MAX SEARCHES FOR INTERMEDIATE-SCALE ANISOTROPY OF THE COSMIC MICROWAVE BACKGROUND

Space Sciences Laboratory and Department of Physics, University of California, Berkeley, CA 94720, U.S.A.

J. GUNDERSEN, P. MEINHOLD, M. LIM AND P. LUBIN
Department of Physics, University of California at Santa Barbara, Santa Barbara, CA 93106, U.S.A.

G. SMOOT
Lawrence Berkeley Laboratory, Berkeley, CA 94720, U.S.A.

(Received 6 August 1993)

Abstract—The balloon-borne Millimeter-Wave Anisotropy Experiment (MAX) is designed to measure the fluctuations in the cosmic microwave background (CMB) on angular scales from 0.3 to several degrees. The long term goal is to measure many pixels on the sky at a level approaching $\Delta T/T(CMB) = 1 \times 10^{-4}$. These angular scales fill an important gap between the angular scales < 10 arcmin which are accessible from conventional radio telescopes and the angular scales > 7 deg which have been measured by the COBE satellite. They are of particular importance to scientific issues such as galaxy formation, dark matter, and the Sunyaev–Zel’dovich effect.

I. INTRODUCTION

The MAX experiment, which was flown for the fourth time in June 1993, currently consists of a four-band dichroic bolometric photometer mounted on a 1-m low background off-axis balloon telescope with an 0.5° FWHM beam in all bands. It can be pointed to an accuracy of 1 arcmin and has a nutating secondary mirror. The experiment is carried out by modulating the beam on the sky sinusoidally through $\pm 0.68^\circ$ while scanning the azimuth angle continuously over 6° to produce $\sim 15$ independent measurements of temperature differences on the sky. By choosing a region to the east or the west it is possible to observe a 6° long line on the sky for 1.4 h.

The dichroic photometer used for MAX has 20–30% filter bands at 3, 6, 9 and 15 cm$^{-1}$ which cover the high frequency side of the window between galactic dust emission at higher frequencies and galactic synchrotron and free–free emission at lower frequencies. Much has been learned from the third flight of MAX about the relation between millimeter wave dust emission and IRAS 100 $\mu$m dust emission in dark regions of the sky. Useful regions for CMB observations exist where confusion due to conventional galactic dust emission contrast on the MAX angular scale is estimated to be equal to or less than $\Delta T/T(CMB) = 2 \times 10^{-6}$ at 6 cm$^{-1}$. Tight limits have also been placed on the possibility of emission from cold dust. Despite this progress, it is not clear whether balloon CMB anisotropy measurements like MAX or lower frequency ground-based measurements will have less problem with foreground sources. The COBE data are not directly applicable since each source of interference has its own dependence on angular scale. For example, the 100 $\mu$m IRAS dust emission contrast decreases$^{(1)}$ with decreasing angular scale.

As described below, observations near the star Mu Pegasi during the third flight of MAX reported by Meinhold et al.$^{(2)}$ give upper limits to CMB fluctuations of $\Delta T/T \leq 2.35 \times 10^{-3}$ for
angular scales of 25 arcmin. Observations near the star Gamma Ursae Minoris during the second and third flights of MAX reported by Alsop et al.\(^5\) and Gundersen et al.\(^6\) show structure on the sky at the level of \(\Delta T_{\text{max}} / T(\text{CMB}) = 4.7 \pm 0.8 \times 10^{-5}\) on the same angular scale, which may be CMB anisotropy. If confirmed, this observation, together with the COBE normalization of the power spectrum of CMB fluctuations will provide a powerful test of mechanisms for structure formation in the universe.

The capabilities of the MAX experiment are being continuously upgraded. The bolometers are now cooled to 85 mK with an adiabatic demagnetization refrigerator (ADR) to obtain a single chopped CMB sensitivity of \(\sim 100 \mu\text{K}\sqrt{\text{s}}\), which will produce measurements at \(\Delta T_{\text{max}} / T(\text{CMB}) \sim 3 \times 10^{-6}\). This is a factor \(\sim 3\) better than the 300 mK photometer used on the third flight. The spectral coverage was extended by adding a band at 3 cm\(^{-1}\) for the fourth flight. Work is well advanced on a 1.3 m telescope that will permit smaller beam sizes, larger modulation amplitudes and is compatible with multi-pixel arrays. Designs for an 8 pixel four-color dichroic receiver are in progress.

The ADR and 85 mK bolometers now being used for MAX were developed for the long wavelength bands on SIRTF. The use of ADR’s for astronomy was first proposed by one of the authors in 1977 and a miniature demonstration ADR was reported by Britt and Richards.\(^5\) The SIRTF ADR has been described by Timbie et al.\(^6\) and more recently by Clapp et al.\(^7\) Although the bolometric bands were removed from SIRTF to reduce cost, this remains the technology of choice for millimeter and submillimeter wave photometry from space. Future applications include the Submillimeter Intermediate Mission and the Far-InfraRed Explorer (which is being designed to carry out the SIRTF long-wavelength science) as well as the FIRST mission of the European Space Agency.

The paper is organized as follows. After a brief discussion of the scientific goals of MAX in Section II, a summary is given in Section III of results from the third flight. The summary borrows freely from recent reports by Meinhold et al.\(^5\) and Gundersen et al.\(^6\). Section IV then describes the improvements made in MAX for the fourth flight and the scientific goals of that flight.

**II SCIENCE**

*CMB anisotropy*

Measurements of the anisotropy of the cosmic microwave background (CMB) provide an effective method for testing and constraining models of cosmic structure formation. At small angular scales (<10') these measurements provide constraints on scenarios of galaxy formation. To date, only upper limits have been established on the anisotropy of the CMB at these small angular scales.\(^8\) On large angular scales (>2'), anisotropy measurements probe causally disconnected regions of the sky and provide critical information on the primordial gravitational potential fluctuations. The COBE satellite has detected anisotropy at angular scales >7'.\(^9\) Anisotropy measurements on medium angular scales constrain scenarios of large scale structure formation and the values of certain global parameters in cosmic evolution models.\(^10,11\) Over the past 4 years, there has been a concerted effort to search for medium scale anisotropy.\(^12,13,14\)

Measurements of CMB anisotropy over a range of angular scales can be interpreted as constraining the power spectrum of the fluctuations as a function of angular frequency (or the quantum number \(l\) of the spherical harmonic). Figure 1 shows two theoretical power spectra\(^15\) computed for generic cold dark matter (CDM) models with \(\Omega = 1\). The theoretical results are sensitive to assumptions such as the Baryon density \(\Omega_b\) as is shown. Figure 1 also shows the window functions over which various experiments sample the power spectrum. Experiments such as COBE and the MIT balloon experiment, which have no sky chopping, have window functions which extend to small \(l\). Chopped experiments such as the south pole measurements of the UCSB\(^12,14\)
MAX searches for intermediate-scale anisotropy of CMB

The MAX experiment was designed to test CDM models which predict a characteristic peak in the power spectrum near the horizon scale at $l \sim 200$. Bond and Gorski have predicted that MAX should observe $\Delta T_{\text{rms}}/T(\text{CMB}) = 2-3 \times 10^{-5}$ for CDM models normalized to the COBE observation at angular scales $> 10^\circ$. It should be kept in mind that other models which include hot dark matter, strings or late reionization predict quite different power spectra. Observations of this power spectrum are of great importance for the progress of cosmology.

The MAX experiment also provides an opportunity to observe the Sunyaev–Zel’dovich (SZ) effect in nearby clusters of galaxies. Such measurements are of great value since, when combined with X-ray observations, they allow a model of the cluster to be made from which the distance (and thus the hubble constant) and also the proper motion of the cluster can be estimated. The scattering of CMB photons by the hot intra-cluster medium reduces the temperature at 3 and 6 cm$^{-1}$, has little effect at 9 cm$^{-1}$ and increases the temperature at 15 cm$^{-1}$. With the beam size and chop for MAX, the predicted peak-to-peak signal from Coma is $\Delta y = 12 \times 10^{-5}$. Here, the Compton parameter $y$ is the integral of the cluster gas pressure along the line of sight. The present sensitivity of MAX in one second of integration is $\Delta y = 5, 17, 10,$ and $8 \times 10^{-5}$ at 3, 6, 9 and 15 cm$^{-1}$ respectively. One hour of observation should thus provide an accurate measurement. Data from MAX will be far less troubled by interference from radio point sources than lower frequency measurements. It may be necessary to subtract dust emission as was done for the Mu Pegasi data from the third flight, although the dust contrast from our galaxy is expected to be small in this region.

![Fig. 1. Power spectrum of CMB fluctuations calculated for CDM models compared with the window functions of recent experiments.](image)
III. RESULTS FROM THE THIRD FLIGHT OF MAX

The apparatus used thus far for the MAX experiment and the results of the first two flights are described in the literature.\(^4,13,18\) Two searches for CMB anisotropy were carried out during the third flight of MAX in June 1991. The data were filtered to remove transients due to occasional cosmic ray interactions and RF interference, demodulated and then coadded in azimuth angle on the sky. The statistical errors computed were comparable to the detector noise measured in the laboratory. A small offset was subtracted to remove slow drifts which occur over the time for one full cycle of the azimuth scan. The data were calibrated in units of antenna temperature by comparing them to the signal reflected from a membrane calibrator inserted into one lobe of the chopped beam at the prime focus. Jupiter was observed to check this calibration.

**Mu Pegasi**

Figure 2 shows the structure observed in a 1.4 h measurement near the star Mu Pegasi which was located toward the east where there was little sky rotation. This target was a compromise between moderately low dust emission, the availability of guide stars, and the absence of RF interference. Other regions exist where the IRAS 100 \(\mu\)m dust emission contrast is a factor 10 smaller.

The response of MAX to the galactic dust emission measured by IRAS is shown in Fig. 2. There is an extremely good correlation between the IRAS data which are shown as solid lines and the MAX measurements, leaving little doubt that most of the measured structure in the higher frequency bands is due to ISD emission. An analysis of the MAX measurements of galactic dust emission has been given by Fischer et al.\(^9\) The measurement of dust structure at such a small level (10–50 \(\mu\)K) demonstrates how far the system noise integrates down, and how well sidelobes and a number of other potential systematic problems have been controlled.

There is evidence for a second component in the data in addition to IRAS dust, especially at 6 cm\(^{-1}\). Two component internal fits to the data produce one component which is spectrally and morphologically like the IRAS 100 \(\mu\)m dust, and a "second component", possibly independent of the dust. This modeling uses up a large number of degrees of freedom, and the second component signal varies in both shape and spectrum depending on the choice of fitting parameters, and on the details of the data reduction.

Since these data do not uniquely determine the shape or spectrum of the "second component" or residual signal, they were analyzed in terms of an upper limit to CMB anisotropy only. This does not rule out the possibility that some or all of the residual signal is due to CMB fluctuations. Fitting the data to two component models including dust and 2.735 K Planck (CMB) emission yields a conservative upper limit to CMB fluctuations of \(\Delta T/T \leq 2.35 \times 10^{-5}\) for a gaussian autocorrelation function (GACF) at an angular scale of 25 arcmin. If the second component is interpreted as due to CMB anisotropy, it implies fluctuations with an r.m.s of 45 \(\mu\)K, referred to the window function set by the observing strategy.

**Gamma Ursae Minoris**

Figure 3 shows a sample of 16 of the 39 pixels measured for 1.4 h near the star Gamma Ursae Minoris (GUM) which was located in the north where there was significant sky rotation. This target was chosen because it had low IRAS 100 \(\mu\)m dust emission and because structure had been observed in the same region in the second flight of MAX which was not compatible with dust emission.\(^4\)

The essential features of the data set are apparent in Fig. 3. First, there is statistically significant structure in the 6, 9, and 12 cm\(^{-1}\) channels. The r.m.s. values of \(\Delta T_A\) are 48 ± 10, 26 ± 6, and 11 ± 3 \(\mu\)K for the 6, 9, and 12 cm\(^{-1}\) channels, respectively. These r.m.s. values of \(\Delta T_A\) are the square root of the difference between the variance of the 39 pixel means and the variance due to detector
MAX searches for intermediate-scale anisotropy of CMB

Fig. 2. Antenna temperature differences for the 6, 9 and 12 cm\(^{-1}\) bands near Mu Pegasi. To scale the data to a 2.74 K blackbody multiply by 2.3, 5.6, and 20.5 respectively. The solid lines are scaled from the IRAS 100 \(\mu\)m dust emission.

Noise. The 1\(\sigma\) error on each r.m.s. includes a statistical error and a \(\pm 10\%\) estimate for the systematic error in the absolute calibration. The values of the reduced \(\chi^2\) for 38 d.f. are 4.02, 3.93, and 2.01, respectively. Second, Fig. 3 shows a large correlated component in the 6 and 9 cm\(^{-1}\) channels which is much smaller in the 12 cm\(^{-1}\) channel. Third and last, the amplitude of the structure as measured in antenna temperature decreases with increasing frequency.

In the following, a discussion of potential sources of confusion is presented, and the observed structure is characterized and compared to other anisotropy measurements. The best evidence that the structure is not due to sidelobes comes from the Mu Pegasi scan described above which tracked in elevation from 36 to 55°. Any sidelobe contamination from the Earth is expected to be larger in the first half of the Mu Pegasi scan than in the GUM scan. Also, any sidelobe contamination from the balloon would be larger in the second half of the Mu Pegasi scan than in the GUM scan.
The 95% confidence level upper limits to the GACF at 25" for the Mu Pegasi scan (after subtracting structure identified as dust emission) are $\Delta T/T_{\text{cmb}} = 2.6 \times 10^{-3}$ and $2.9 \times 10^{-5}$ for the first and second halves, respectively. These limits on the sidelobe contamination are more stringent than direct sidelobe measurements and are considerably less than the structure shown in Fig. 3.

The falling spectrum of the observed structure indicates that it is not due to the atmosphere or to IRAS 100 µm dust. In addition, an extrapolation from the IRAS 100 µm map as was done for the Mu Pegasi data, suggests that the differential dust emission in the GUM region is very low.

Synchrotron emission in the MAX bands has been estimated by scaling the Haslam et al. (20) 408 MHz map as $\Delta T \propto v^{-2.7}$. These estimates are less than 1% of the observed structure. The largest gradient in the 408 MHz Haslam map in this region is due to the quasar 3C309.1. The statistical significance of the structure in Fig. 3 does not change if the pixels overlapping 3C309.1 are removed.

Free-free emission is the least well characterized of the known galactic contaminants. Free-free emission is traced by Hα emissions, but no small scale Hα data are available for the GUM region. Estimates based on Hα observations reported by Reynolds (21) in other parts of the sky give less than

![Figure 3](image-url)

Fig. 3. Antenna temperature differences for the 6, 9 and 12 cm$^{-1}$ bands near Gamma Ursae Minoris. The factors used to scale these data to a 2.74 K blackbody are given in the caption to Fig. 2.
10% of the observed structure. An alternative estimate is obtained from the conservative assumption that the entire 408 MHz r.m.s. (excluding the quasar) is due to free–free emission. Extrapolating to our frequencies using $\Delta T_n \propto n^{-2/3}$, gives 10% of the measured r.m.s.

Measurements of the CO($J = 1 - 0$) transition in the GUM region\(^{(22,23)}\) show that there is no emission above 1 K km s\(^{-1}\). A 1 K km s\(^{-1}\) CO cloud filling a beam would cause approximately a 10 $\mu$K signal at 6 cm\(^{-1}\) and a 5–10 $\mu$K signal at 9 cm\(^{-1}\).

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. One measure of structure is the weighted r.m.s. of the 6 and 9 cm\(^{-1}\) data which give $\Delta T_{r.m.s.}/T_{CMB} = 4.7 \times 0.8 \times 10^{-3}$. This is to be compared with a prediction of 2–3 $\times 10^{-5}$ from CDM models discussed above. If the CMB anisotropy is assumed to have a Gaussian autocorrelation function with a coherence angle of 25', then the most probable value is $\Delta T/T_{CMB} = 4.2^{+0.7}_{-0.3} \times 10^{-4}$, where the $\pm$ refer to the 95% confidence limits. The size of this structure is similar to that observed in the second flight of MAX which measured a most probable amplitude for a GACF of $4.5^{+0.4}_{-0.3} \times 10^{-5}\(^{(40)}\). A direct comparison of the morphology of the data sets from the second and third flights is not possible since the scans did not overlap significantly. The lower limit obtained from the GUM scan is larger than the upper limit of $2.4 \times 10^{-5}$ obtained from the Mu Pegasi scan. Therefore, if all the structure measured in the GUM scan is CMB anisotropy, the hypothesis that CMB anisotropy is Gaussian distributed is ruled out at the 3$\sigma$ level.

IV. FOURTH FLIGHT

A number of major improvements were incorporated into MAX for the fourth flight in May 1993. An improved star sensor was included to increase the number of useful guide stars. The telescope baffles were redesigned and new sidelobe measurements made giving less than –65 dB for angles $> 10^\circ$ from the beam. A new four-channel dichroic photometer was constructed which uses bolometric detectors cooled to 85 mK\(^{(24)}\) with an ADR. The sensitivity to RF interference was reduced by more than 30 dB. The optical sensitivity to CMB anisotropy measured in the laboratory is a factor $\sim 3$ better than for the third flight. The new measurements will be at the level of $\Delta T_{r.m.s.}/T_{CMB} = 3 \times 10^{-6}$. An additional factor of order 2 should be available with further optimization. Of great scientific importance is the addition of a very sensitive 3 cm\(^{-1}\) band which will place limits on sources of galactic confusion with falling spectra such as synchrotron radiation and free–free emission. Also, the band centered at 12 cm\(^{-1}\) has been shifted to 15 cm\(^{-1}\) to provide better dust discrimination.

The fourth flight of MAX took place in June 1993. An attempt will be made to have the fifth flight of MAX in August 1993. The goals include several deep scans to explore CMB anisotropy, a search for the Sunyaev–Zel'dovich effect in the Coma cluster, and also searches for several possible systematic errors. All of these goals will benefit greatly from the increased sensitivity.

Acknowledgements—This work was supported by the National Science Foundation through the Center for Particle Astrophysics (Co-operative Agreement AST-9120005) and the National Aeronautics and Space Administration under grants NAGW-1062 and FD-NAGW-2121.

REFERENCES