MEASUREMENTS OF ANISOTROPY IN THE COSMIC MICROWAVE BACKGROUND RADIATION AT 0.5 SCALES NEAR THE STARS HR 5127 AND $\phi$ HERCULIS

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ABSTRACT

We present measurements of cosmic microwave background (CMB) anisotropy near the stars HR 5127 and $\phi$ Herculis from the fifth flight of the Millimeter-wave Anisotropy eXperiment (MAX). We scanned 8° strips of the sky with an approximately Gaussian 0.5° FWHM beam and a 1° peak to peak sinusoidal chop. The instrument has four frequency bands centered at 3.5, 6, 9, and 14 cm$^{-1}$. The IRAS 100 $\mu$m map predicts that these two regions have low interstellar dust contrast. The HR 5127 data are consistent with CMB anisotropy. The $\phi$ Herculis data, which were measured at lower flight altitudes, show time variability at 9 and 14 cm$^{-1}$, which we believe to be due to atmospheric emission. However, the $\phi$ Herculis data at 3.5 and 6 cm$^{-1}$ are essentially independent of this atmospheric contribution and are consistent with CMB anisotropy. Confusion from Galactic foregrounds is unlikely based on the spectrum and amplitude of the structure at these frequencies. If the observed HR 5127 structure and the atmosphere-independent $\phi$ Herculis structure are attributed to CMB anisotropy, then we find $\Delta T/T = (\langle I(l + 1)C^2\pi \rangle)^{1/2} = 1.2_{-0.4}^{+0.4} \times 10^{-5}$ for HR 5127 and $1.9_{-0.7}^{+0.7} \times 10^{-5}$ for $\phi$ Herculis in the flat band approximation. The upper and lower limits represent a 68% confidence interval added in quadrature with a 10% observation uncertainty.

Subject headings: cosmic microwave background — cosmology: observations

1. INTRODUCTION

Measurements of the anisotropy of the cosmic microwave background (CMB) provide an effective method for constraining models of large-scale structure formation. Standard inflationary models predict a Doppler peak at angular scales $\approx 1^\circ$. The Millimeter-wave Anisotropy eXperiment (MAX) measures anisotropy on 0.5 angular scales. MAX has presented CMB results for six sky regions from four previous flights: MAX1 (Fischer et al. 1992), MAX2 (Alsop et al. 1992), MAX3 (Meinhold et al. 1993a; Gundersen et al. 1993; Fischer et al. 1995), and MAX4 (Clapp et al. 1994; Devlin et al. 1994). Several other ground-based and balloon-borne experiments have also reported detections at these angular scales (de Bernardis et al. 1994; Gundersen et al. 1995; Netterfield et al. 1995; Ruhl et al. 1995; Cheng et al. 1996). In this paper we report on two new CMB observations from the fifth flight of MAX (MAX5).

2. INSTRUMENT

The instrument has been described in detail elsewhere (Fischer et al. 1992; Alsop et al. 1992; Meinhold et al. 1993b). MAX is an off-axis Gregorian telescope with a bolometric photometer mounted on an attitude-controlled balloon plat-
best-fit beam size and the temperature of Jupiter (Griffin et al. 1986). We assume a 10% uncertainty in calibration. The calibration is such that a chopped beam centered between sky regions with temperatures $T_1$ and $T_2$ would yield $\Delta T = T_1 - T_2$ in the absence of instrumental noise.

Anisotropy experiments are potentially susceptible to off-axis response to local sources. We measured the unchopped off-axis response in the 3.5 cm$^{-1}$ band to be $\pm 70$ dB below the on-axis response at angles from $15^\circ$ to $25^\circ$ in elevation above the bore sight. We have not made comparable measurements of the chopped sidelobe response in azimuth. Our strongest argument against sidelobe contamination is that the observed structure is stationary on the sky while the horizon and local foregrounds shift. The elevation of the observation changes from $42^\circ$ to $31^\circ$ and from $46^\circ$ to $39^\circ$ for HR 5127 and $\phi$ Herculis, respectively. Sidelobe response from the Earth and the balloon should change over time. To minimize sidelobe response from the Moon, we observe when the Moon is not full. The Moon was $\sim 56^\circ$ away from HR 5127 and $\sim 66^\circ$ away from $\phi$ Herculis.

4. DATA ANALYSIS

4.1. Data Reduction

We exclude $\sim 15\%$ of the data in the removal of transients due to cosmic rays (Alsop et al. 1992). We demodulate the detector output using the sinusoidal reference from the chopping secondary to produce antenna temperature differences $\Delta T_a$ on the sky. The demodulation produces data sets in phase and $90^\circ$ out of phase with the optical signal as defined by the calibration. The noise averaged over the observations gives respective CMB sensitivities of 590, 270, 620, and 4800 $\mu$K s$^{1/2}$ for HR 5127 and 600, 300, 630, and 4800 $\mu$K s$^{1/2}$ for $\phi$ Herculis in the 3.5, 6, 9, and 14 cm$^{-1}$ bands. The slight differences in sensitivies are due to long timescale drifts in instrument gain.

The signal in each band is offset from zero for both observations because of chopped primary mirror emissivity differences and chopped atmospheric emission. The mean instrumental offsets in antenna temperature were 0.7, 0.2, 1.5, and 3.0 mK in the 3.5, 6, 9, and 14 cm$^{-1}$ bands. The offset fluctuates with a period of $\sim 300$ s and amplitudes of 200 $\mu$K and 300 $\mu$K at 9 and 14 cm$^{-1}$. We subtract the offset and offset drift with a linear least-squares fit to each 72 s half-scan from 0$^\circ$ to $\pm 4^\circ$ to 0$^\circ$. This method removes the $\sim 300$ s fluctuations as long as the fluctuations are not phase-synchronous with the scan period. The residual temporal correlation between frequency bands is a few percent.

For each observation, we calculate the means and $1\sigma$ uncertainties of the $\Delta T_a$ for 29 pixels separated by $17^\circ$ on the sky. The uncertainties are consistent with the integration time and the Gaussian random instrument noise. Figure 1 shows the measured $\Delta T_a$ for the HR 5127 observation. There is significant signal that is not consistent with Gaussian random instrument noise. (Reduced $\chi^2 = 49/29$, 156/29, 86/29, and 77/29 at 3.5, 6, 9, and 14 cm$^{-1}$.) By comparison, the out of phase components are consistent with Gaussian random instrument noise. (Reduced $\chi^2 = 42/29$, 38/29, 15/29, and 35/29 at 3.5, 6, 9, and 14 cm$^{-1}$.) In addition to the correlated structure at 3.5, 6, and 9 cm$^{-1}$, there is structure at 14 cm$^{-1}$. If we divide the observation into two equal time periods, the differences between the two halves are consistent with zero at 3.5 and 6 cm$^{-1}$ (reduced $\chi^2 = 21/29$ and 22/29), suggesting that the signal is neither sidelobe response nor atmospheric emission. We interpret the time variable structure at 9 and 14 cm$^{-1}$ as atmosphere (reduced $\chi^2 = 34/29$ and 55/29).

4.2. Spectral Discrimination

In order to test the hypothesis that the signals in all frequency bands originate from a single morphology, we determined a best-fit sky model $y_i$ by minimizing

$$\chi^2 = \sum_{j=1}^{j=1} \sum_{i=1}^{i=1} (x_{ij} - a_j y_i)^2 / \sigma^2_{ij},$$

where $x_{ij}$ and $\sigma_{ij}$ are the measured mean and uncertainty in angular bin $i$ for frequency band $j$. The $a_j$ denote the set of
scale factors for an astrophysical process. Table 1 gives reduced $\chi^2$ using scale factors $a_i$ for CMB, free-free, synchrotron, and dust emission. The HR 5127 data set is spectrally consistent with free-free, synchrotron, and CMB emission. The complete $\phi$ Herculis data set is not spectrally consistent with any of the processes. However, the $\phi$ Herculis data at 3.5 and 6 cm$^{-1}$ are spectrally inconsistent with synchrotron emission and spectrally consistent with free-free, dust, and CMB emission.

4.3. Galactic and Extragalactic Emission
At 6, 9, and 14 cm$^{-1}$, the predominant astrophysical source of confusion is thermal emission from interstellar dust. Using a brightness scaling for high-latitude dust (Meinhold et al. 1993a; Fischer et al. 1995), we can extrapolate the IRAS 100 $\mu$m data (Wheeler et al. 1994) to our frequency bands. At most, we expect the differential dust emission to contribute a few microkelvins in antenna temperature at 14 cm$^{-1}$ and negligibly at lower frequencies in both HR 5127 and $\phi$ Herculis. The observed 14 cm$^{-1}$ structure in $\phi$ Herculis does not correlate with the structure obtained by convolving our beam and scan pattern with the IRAS 100 $\mu$m map.

The Herbig & Readhead (1992) catalog has no bright radio sources in either region. The convolution of our scan pattern with the 30$'$ x 30$'$ smoothed 408 MHz Haslam et al. (1982) map sets conservative amplitude limits on free-free and synchrotron emission. Assuming antenna temperature scales as $T_A^{1.4}$, we obtain $\lesssim 1\%$ and $\lesssim 10\%$ of the observed structure at 3.5 cm$^{-1}$ for synchrotron ($\beta = -2.7$) and free-free emission ($\beta = -2.1$), respectively.

4.4. Atmosphere

During the $\phi$ Herculis observation the balloon altitude dropped to 32 km. Altitude fluctuations of $\sim 50$ m every $\sim 300$ s correlate with $\sim 300$ $\mu$K detector offset fluctuations at 14 cm$^{-1}$. If we process the balloon altitude like a detector signal, removing offset and offset drift for each half-scan and calculating a mean for each azimuth bin, we find that the 14 cm$^{-1}$ structure in $\phi$ Herculis correlates with the binned balloon altitude with a linear correlation coefficient $R = -0.68$, suggesting that the observed structure is due to atmospheric contamination. We expect to observe less atmospheric emission during the HR 5127 observation because the average balloon altitude was 35 km.

If all the structure at 14 cm$^{-1}$ is attributed to modeled atmospheric contamination (Airhead Software, Boulder, CO), we obtain $<5\%$ and $<10\%$ of the observed structure at 3.5 and 6 cm$^{-1}$, respectively. The structure at 3.5 and 6 cm$^{-1}$ is also less correlated with the binned balloon altitude ($R = -0.09$ and $-0.17$). In our CMB analysis of $\phi$ Herculis, we consider only the 3.5 and 6 cm$^{-1}$ data. An alternative analysis that considers the linear combinations of all frequency band data orthogonal to the atmospheric contamination yields the same CMB anisotropy confidence intervals within 5%. Similar analyses have been used to separate CMB from other astrophysical sources (Dodelson & Stebbins 1994).

5. DISCUSSION

We model the anisotropy with a correlation function $(\Delta T(x_1) \Delta T(x_2)) = C_0(\theta)$, using a likelihood ratio statistic to set limits on the amplitude of the fluctuations $C_0^{1/2}$ (Cheng et al. 1994). We include correlations between frequency bands in the covariance matrix. However, the off diagonal elements affect the calculated values of $C_0^{1/2}$ by $\pm 2\%$.

To set limits on the CMB anisotropy, we include the 3.5, 6, and 9 cm$^{-1}$ data for the HR 5127 observation and the 3.5 and 6 cm$^{-1}$ data for the $\phi$ Herculis observation. Assuming a

\begin{table}[h]
\centering
\begin{tabular}{lcccc}
\hline
Observation & CMB & Free-Free$^b$ & Synchrotron$^c$ & Dust$^d$ \\
\hline
HR 5127 & 97/87 & 92/87 & 100/87 & 136/87 \\
$\phi$ Herculis & 119/87 & 132/87 & 164/87 & 170/87 \\
$\phi$ Herculis (3.5 and 6 cm$^{-1}$ only) & 25/29 & 36/29 & 50/29 & 29/29 \\
\hline
\end{tabular}
\caption{Spectral Constraints$^a$}
\end{table}

$^a$ Reduced $\chi^2$ from eq. (1), using $a_i$ for different astrophysical processes. Calibration uncertainty included.

$^b$ Assumes brightness $I_r \propto \nu^{0.1}$.

$^c$ Assumes $I_r \propto \nu^{-0.7}$.

$^d$ Assumes $I_r \propto \nu^{4.8} \times B_r (T=18 \text{ K})$, where $B_r$ is the Planck function.
Gaussian 0.5 FWHM beam, we present two measures of the fluctuations in Table 2 for each observation. We find the 68% confidence interval for $C_1^{1/2}$ for a Gaussian correlated sky $c(\theta) = \exp \left(-\theta^2/2\theta^2\right)$ where $\theta_c = 25''$ (GACF). The central value represents the $C_1^{1/2}$ for which the cumulative distribution function equals 50%. We also find a flat band power estimate \( (l(l+1)C_{l}/2\pi)^{1/2} \) for $c(\theta) = (1/4\pi) \sum (2l+1)C_{l}(\cos \theta)$ where $C_{l} \propto 1/(l+1)$.

Table 2 also lists MAX4 CMB anisotropy results. The GACF limits are as much as 20% lower than previously published (Clapp et al. 1994; Devlin et al. 1994). The previous MAX4 analyses did not include sufficient power in the off-diagonal elements and improperly normalized the larger beam sizes in the theoretical covariance matrix. The distributed data sets have not changed.

Bayesian analyses and likelihood ratio analyses of the MAX4 and MAX5 data sets yield similar $\Delta T/T$ confidence intervals except for $\sigma$ Herculis. The 68% confidence interval GACF $\Delta T/T$ for $\sigma$ Herculis is $4.0_{-1.7}^{+1.8} \times 10^{-5}$ for a Bayesian analysis and $2.8_{-0.7}^{+2.9} \times 10^{-5}$ for a likelihood ratio analysis. The discrepancy between the two analyses is being investigated.

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