A MILLIMETER-WAVE ANISOTROPY EXPERIMENT (MAX) TO SEARCH FOR ANISOTROPY IN THE COSMIC BACKGROUND RADIATION ON MEDIUM ANGULAR SCALES

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ABSTRACT

We report preliminary results from two balloon flights of a millimeter-wave telescope designed to measure anisotropy in the cosmic microwave background (CMB) on angular scales from 0.3 to 3 degrees. The receiver used in the first flight, in November 1989, was a dichroic, ^{3}He-cooled bolometric photometer with passbands centered at 3, 6, 9, and 12 cm^{-1}. During this flight we measured the spectrum of the brightness of the galactic plane at a galactic longitude of $\ell_{II} = 24$ degrees and searched for CMB anisotropy at nine points centered near the north celestial pole (NCP). The noise in the 6 cm^{-1} band integrated down to one sigma errors of 140 μK per point over the 40 minute observation near the NCP. After further analysis these data will set an upper limit on CMB anisotropy of $\Delta T/T < 1\text{-}2 \times 10^{-4}$ (95% CL) for Gaussian correlation functions with a correlation length of 0.5 degree. The second flight, in July 1990, employed improved bolometric detectors. The 3 cm^{-1} band was removed in order to increase the efficiency of the remaining bands. Preliminary analysis of the data gives a factor of 3 improvement in sensitivity over the first flight in the 6 cm^{-1} band. Future plans include a new receiver to provide an additional factor of 5 improvement in sensitivity and a new balloon-borne telescope which is optimized for low-background bolometric detectors at millimeter wavelengths.

INTRODUCTION

Measurements of the anisotropy of the CMB on angular scales from 0.3 to 3 degrees provide information on primeval density perturbations that were just entering the causal horizon at decoupling and place powerful constraints on the cold dark matter scenario of galaxy formation (Vittorio et al., 1989, Bond et al., 1989). Sensitive experiments which probe these angular scales are now being conducted by groups using a variety of instrumentation ground-based and balloon-based platforms (de

Bernardis et al., 1990, Timbie and Wilkinson, 1990, Meyer, 1990, Meinhold and Lubin, 1990). As the sensitivity of the instruments improves, systematic effects and/or confusion with galactic emission will limit the accuracy of the observations. Observations at several wavelengths will be necessary in order to discriminate between anisotropy in the galactic and cosmic backgrounds. At present it is not known which combination of instruments and observing sites will provide the best control of systematic errors at those wavelengths. All promising avenues should be pursued. This paper describes two flights of a balloon-borne millimeter-wave telescope developed to provide a low background environment for bolometric receivers.

INSTRUMENT

The instrument is a pointed, 1-meter off-axis balloon-borne telescope (Meinhold, 1989) which has been modified with a new chopping secondary mirror and a multi-band bolometric receiver (Fischer et al., in preparation). The feed horn accepts radiation from the sky in a 0.5 degree (FWHM) Gaussian beam. All of the mirrors are underfilled to minimize beam spillover at the mirror edges (Fig. 1). The beam is sinusoidally chopped at 5.4 Hz between two points on the sky separated by 1.2 degrees. The gondola azimuth can be wobbled back and forth over a fixed number of positions on the sky, each separated by the effective chopper throw, or scanned continuously. The receiver is a dichroic photometer which simultaneously observes

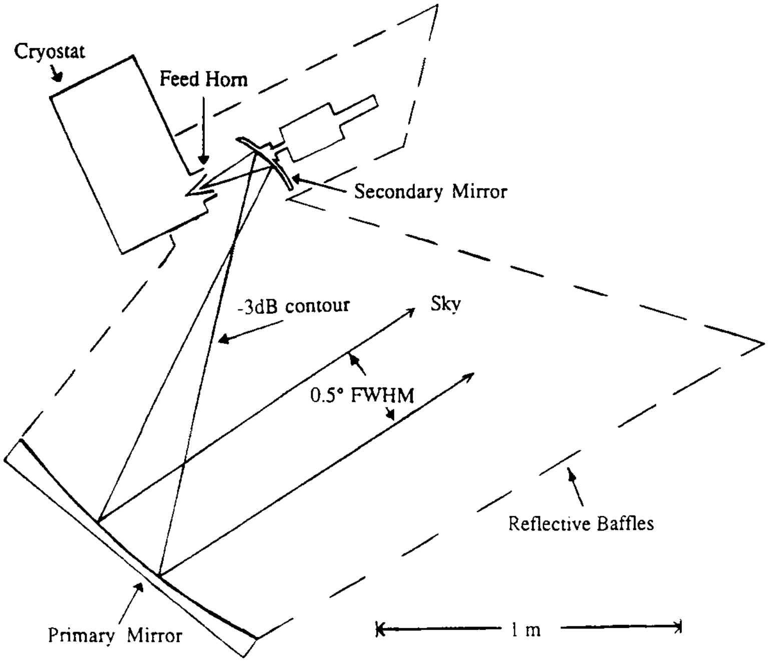

Figure 1. Sideview of telescope. Optical rays indicate nominal -3 dB contours. Dashed lines indicate reflecting baffles which block direct earthshine paths to optical surfaces.

four passbands centered at 3, 6 ,9 , and 12 cm^{-1}. The detectors are ^{3}He-cooled bolometers operating near 0.3 K. The system is calibrated every 30 minutes during the flight by moving a partially reflecting membrane into one lobe of the chopped antenna beam near the prime focus. The membrane reflects a known fraction (between 10^{-3} and 10^{-2}) of an ambient temperature blackbody source into that lobe. The reflectivity of the calibrator membrane is measured in the laboratory to vary from 10^{-3} to 10^{-2} at frequencies from 3 to 12 cm^{-1}.

GALACTIC EMISSION

During the first flight, in Nov. 1989, we measured the integrated emission from the galactic plane in four bands at a galactic longitude of 24 degrees. The telescope scan direction was inclined at an angle of 64 degrees to the galactic plane, measured from the direction of increasing galactic longitude. The beam was chopped along the scan direction, producing the differential measurement of the sky brightness as a function of the scan angle shown in Fig. 2. The data are strongly correlated with the signal expected from interstellar dust at 100 μm, calculated by convolving the 100 μm IRAS map with the effective shape of our chopped antenna beam.

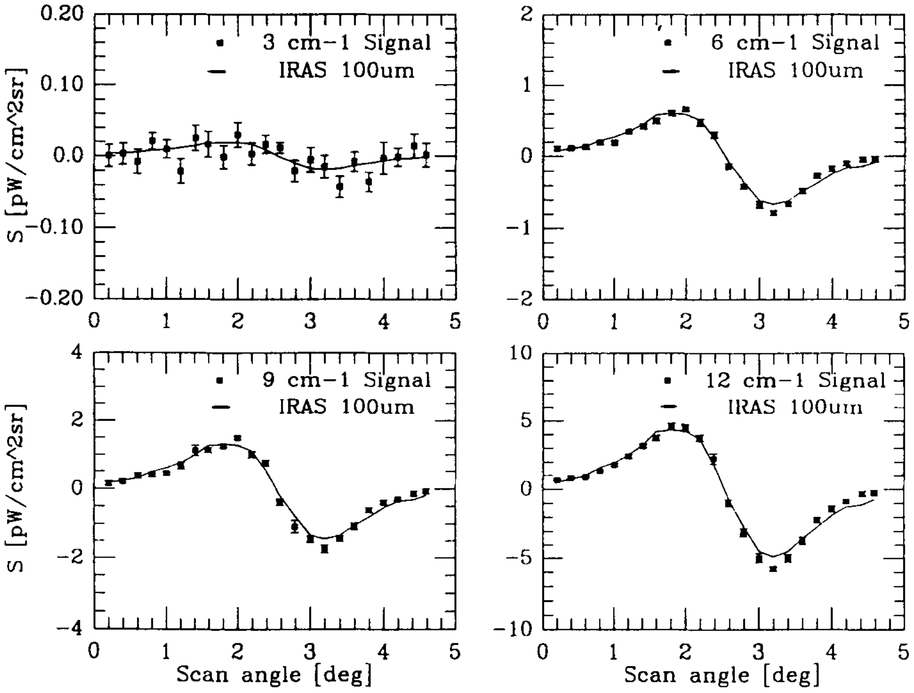

Figure 2. Measured differential signals from the galactic plane emission at $\ell_{II} = 24$ degrees. The solid line shows the signal calculated by convolving the 100 μm IRAS signal with the effective shape of the chopped antenna beam. The amplitude of the calculated signal has been fit to the measured data separately for each passband.

Figure 3 shows the IRAS correlated component of the measured sky brightness as a function of frequency for the 6, 9, and 12 cm^{-1} bands. For comparison, we also show three plausible models for the thermal dust emission, each normalized to the IRAS brightness at 100 cm^{-1}. The models for dust emissivity assume a power law frequency dependence for the emissivity with index n = 0, 1, and 2 and a dust temperature T_{dust} = 20 K. Because the filter bands have a finite bandwidth, the effective frequency of each passband moves toward higher frequency for the steeper dust spectra. This effect is so strong for the 3 cm^{-1} passband that it does not constrain the data. Three points are displayed for each of the other bands, corresponding to the three dust indices n = 0, 1, and 2.

These data are consistent with an emissivity index n between 1 and 2. Given such a steep spectrum, it should be possible to correct the CMB measurements for contamination from dust emission. Galactic dust emission can be identified in the 12 cm^{-1} band and subtracted from the 3 or 6 cm^{-1} bands. It will be important to study regions off of the galactic plane to verify that this spectrum of galactic emission is representative of other galactic latitudes.

CMB ANISOTROPY

During the first flight we observed nine points near the NCP, each separated by 1 degree in scan angle. The telescope was wobbled back and forth in a step-and-integrate mode. The integration time between steps was 1 minute. The total observation time was 40 minutes. Figure 4 shows the binned 6 cm^{-1} data as a function of scan angle. The other bands did not have sufficient sensitivity to provide interesting upper

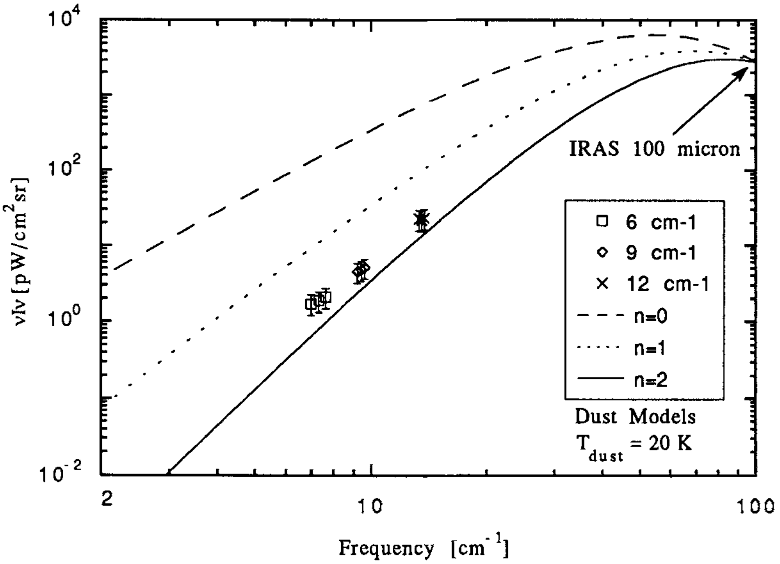

Figure 3. Measured galactic plane brightness as a function of frequency. The curves indicate three thermal dust emission models with emissivity indices n= 0, 1, and 2, and dust temperature T_{dust} = 20 K.

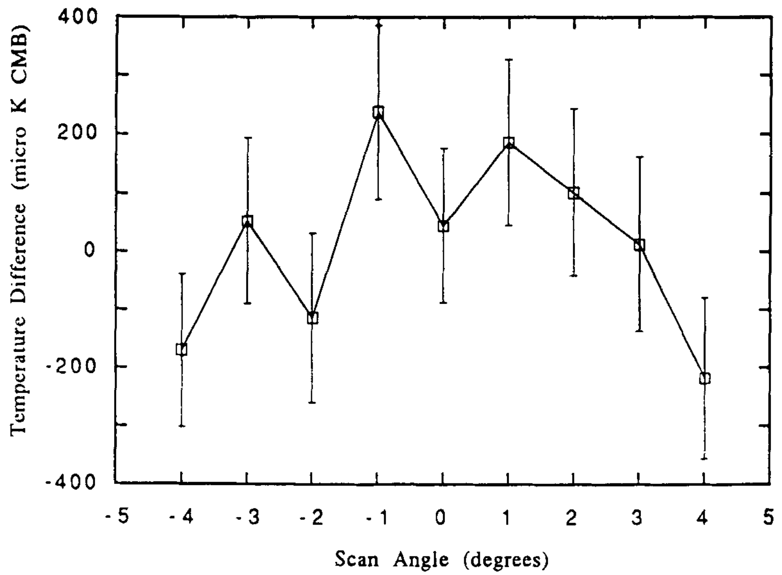

Figure 4. Measured temperature differences in the 6 cm^{-1} band vs. scan angle. These data were measured during the NCP scan of the first flight.

limits and are not shown. A constant offset was subtracted from the binned data. The noise in the 6 cm^{-1} data has a level consistent with detector noise. The noise is Gaussian distributed as judged by a histogram and integrates down as $t^{-1/2}$.

The 1-sigma error bars for each binned point are about 140 μK (2.7K thermodynamic). The χ^2 for these data is 10 for 8 degrees of freedom (9 points minus one for offset subtraction). The probability of obtaining a χ^2 this large or larger is 0.26 which is reasonably consistent with no sky signal. Using a standard likelihood ratio analysis these data will set an upper limit to CMB anisotropy of $\Delta T/T < 1\text{-}2 \times 10^{-4}$ (95% CL) for Gaussian correlation functions with a correlation length of 0.5 degree.

Analysis of the data from the second flight is still in progress. We have determined that the sensitivity of the 6 cm^{-1} band was improved by a factor of 3 over the first flight. During the second flight we obtained 1.3 hours of integration time searching for CMB anisotropy. If the noise integrates down then we may expect to set the limits to $\Delta T/T$ shown in the table below.

Flight Date	Sensitivity Relative to First Flight	Integration Time [Hours]	$\Delta T/T$ [95% UL]
Nov. 89	1	0.7	$1\text{-}2 \times 10^{-4}$
July 90	0.3	1.3	(3×10^{-5})
Spring 91	(0.3)	(6)	(1×10^{-5})
Fall 91	(0.07)	(6)	(2×10^{-6})

(Note that the quantities in parentheses are anticipated but not yet achieved.)

Future plans include a flight of the same receiver in the spring of 1991 with a goal of 6 hours of integration time. We plan to fly a new receiver in the fall of 1991 with an additional factor of 5 improvement in sensitivity. This receiver will use bolometric detectors cooled to 100 mK with an adiabatic demagnetization refrigerator developed for use on SIRTF (Timbie, Bernstein and Richards, 1989). These measurements have the potential to reach the levels of sensitivity shown in the above table.

As the receiver sensitivity continues to increase systematic effects will become more important. A new telescope is being developed which is optimized for balloon-borne bolometric observations at millimeter wavelengths. The issues the new design will directly address are as follows: 1) minimum sidelobe response and low emissivity optics, 2) minimum telescope mass which will allow high altitude flights to minimize atmospheric emission, 3) the choice of observing strategies which maximize our immunity to time varying signals and provide the best diagnostic information on any sources of drift.

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