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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 report preliminary results from two balloon flights of an experiment designed to search for anisotropy in the cosmic background radiation (CBR) 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 measured the spectrum of the brightness of the galactic plane at a galactic longitude of l_{II}=24° and searched for CBR anisotropy at nine points centered near the north celestial pole. These data set an upper limit on CBR anisotropy of DT/T < 1. x 10^{-4} (95% CL) for a Gaussian correlation function with a correlation length of 0.3°. The second flight, in July 1990, featured more sensitive detectors. We searched for CBR anisotropy at seven points near the star, Gamma Ursa Minoris. Despite a large, long timescale drift in the signals, detector limited performance was achieved for anisotropies on scales < 5°. The statistical noise per point was almost five times smaller than in the first flight. Analysis of this data is still in progress. We also discuss future plans for improved receivers and a new telescope.

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 (e.g. Bond, 1989). These scales correspond to the distances probed by existing, large scale structure observations and to the causal horizon size at decoupling. Current upper limits restrict anisotropies on these scales to a several parts in 10^5 . (Meinhold and Lubin, 1990, Timbie and Wilkinson, 1990.) 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, where the ratio of CBR to galactic anisotropy is highest, galactic emission will foil naive attempts to probe anisotropy to below the 10^{-5} level. Noise created by imperfect subtraction of the uniform but very large background of atmospheric emission, telescope mirror emission and CBR will also rise in proportion to the sensitivity of the receiver. We have developed a multi-frequency bolometric receiver which combines the high sensitivity of bolometric detectors with the increased galactic emission and systematic error rejection capability of simultaneous, multi-frequency observing. The receiver was installed on a low-sidelobe telescope, which we designed to minimize background emission and beam modulation systematics, and flown at high altitude on a balloon to reduce atmospheric emission and noise.

INSTRUMENT

The instrument is a pointed, off-axis telescope with a one meter primary mirror, a chopping secondary mirror and a multi-band bolometric receiver (Meinhold, 1989, Fischer et al. in preparation). 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 were designed large compared to the beam. Such errant rays would increase the background since they strike baffles which are much more emissive than the mirrors.

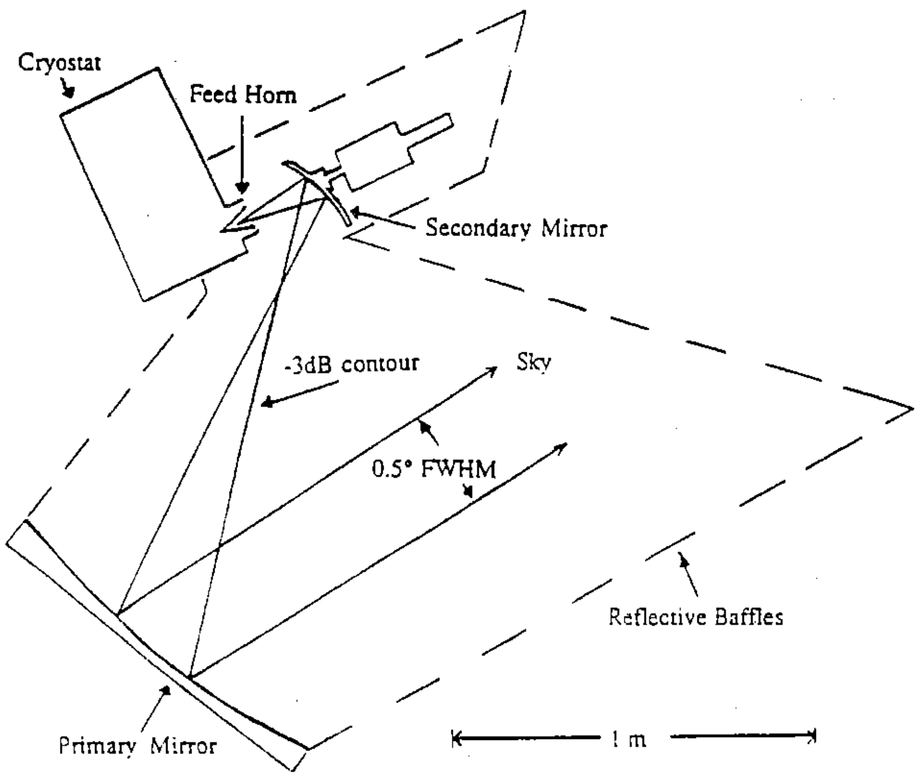

Figure 1. Side view of the telescope. Optical rays indicate nominal -3 dB contours. Dashed lines indicate reflecting baffles which block direct earthshine paths to optical surfaces.

The beam is sinusoidally chopped at 6.1 Hz between two points on the sky separated by 1.2 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 timescale. 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} channel was removed for the second flight. The detectors were ^3He cooled to below 0.3 mK.

The system can be calibrated during the 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. 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 the calibration.

GALACTIC EMISSION

In order to subtract galactic emission from a CBR anisotropy observation, the spectrum of the emission must be known and the spectrum must differ substantially from the CBR anisotropy spectrum. We observed emission from the galactic plane

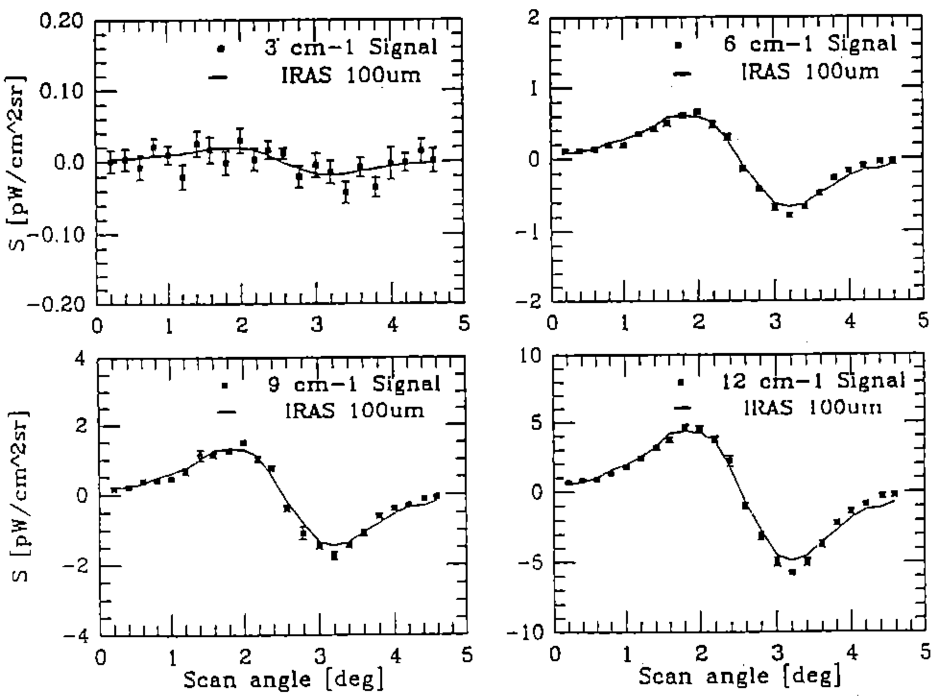

Figure 2. Measured differential signals from the galactic plane emission at l_{II} = 24°. The solid line shows the signal calculated by convolving the 100 μm IRAS signal with the effective shape of the chopped antenna beam. The amplitude of the calculated signal has been fit to the measured data separately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

during the first flight to obtain a high signal to noise measurement of the galaxy spectrum. 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 100μm map for comparison. Fig. 2 shows the correlation between the observed signal and the IRAS 100μm data. The steeply rising spectrum inferred from the correlations indicates that the signal was dominated by dust emission.

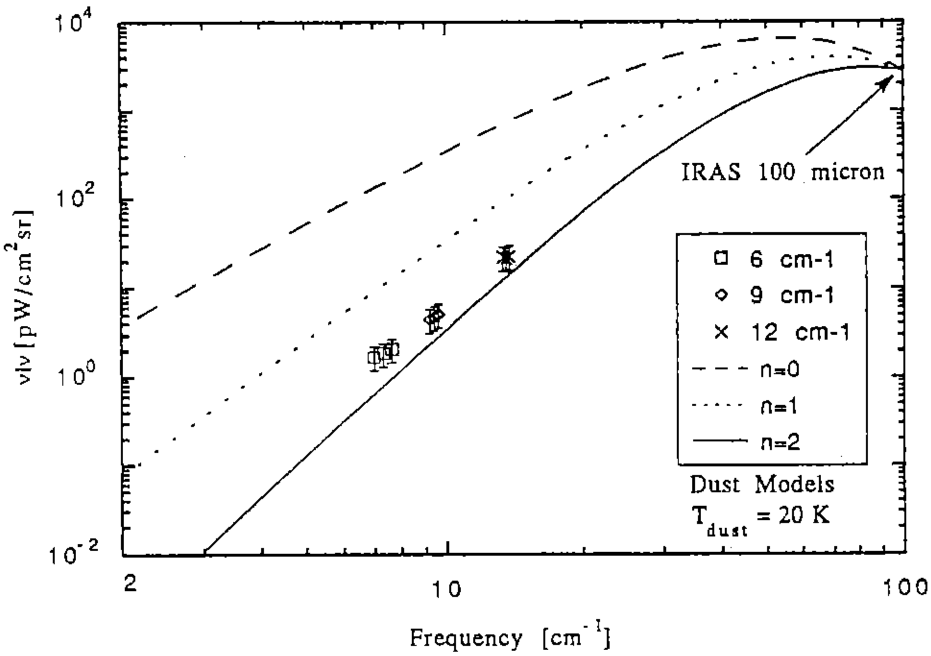

Figure 3. Measured galactic plane brightness as a function of frequency. The curves indicate three thermal dust emission models with emissivity indices n=0, 1, and 2, and dust temperature T_{dust} = 20 K.

Fig. 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 emission assume a power law frequency dependence for the emissivity with index, n = 0, 1 and 2, and a dust temperature, Tdust = 20°K. Because the filter bands have a finite bandwidth, the effective frequency of each passband moves toward higher frequency as the dust spectrum steepens. Three points, corresponding to the three dust spectral indices, are displayed for each of the bands. The 3 cm^{-1} data is not shown because of its low signal to noise ratio.

These data are consistent with an emissivity index, n, between 1 and 2. Other authors, Lubin et. al., 1989 and Page et. al., 1990, report emissivity indices in the same range. If the spectrum at high galactic latitudes is similarly steep, dust emission should be easily removed from multi-band, millimeter-wave CBR anisotropy observations. The spectrum at high latitudes may differ, however. Dust at high galactic latitudes is well correlated with HI column density while dust in the plane near the galactic center is better correlated with CO emission (Sodroski et. al., 1987); 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, however, the spectrum can be readily differentiated from a CBR anisotropy spectrum.

FIRST FLIGHT CBR ANISOTROPY SEARCH

During the first flight we observed nine points near the North Celestial Pole; each point was separated by 1° in scan angle. The telescope was wobbled back and forth in a step-and-integrate mode. The integration time between steps was 1 minute and the total observation time was 40 minutes. The observation was a small fraction of the total balloon flight duration, 10 hours, because the chopper malfunctioned several hours into the flight. Fig. 4 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 errorbars for each binned point are approximately 140mK (ΔT of a 2.7K blackbody). A standard likelihood ratio analysis yielded an upper limit on CBR anisotropy of 1.0×10^{-4} for a correlation angle of 0.3°.

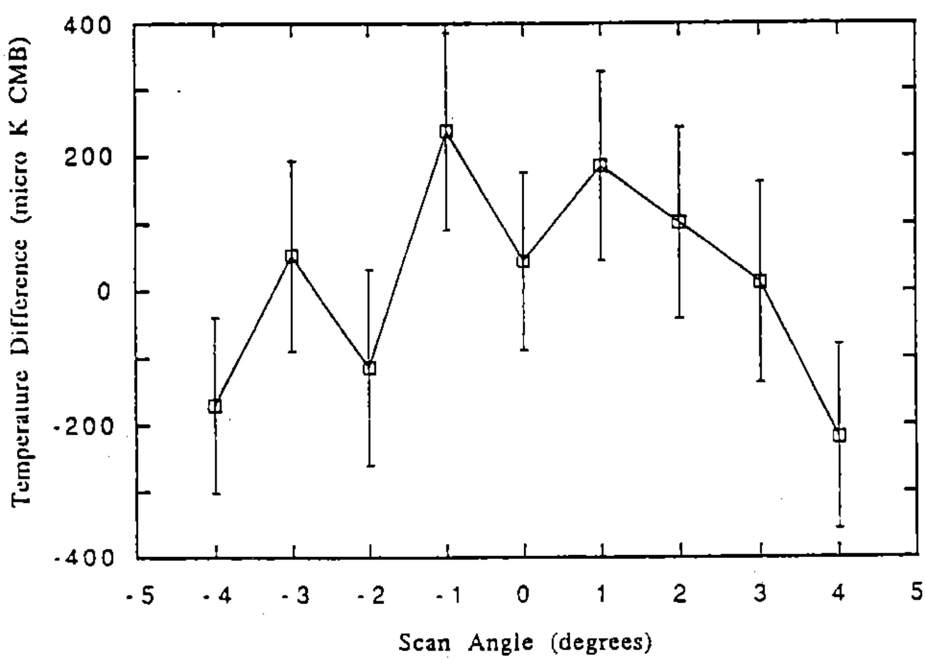

Figure 4. Measured temperature differences in the 6 cm^{-1} band vs. scan angle. These data were measured during the NCP scan of the first flight.

SECOND FLIGHT CBR ANISOTROPY SEARCH

For the second flight, the 3 cm^{-1} channel was removed in order to increase the sensitivity of the higher frequency channels. New detectors with three times better sensitivity were also added in the 6 and 9 cm^{-1} channels. The modified receiver achieved three times better sensitivity at 6 cm^{-1} and 7 times at 9 cm^{-1}. Fig. 5 shows the distribution of the short term noise observed in flight at 6 cm^{-1} and indicates a 0.65 mK/rt s single chopped sensitivity.

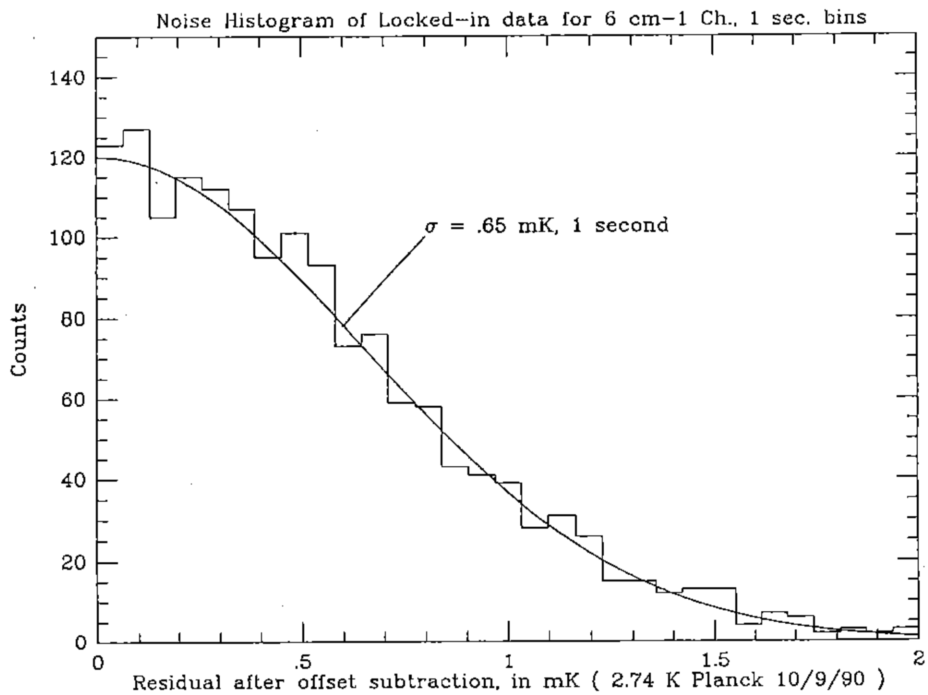

Figure 5. Distribution of short term noise in the 6 cm-1 channel during the second flight.

Though the second flight also lasted 10 hours, a malfunction again limited the CBR observation to a small fraction of the available time. The CBR search began toward the end of the flight because a software error in the guidance system computer prevented the gondola from stabilizing earlier. 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 performed at 20 second intervals. The integration points were spaced 1° apart. Seven complete scans were performed in each half of the observation yielding a total of 28 observations per integration point. The scan pattern and the 196 integrations for the 6, 9 and 12 cm^{-1} bands are plotted in Fig. 6.

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

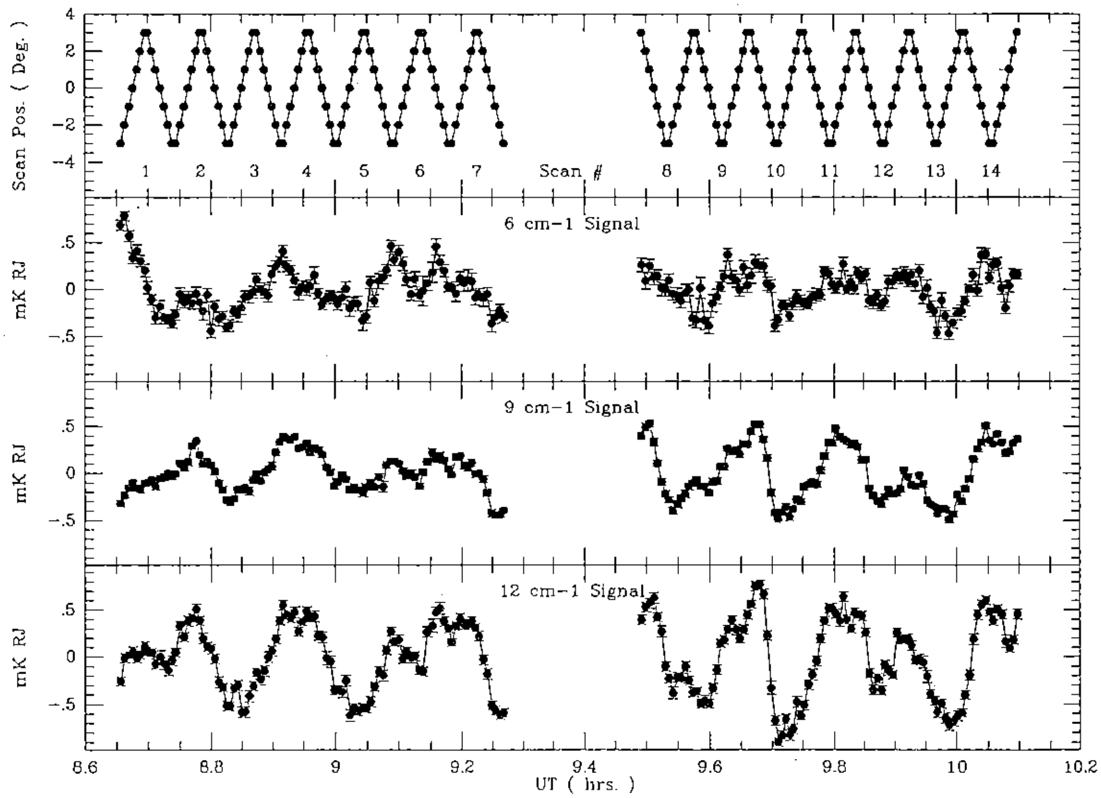

Figure 6. Second flight CBR anisotropy scan pattern and azimuth binned signals for the 6, 9, and 12 cm^{-1} channels. An offset and a gradient have been removed from each half of the data. The calibration which divides the observation is not shown

A rapid rotation in azimuth performed later in the flight as a diagnostic produced signal modulations of similar amplitude and spectrum to the noise in Fig. 6 but the modulation rate was much more rapid. 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. The low frequency noise observed during the first flight was dramatically lower. (Fig. 7)

Because the scan modulation of the observation position was relatively rapid, most of the low frequency noise was outside the frequency range in which CBR anisotropy information would be located. Fig. 8 shows the effect of a highpass filter on the noise in the 12 cm^{-1} channel; near detector noise can be achieved by filtering the data with a highpass that removes the signal from only the largest angular scale anisotropies. When the data is averaged into seven final data points, one sigma errors per bin are all below 40 mK. The data should have the sensitivity to set a limit $< 3 \times 10^{-5}$ for a 0.3° correlation angle. Data analysis is still in progress.

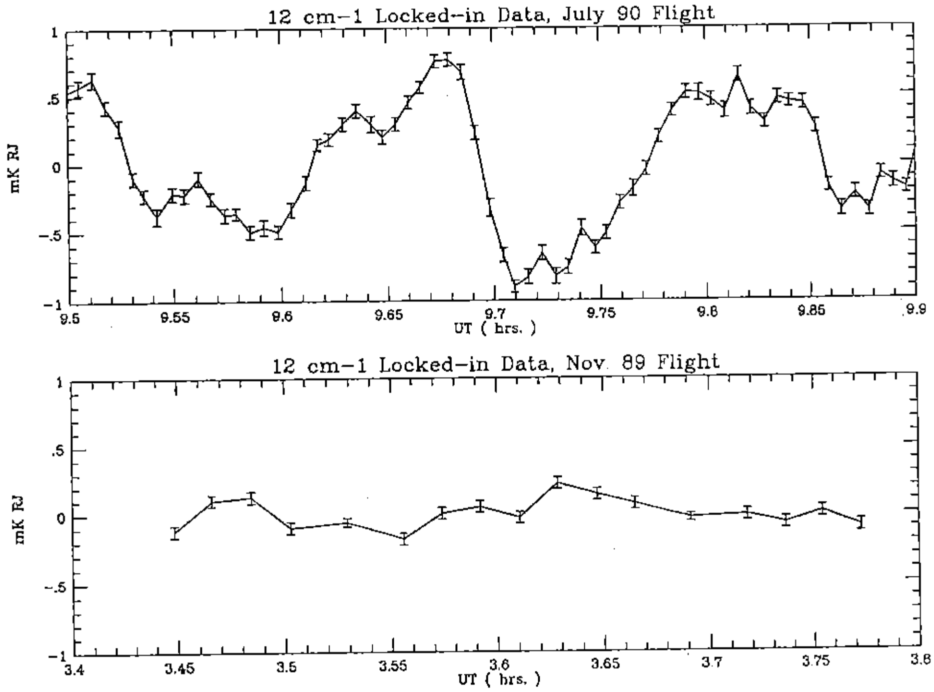

Figure.7 A comparison between the low frequency noises observed in the 12 cm^{-1} channel during the two MAX flights. A constant offset has been removed from both data sets.

FUTURE PLANS

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

1. Another flight of the ^3He detectors in May 1991. The flight will be at higher altitude and the filters will be modified to reduce atmospheric emission. The objectives are to reduce and understand the low frequency noise observed in the second MAX flight and to increase the observation duration. An eight hour observation would have almost triple the sensitivity of the second flight's. An observation of the Sunyaev-Zeldovich effect for the Coma cluster is also planned.

2. A new receiver with detectors cooled to 100 mK by an adiabatic demagnetization refrigerator is nearing completion. These detectors will have 5x greater sensitivity. A flight with this receiver is planned for the coming year. This large improvement in sensitivity will likely produce both exciting data and information on systematics which may limit the sensitivity.

3. A new telescope is under development. Photon shot noise in the emission from the primary mirror will become the dominant fundamental noise source for 100 mK detectors. A new, lower emissivity primary mirror is currently under construction. Systematic noise caused by the motion of the beam on the primary mirror is also expected to become a problem for the more sensitive receiver. A new modulation scheme involving the motion of the primary instead of the secondary is being designed to eliminate this noise.

4. Ultimately, photon shot noise in the emission from the mirror and atmosphere will limit the sensitivity of any receiver. Array receivers are currently being studied to improve sensitivity further. Multiple pixels allow longer integration times per observation point.

Table 1 shows the schedule of previous and planned flights and the upper limits they have set or should set in the absence of interfering systematic problems or real anisotropy.

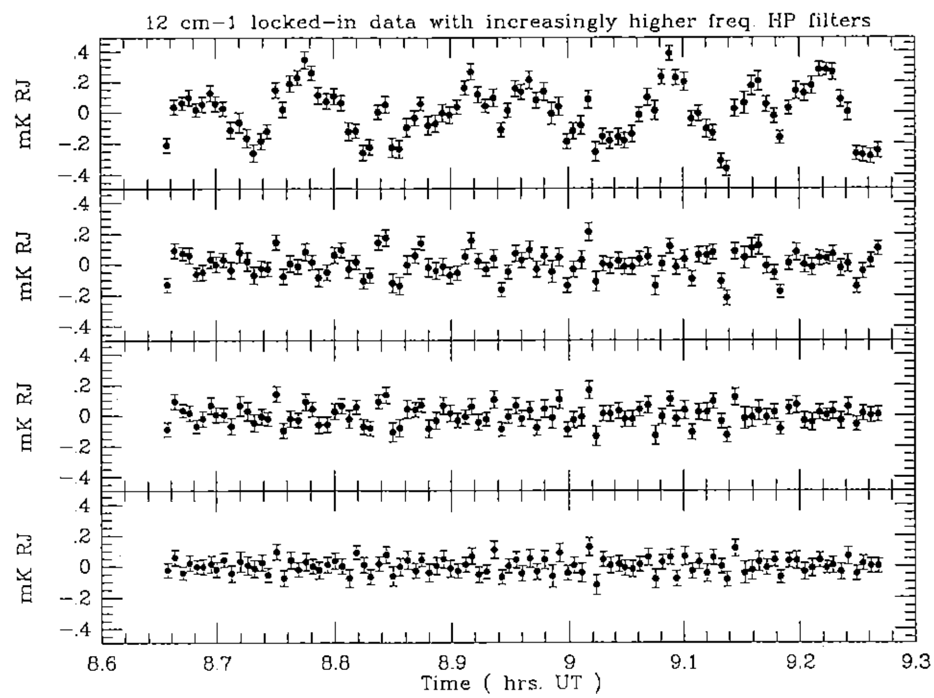

Figure 8. The effect of highpass filtering in time on the excess noise in the 12 cm^{-1} channel. The topmost data have had only signals with frequencies lower than any detectable CBR anisotropy would produce removed. The lower data have had increasingly higher frequencies removed. Only anisotropies with periods < 5° remain in the bottom most data.

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

Table 1. Sensitivity of past and future MAX flights. Quantities in parentheses are anticipated but not yet achieved.

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