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A STATUS REPORT ON MAX, A MILLIMETER-WAVE ANISOTROPY EXPERIMENT TO SEARCH FOR ANISOTROPY IN THE COSMIC BACKGROUND RADIATION ON INTERMEDIATE ANGULAR SCALES

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ABSTRACT

We summarize three balloon flights of an experiment designed to search for anisotropy in the cosmic microwave background (CMB) on angular scales from 0.3 to 3 degrees. The instrument was a multiband, ^{3}He-cooled bolometric photometer installed on a pointed, low background telescope. During the first flight, in November 1989, we searched for CMB anisotropy at nine points centered near the north celestial pole. The data set an upper limit on CMB anisotropy of $\Delta T/T < 7 \times 10^{-5}$ (95% CL) for a Gaussian correlation function with a correlation length of 0.3°. The second flight, in July 1990, used more sensitive detectors. We searched for CMB anisotropy at seven points near the star, Gamma Ursa Minoris. The statistical noise at each point was low enough to place an upper limit of $\Delta T/T < 3 \times 10^{-5}$ for Gaussian anisotropies, however, a sky correlated signal was observed. The spectrum of the signal observed in the three bands was consistent with a

CMB anisotropy, but concerns about possible systematic errors prevent the unique interpretation of the signal as being cosmological. A very successful third flight took place in June 1991, but the data analysis is not completed. We also discuss future plans for improved receivers and a new telescope.

1. Introduction

A variety of models for structure formation in the universe, including the standard cold dark matter model, predict the largest anisotropies at angular scales from 0.3 to 3 degrees.[1] These scales correspond to the distances probed by observations of the large scale distribution of galaxies and clusters and to the size of the causal horizon at decoupling. Current upper limits[2-4] restrict anisotropies on these scales to several parts in 10^5. Though improvements in detector technology have increased the raw sensitivity available to improve upon these observations, strategies for subtracting galactic emission and avoiding increasingly problematic, systematic noise sources are required to realize the potential of these detectors. Even in the millimeter wave region galactic emission is expected to require careful subtraction in order to probe anisotropy below the 10^{-5} level. Noise created by imperfect subtraction of the very large background of atmospheric emission, telescope mirror emission and CMB will also rise in proportion to the sensitivity of the receiver. We have developed a multi-frequency receiver which combines the high sensitivity of bolometric detectors with the capability for rejection of galactic emission and systematic errors of simultaneous, multi-frequency observations. The receiver was installed on a low-sidelobe telescope, which was designed to minimize background emission and beam modulation systematics, and flown on a high altitude balloon to reduce atmospheric emission and noise.

2. Instrument

The instrument is a pointed, off-axis telescope[5] with a one meter primary mirror, a chopping secondary mirror and a multi-band bolometric receiver.[6] The receiver accepts radiation from the sky in a 0.5 degree FWHM Gaussian beam. To minimize the fraction of rays accepted by the receiver which miss either of the mirrors, the mirrors are large compared to the beam. Such errant rays would increase the background since they strike baffles which are much more emissive than the mirrors and could introduce systematic errors arising from structure in the radiation from the earth or the balloon.

The beam is sinusoidally chopped at 6 Hz between two points on the sky separated by 1.3 degrees. This chop is achieved by rotation of the secondary mirror around the receiver-feedhorn axis. The chopping mechanism has been optimized for high stability in both amplitude and zero position. The gondola azimuth can be changed continuously or in steps on a several second time scale. After entering the receiver feedhorn and passing through blocking filters, the beam is divided into separate frequency bands by the selective reflection and transmission of mesh interference filters and then concentrated onto the four, separate bolometric detectors. During the first flight, the bands were centered at 3, 6, 9, and 12 cm^{-1}. The 3 cm^{-1} band was removed for the second and third flights which improved the optical efficiency of the other bands. The detectors were cooled below 0.3 mK with ^{3}He.

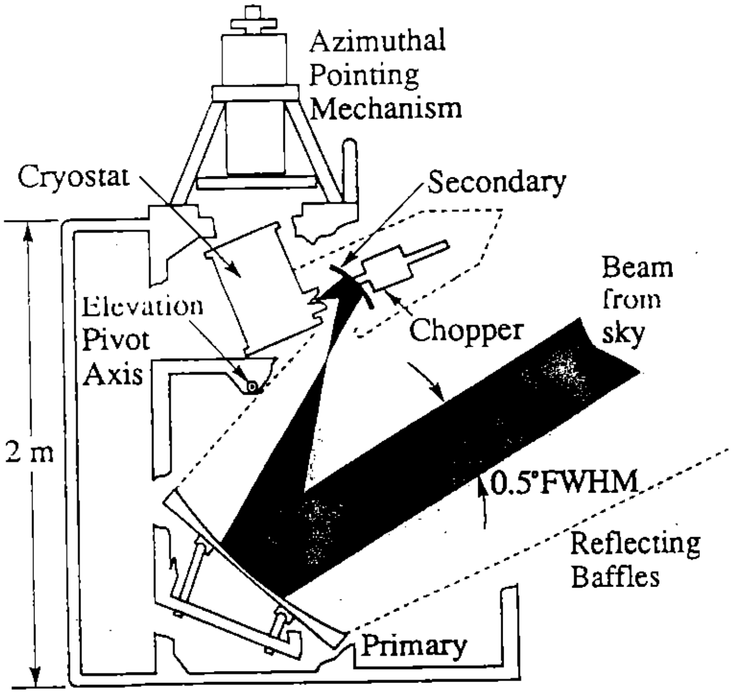

Figure 1. Side view of the telescope. The shaded region indicates nominal -3dB contours. Dashed lines indicate reflecting baffles which block direct earthshine paths to optical surfaces.

The system is calibrated during flight by moving a partially reflecting membrane into the prime focus from one side. The membrane reflects a reproducible fraction of an ambient temperature blackbody source into the receiver. The reflectivity of the calibrator membrane was measured in the laboratory and ranged from 10^{-3} to 10^{-2} at frequencies from 3 to 12 cm^{-1}. The signals from planets scanned in flight provide a check on this calibration.

3. Galactic Emission

In order to subtract galactic emission from an observation of the anisotropy of the CMB, the spectrum of the emission must be known and the spectrum must differ substantially from the CMB anisotropy spectrum. We observed emission from the galactic plane during the first flight in November 1989 to obtain a high signal-to-noise ratio measurement of the spectrum of galactic emission. The scan passed across the plane at a galactic longitude of 24° at an inclination of 26° from the normal. The beam was chopped along the scan direction, producing a differential measurement of the sky brightness as a function of scan angle. A model of the chopped beam was also scanned across the IRAS 100 μm map for comparison and was in very good agreement with the observations. The spectrum derived from these observations, plus previous observations at 300, 250, and 150μ by Hauser et al.,[7] and the IRAS 100μ point was consistent with a gray body with $T = 25K$ and an emissivity index of about 1.6, in good agreement with the average spectral index of 1.65 from COBE.[8]

If the dust emission spectrum at high galactic latitudes is as steep as that in the plane of the galaxy, it should be easily removed from multi-band, millimeter-wave CMB anisotropy observations. The spectrum at high latitudes may differ, however. Dust at high galactic latitudes is well correlated with the HI column density while dust in the plane near the galactic center is better correlated with CO emission;[9] the different conditions of the dust in molecular clouds could lead to different emissivities and temperatures. As long as the dust emissivity index is positive and the dust temperature $T \gtrsim 5K$, however, the spectrum can be distinguished from a CMB anisotropy spectrum.

4. First Flight CMB Anisotropy Search

During the first flight, which took place in November 1989 at a float altitude of ~30 km, we observed a strip of sky near the north celestial pole . The observation was divided into two 20 min. scans by a 24 min. calibration sequence. In each scan, the telescope azimuth was wobbled back and forth in a nine point step and integrate pattern; each point was separated by 1° in scan angle. We observed a total of 13 points, separated by more than one beam width, because the Earth's rotation caused the edges of the scan pattern to rotate. Fig. 2 shows the azimuth binned 6 cm^{-1} data as a function of scan angle after an offset was removed. The other bands did not have sufficient sensitivity to provide interesting upper limits and are not shown. The scatter in the 6 cm^{-1} data has a χ^2 probability of 0.26 and thus is consistent with detector noise. The one sigma error bars for each binned point are approximately 140 μK (ΔT of a 2.7 K blackbody). A standard likelihood ratio analysis yielded a 95% CL upper limit on CMB anisotropy of $\Delta T/T \leq 7 \times 10^{-5}$ for Gaussian fluctuations with a correlation angle of 0.3°.

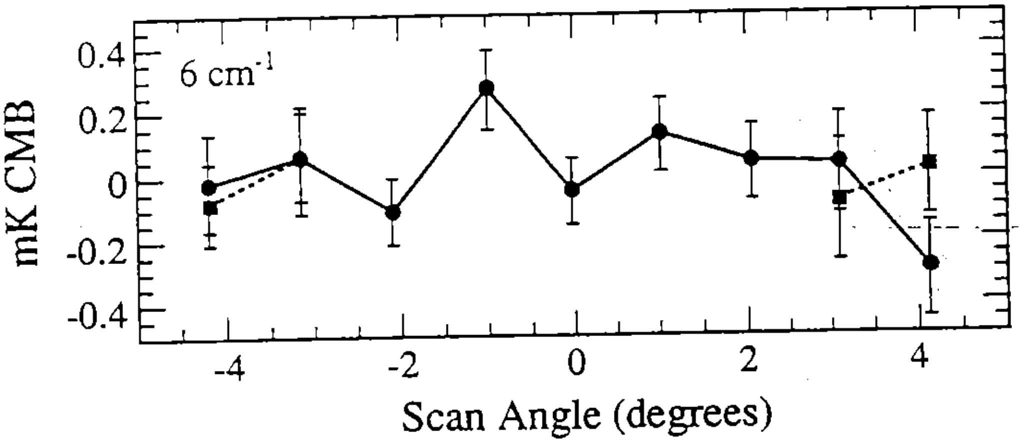

Figure 2. Temperature differences in the 6 cm^{-1} band vs. scan angle measured at the north celestial pole during the first flight. The points connected with dotted lines were observed during the second scan and did not overlap with the points from the first scan due to sky rotation.

5. Second Flight CMB Anisotropy Search

The second flight took place June 1990 at a float altitude of ~30 km. The 3 cm^{-1} band was removed in order to increase the sensitivity of the higher frequency bands. New detectors with three times better sensitivity were also added in the 6 and 9 cm^{-1} bands. The modified receiver achieved three times better sensitivity at 6 cm^{-1} and seven times at 9 cm^{-1}. The search was divided into two 37 minute observations by a 13 minute calibration. The scan pattern consisted of discrete azimuth steps between seven integration points measured at 20 second intervals. The integration points were spaced 1° apart.

Noise well in excess of detector noise was apparent in all three bands. A crude correlation between the bands allowed the determination of a spectrum for the noise which was steeper than Rayleigh-Jeans. The noise was not correlated with azimuth so it could not have been caused by CMB anisotropy or any other source fixed in the sky.

A rapid rotation performed late in the flight produced signal modulations similar in amplitude and spectrum to the excess noise observed during the CMBR integration, but with much more rapid variations. This suggests that the excess noise was due to emission from the sky which varies with both azimuth and time. This test suggests that the rapid azimuth rotation modulated the signal. Since only the earth, the atmosphere, and the balloon do not rotate with the gondola, they are the likely sources. The source could not have been stable on the time scale of a scan because azimuth correlation would have been apparent. The spectrum of the emission was inconsistent with oxygen and water but was marginally consistent with ozone. The possibility that emission from the balloon or the earth was accepted in the sidelobes of the instrument cannot be eliminated. This low frequency noise in the second flight was dramatically larger than during the first flight (Fig. 3).

Because the scan modulation was relatively rapid, most of the low frequency noise was outside the frequency range in which CMB anisotropy information would be located. Near detector-noise-limited performance was achieved by filtering the data with a highpass filter that removed signal from only the largest angular scale anisotropies. When the data were averaged into seven final data points, the one sigma errors per bin were all below 40 μK. The data have the sensitivity to set a limit below 3×10^{-5} for a 0.3° correlation angle, but a sky correlated signal was observed.

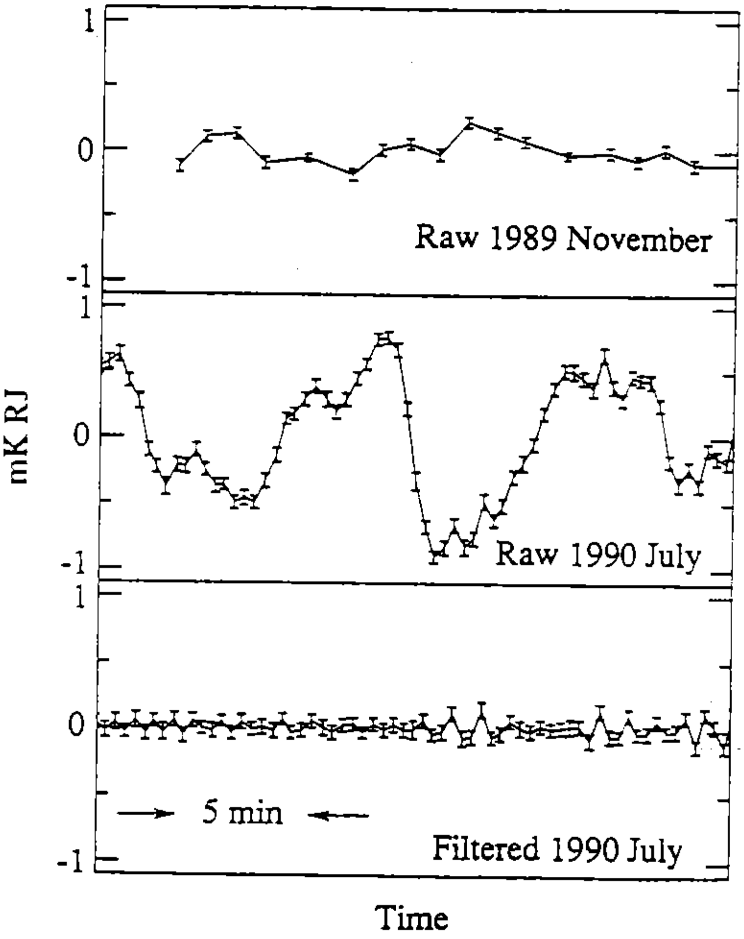

Figure 3. Comparison of the offset drifts in the 12 cm^{-1} band during the first two flights, and the effect of high pass filtering on the offset drift during the second flight.

Figure 4 shows azimuth-binned observations near Gamma Ursae Minoris from the second flight. Signals in excess of the statistical noise are present in the 6 and 9 cm^{-1} bands.[10] These signals have a high degree of statistical significance, even when the data are divided into two halves.

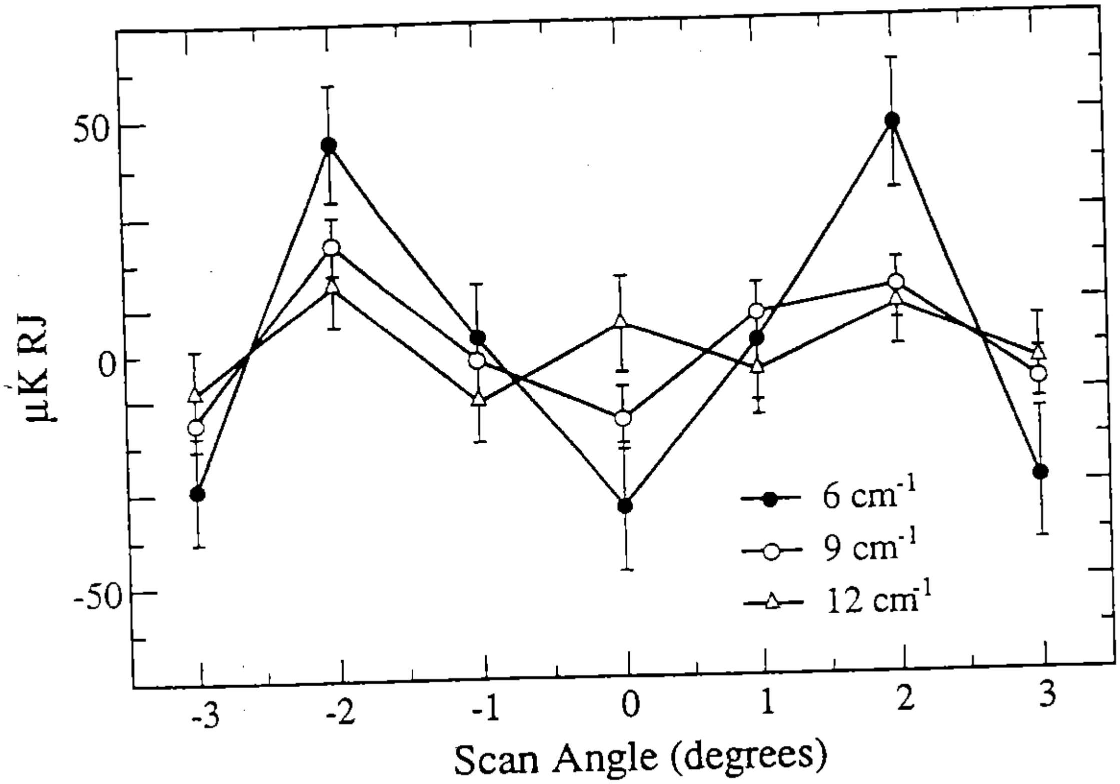

Figure 4. Temperature differences in the 6, 9 and 12 cm^{-1} bands vs. scan angle measured in 74 min. near Gamma Ursae Minoris during the second flight. High pass filtering has removed four degrees of freedom from the seven points for each band.

Arguments have been presented in Alsop et al.[10] to show that this signal does not arise from local in-band sources such as the earth or the atmosphere, or from instability of the chopper motion, gain changes or crosstalk. Many of these arguments are based on the observed spectrum of the signal that is shown in Fig. 5 as a color-color diagram. Sources with Rayleigh-Jeans spectra or steeper are excluded with greater than 95% confidence. If conventional spectral indices of -2.7 and -2.1 are assumed, synchrotron radiation and bremstrahlung are constrained to be less than 10 percent of the observed signal by the 408 MHz Haslam et al.[11] map. Also, the spatial features in that map do not agree with the observations.

The bolometric detectors were observed to be sensitive to radio frequency interference both from the on-board transmitters and from external sources. Since the strength of the interference was different in different bands, a "spectrum" of RF interference could be calculated which lies within the 98% contour in Fig. 5. Although it is unlikely that this interference would cause a stable scan synchronous effect, this possibility cannot be eliminated. Consequently, a detection of a CMB anisotropy cannot be claimed based on these data.

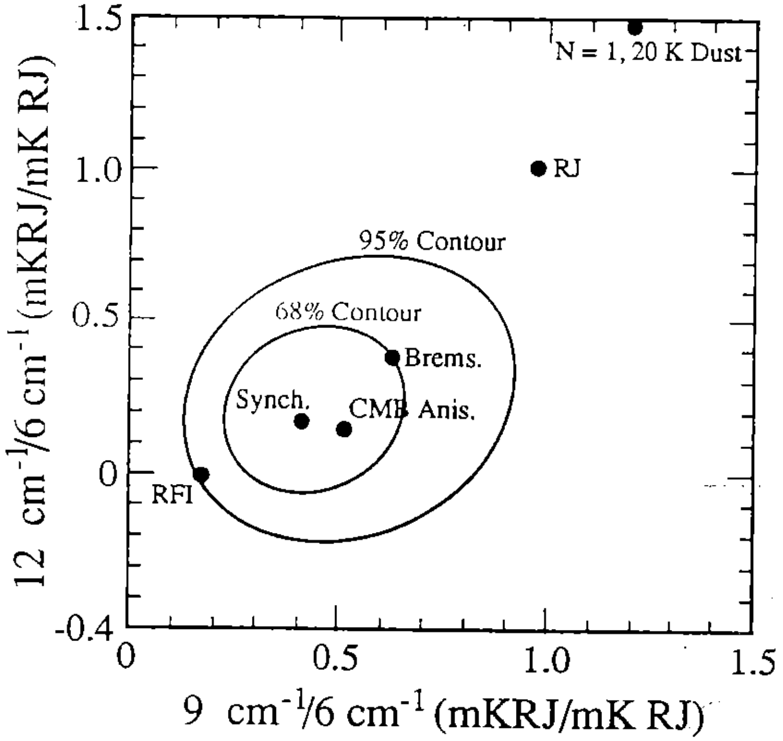

Figure 5. The observed scan-correlated signals described as contours constraining the ratios of the 9 and 12 cm^{-1} signals to the 6 cm^{-1} signal. Also shown are the ratios that would occur for various possible non-cosmological sources.

6. Third Flight

The third flight of the MAX experiment took place in June 1991 at a float altitude of ~35 km. Several hours of high quality data were obtained including three deep integrations on the CMB. Although data analysis is not complete, there is every indication that these measurements will give significant new information on the anisotropy of the CMB on intermediate angular scales.

7. Future Plans

The flights of the MAX experiment reported here were part of an ongoing program to develop balloon-borne bolometric receivers for observation of CMB anisotropies at the 10^{-6} level. Both laboratory technology development and practical observing experience are required to achieve this goal. The previous MAX flights have provided important feedback on observing strategies and difficulties which is currently guiding future plans. These plans include:

1. A new receiver with detectors cooled to 100 mK by an adiabatic demagnetization refrigerator is nearing completion. These detectors will have 3 times greater sensitivity than the detectors used in the second and third flights. A flight with this receiver is planned for late 1992. This large improvement in sensitivity will likely produce both exciting data and information on systematics.

2. Ultimately, photon shot noise in the emission from the mirror, the atmosphere, and the CMB will limit the sensitivity of any receiver. Array receivers are currently being developed to improve sensitivity further. Multiple pixels allow longer integration times per observation point. A new, 1.2 m light weight primary mirror is currently under construction. A new modulation scheme involving the motion of the primary instead of the secondary is being designed to preserve optical performance over the field of view of the array.

8. Acknowledgements

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