subtraction of the offsets and drifts by a linear least squares fit to each half scan reduced the noise somewhat at 6, 9, and 14 cm^{-1}. No significant changes in the astrophysical signal levels were observed, as expected, since MAX is not sensitive to such large angular scales.

For each scan, the means, variances, and 1 σ error bars of the antenna temperature differences were calculated for 21 pixels separated by 17′ on the sky. The data are available from the authors. Most of the essential features of the data are apparent in Figures 1*a* and 1*b*. In both observations there is statistically significant correlated structure in the 3.5, 6, and 9 cm^{-1} bands. The amplitude of the structures, as measured in antenna temperature, decreases with increasing frequency. There is no significant signal at 14 cm^{-1} in the Sigma Herculis scan, but there is a small uncorrelated signal at 14 cm^{-1} in the Iota Draconis scan. The correlations for the Sigma Herculis scan are 0.55 (3.5–6), 0.46 (3.5–9), 0.21 (6–9). The correlations for the Iota Draconis scan are 0.33 (3.5–6), 0.43 (3.5–9), 0.42 (6–9), −0.03 (3.5–14), 0.12 (6–14), 0.20 (9–14). Both the values of the rms ΔT_A, corrected for the contribution from detector noise, and the probability of reproducing the measured rms ΔT_A with Gaussian random noise are shown in Table 1. The error on each rms includes a statistical error and a $\pm 10\%$ estimate for the uncertainty in the calibration.

In order to further test the hypothesis that the signals in the 3.5, 6, and 9 cm^{-1} bands are correlated, a best-fit model was determined by minimizing

$$\chi_R^2 = \sum_{j=1}^{3} \sum_{i=1}^{21} (x_{ij} - a_j y_i)^2/\sigma_{ij}^2 . \quad (1)$$

Here x_{ij} and σ_{ij} are the measured means and variances of the 21 pixels, y_i represents the best-fit sky model, and a_j the best-fit model scale factor for band j. For Sigma Herculis, the probability of exceeding the residual χ_R^2 is 0.20. For Iota Draconis, the probability of exceeding the residual χ_R^2 is 0.48. These good three-band fits indicate that essentially all of the signal in excess of noise in these bands is correlated and consistent with a single spatial distribution of emission. The spectral analysis of the signals must take into account the 0°.55 FWHM beam in

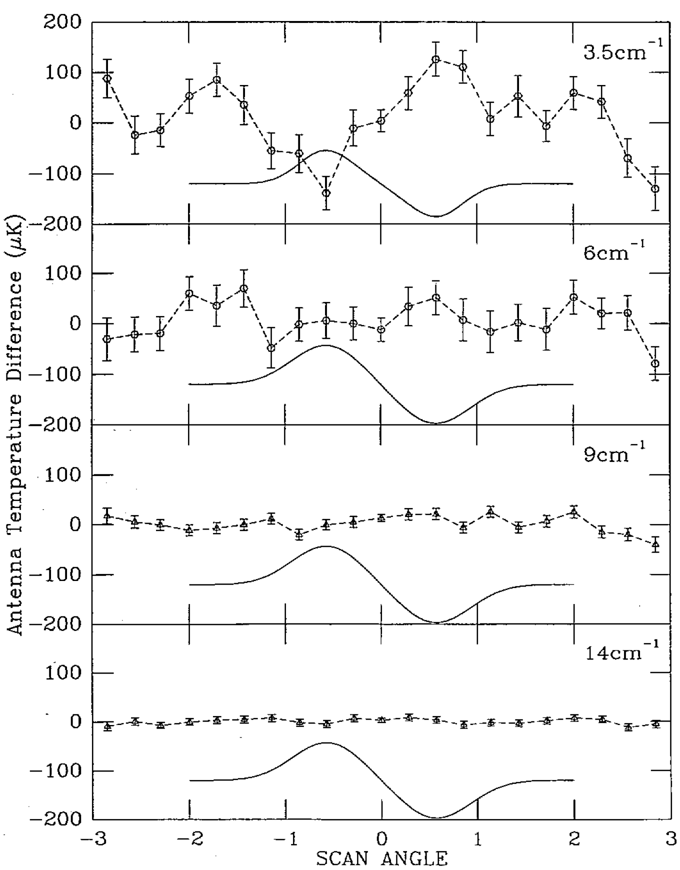

FIG. 1*a*

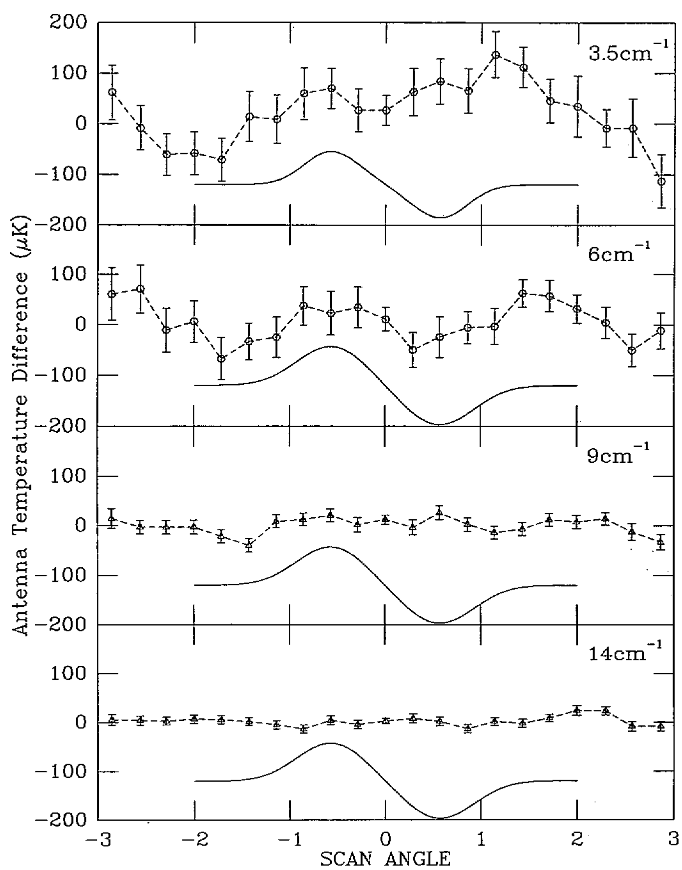

FIG. 1*b*

FIG. 1.—(*a–b*) Antenna temperature differences ($\pm 1\ \sigma$) for the 0.71 hr of data near Sigma Herculis (*a*) and the 0.45 hr of data near Iota Draconis (*b*). Each point is separated by 17′ in azimuth. The solid lines show the response to a point source in each of the bands.

TABLE 1

SIGNAL ROOT MEAN SQUARE IN ANTENNA TEMPERATURE, AND PROBABILITY OF OBSERVED SIGNALS

Band (cm^{-1})	Signal RMS (μK)	Probability
Sigma Herculis Data		
3.5	57 ± 14	$<10^{-9}$
6	13 ± 8	0.30
9	11 ± 3	0.05
14	0 ± 2	0.83
Iota Draconis Data		
3.5	41 ± 14	$<10^{-3}$
6	19 ± 9	0.20
9	9 ± 4	0.06
14	4 ± 2	0.24

the 3.5 cm^{-1} band compared with the 0°75 FWHM beam in the other bands. Table 2 shows the ratio of the signal amplitudes in our bands, and compares them with the ratios predicted by several relevant sky models which specify both the spectrum and angular distribution of emission.

4. POTENTIAL SYSTEMATIC ERRORS

During the entire MAX4 flight, the Sun and Moon were both below the horizon. The unchopped telescope response was measured to be ≥ 65 dB below the peak response elevation at angles from 13° to 35° below the boresight. The design of the telescope baffles was modified for this flight to ensure that no direct or reflected emission from the Earth or balloon could directly illuminate the optical system.

During this flight of the MAX experiment, a region near the star Gamma Ursa Minoris (GUM) was also observed (Devlin et al. 1994). This region of the sky has been observed 3 times by MAX, each with substantially altered baffles, and in this flight with a new receiver and different beam sizes. The elevation of GUM ranged from near 30° in the first observation, near 35° in the second observation to near 48° in the third observation. In each case a comparable signal amplitude was observed, with a spectrum consistent with CMB. It is very unlikely that sidelobe contamination would be reproducible at this level under such drastically changed observing conditions.

TABLE 2

RATIOS OF THE BEST-FIT SIGNAL AMPLITUDES FOR PAIRS OF BANDS COMPARED WITH THEORETICAL MODELS OF EMISSION

Channel Ratio	6/3.5	9/3.5
Best-Fit antenna temperature[a] for Sigma Herculis	0.34 ± 0.12	0.12 ± 0.06
Best-Fit antenna temperature[a] for Iota Draconis	0.46 ± 0.16	0.20 ± 0.07
CMB[b]	0.62	0.25
CMB CDM[c]	0.50	0.20
CMB unresolved source[d]	0.34	0.13
Free-Free[b]	0.37	0.16
Free-Free unresolved source[d]	0.20	0.08

[a] Best-fit ratio $\pm 1\ \sigma$ error. This includes a 10% calibration error.

[b] Ratios calculated with no beam size correction.

[c] Ratios calculated using CMB power spectrum (Sugiyama et al. $\Omega_B = 0.03$, $h = 0.5$) to correct for beam size difference.

[d] Ratios calculated for a point source response. These are considered a lower limit. The uncorrected ratios (see footnote b) are upper limits.

5. FOREGROUND SOURCES

Potential foreground sources of confusion include the atmosphere, interstellar dust emission, synchrotron radiation, free-free emission, the Sunyaev-Zel'dovich (SZ) effect, and radio point sources. The amplitude of the emission in the 14 cm^{-1} band provides stringent limits on flat or rising spectra such as emission from 20 K galactic dust, ambient temperature objects, or the atmosphere. Based on an extrapolation from the *IRAS* 100 μm data (Wheelock et al. 1991) and scaling the brightness by the spectrum for high latitude dust reported by Meinhold et al. (1993a), the differential dust emission in the Sigma Herculis and Iota Draconis regions is expected to be a factor of 2 below the structures measured at 14 cm^{-1} and a factor of 60–100 below the structures measured at 3.5 cm^{-1}. The observed anisotropy is inconsistent with the thermal SZ effect, which would produce anticorrelated structure at 6 and 9 cm^{-1}.

Convolving our scan pattern with the $30' \times 30'$ smoothed version of the 408 MHz Haslam et al. (1982) map and assuming a scaling law $\Delta T_A \propto \nu^{\beta}$ for synchrotron emission, with $\beta = -2.7$, gives rms $\Delta T_A \leq 0.38$, 0.06, 0.02, and 0.006 μK at 3.5, 6, 9, and 14 cm^{-1}, respectively. These estimates account for less than 1% of the observed structure for the Sigma Herculis scan, with similar results for Iota Draconis.

Making the very conservative assumption that the entire 408 MHz rms is due to free-free emission and extrapolating to our frequencies using $\Delta T_A \propto \nu^{-2.1}$ give less than 15% of the measured rms for the Sigma Herculis scan, and less than 25% of the measured rms for Iota Draconis. These amplitude considerations show that free-free emission is not likely to be a large contaminant of the observed signals. A thorough catalog search has been made for bright or inverted spectrum radio sources in these regions. There are no radio point sources of sufficient brightness to produce a measurable signal in either of these scans.

6. DISCUSSION

Since all of the known possible foreground contaminants are considered unlikely, and the spectrum of the structure is consistent with CMB anisotropy, the following discussion interprets the observed structure as CMB anisotropy. The rms of the data give $\Delta T_{\rm rms}/T_{\rm CMB} = 3.2 \pm 0.7 \times 10^{-5}$, $1.20 \pm 0.8 \times 10^{-5}$, and $2.5 \pm 0.8 \times 10^{-5}$ (68% confidence level) for the Sigma Herculis scan, and $\Delta T_{\rm rms}/T_{\rm CMB} = 2.3 \pm 0.8 \times 10^{-5}$, $1.7 \pm 0.8 \times 10^{-5}$ and $2.1 \pm 0.8 \times 10^{-5}$ (68% confidence level) for the Iota Draconis scan, in the 3.5, 6, and 9 cm^{-1} bands, respectively. By integrating the window function for each of the bands over a cold dark matter (CDM) model with $\Omega_B = 0.03$ and h = 0.5 (Sugiyama & Gouda 1993) normalized to the rms amplitude of the anisotropy measured by *COBE* at $\theta > 10°$ (Smoot et al. 1992) a prediction of the rms amplitudes expected for MAX can be made. For the 3.5 cm^{-1} band this is $\Delta T_{\rm rms}/T_{\rm CMB} = 2 \times 10^{-5}$ and for the 6 and 9 cm^{-1} bands $\Delta T_{\rm rms}/T_{\rm CMB} = 1.6 \times 10^{-5}$. The sampling variance, due to the small fraction of sky covered, expected for a single MAX scan is $\approx$25% (Scott et al. 1994).

We have analyzed the data assuming the CMB anisotropy is described by a Gaussian autocorrelation function (GACF) with a coherence angle of 25′. For measurements near the Doppler peak of a standard recombination CDM model, this

TABLE 3

SUMMARY OF MAX RESULTS[a]

MAX 2 GUM	$4.5^{+5.7}_{-2.6} \times 10^{-5}$
MAX 3 Mu Pegasus	$1.5^{+1.1}_{-0.7} \times 10^{-5}$
MAX 3 GUM	$4.2^{+1.7}_{-1.1} \times 10^{-5}$
MAX 4 GUM	$3.7^{+1.9}_{-1.1} \times 10^{-5}$
MAX 4 Iota Draconis	$3.3^{+1.1}_{-1.1} \times 10^{-5}$
MAX 4 Sigma Herculis	$3.1^{+1.7}_{-1.3} \times 10^{-5}$

[a] Most probable values of measured signal amplitudes $\Delta T/T_{\rm CMB}$, assuming a Gaussian autocorrelated sky with a coherence angle of 25′ (95% confidence upper and lower limits).

is a useful approximation. A description of the GACF autocorrelation function analysis used for these data is given in Cheng et al. (1994). The GACF analysis gives most probable values in the 3.5, 6, and 9 cm^{-1} bands of $\Delta T/T_{\rm CMB} = 3.8^{+2.7}_{-1.9} \times 10^{-5}$, $1.2^{+3.2}_{-1.0} \times 10^{-5}$, and $2.6^{+2.8}_{-1.7} \times 10^{-5}$ for the Sigma Herculis scan, and $\Delta T/T_{\rm CMB} = 3.4^{+1.1}_{-1.8} \times 10^{-5}$, $3.3^{+3.5}_{-2.1} \times 10^{-5}$, and $2.8^{+3.4}_{-2.0} \times 10^{-5}$ for the Iota Draconis scan (95% confidence upper, lower limits), respectively. These three numbers can be combined in a simple way by multiplying a fit to the likelihood functions to give $\Delta T/T_{\rm CMB} = 3.1^{+1.7}_{-1.3} \times 10^{-5}$ for the Sigma Herculis scan and $\Delta T/T_{\rm CMB} = 3.3^{+1.1}_{-1.1} \times 10^{-5}$ for the Iota Draconis scan (95% confidence upper, lower limits).

A complete summary of all medium-scale CMB anisotropy results from the MAX experiments is given in Table 3. All these values were determined assuming a CMB described by a GACF with a coherence angle of 25′. All of the scans are statistically consistent, except for the MAX3 Mu Pegasus scan. This scan was different from the other, in that a significant galactic dust signal was present in the data, and was subtracted in the analysis. Calculating a weighted mean and uncertainty in that mean for the six MAX measurements in Table 3, the result is $\Delta T/T_{\rm CMB} = 2.9 \pm 0.5 \times 10^{-5}$. The χ^2 for these six measurements is then 16.9, with a probability of exceeding this χ^2 of 0.5%. This low probability could indicate either a systematic error in the experiment, or that the assumed model of a Gaussian sky is incorrect. If the MAX3 Mu Pegasus scan is excluded, the weighted mean and uncertainty in that mean is $\Delta T/T_{\rm CMB} = 3.6 \pm 0.2 \times 10^{-5}$. The χ^2 for these five measurements is 2.5, with a probability of exceeding this χ^2 of 63%.

7. CONCLUSION

We have presented new results from a search for CMB anisotropy with high sensitivity at angular scales near 1°. Significant structure is detected in the 3.5, 6, and 9 cm^{-1} bands. If all of the structure is attributed to CMB anisotropy with a Gaussian autocorrelation function and coherence angle of 25′ then the most probable values are $\Delta T/T_{\rm CMB} = 3.1^{+1.7}_{-1.3} \times 10^{-5}$ for the Sigma Herculis scan, and $\Delta T/T_{\rm CMB} = 3.3^{+1.1}_{-1.1} \times 10^{-5}$ for the Iota Draconis scan, respectively (95% confidence upper and lower limits). Based on spectral and temporal arguments, sidelobe contamination from Earth, the balloon, and the Galaxy are considered unlikely to cause the observed structure. The data rule out Galactic dust emission via the spectrum, morphology, and amplitude of the structure. Synchrotron and free-free emission are considered unlikely contaminants from estimates of the intensity based on low-frequency maps. The spectrum of the signals at 3.5, 6, 9, and 14 cm^{-1} is consistent with CMB anisotropy.

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