Detection of Degree Scale Anisotropy

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ABSTRACT

Degree Scale Anisotropy Measurements are a crucial testing point for cosmological models. Giving us one of the few probes into density perturbations in the early universe, they promise to be a watershed for future progress in understanding structure formation. Because of the extreme sensitivities needed (1 - 10 ppm) and the difficulties of foreground sources, these measurements require not only technological advances in detector and measurement techniques, but multi spectral measurements and careful attention to low level systematic errors. This field is advancing rapidly and in a true discovery mode. Our own group has been involved in a series of ten experiments over the last five years using the ACME (Advanced Cosmic Microwave Explorer) payload which has made measurements at angular scales from 0.3 to 3 degrees and over a wavelength range from 1 to 10 mm. I will review some of the challenges and potential involved in these measurements, both present and future.

1. INTRODUCTION AND CURRENT STATUS

The Cosmic Background Radiation (CBR) provides a unique opportunity to test cosmological theories. It is one of the few fossil remnants of the early universe to which we have access at the present. Spatial anisotropy measurements of the CBR in particular can provide a probe of density fluctuations in the early universe. If the density fluctuation spectrum can be mapped at high redshift, the results can be combined with other measurements of large scale structure in the universe to provide a coherent cosmological model.

Recent measurements of CBR anisotropy have provided some exciting results. At the largest angular scales, NASA's Cosmic Background Explorer (COBE) satellite has provided the first measurements of large scale CBR anisotropy at a level $\Delta T/T = 10^{-5}$ at 10°. This result may have been corroborated by a balloon survey, but much more remains to be done. While the large scale measurements are useful as a normalization for the fluctuation spectrum, they do not define the spectrum. For this, measurements must be made at smaller angular scales.

At 4°, recent ground-based measurements from Tenerife have set an upper limit to CBR fluctuations of $\Delta T/T \leq 1.6 \times 10^{-5}$. However, new data may have resulted in a possible detection of anisotropy with an amplitude $\Delta T/T \approx 2 \times 10^{-5}$.

At scales near 1 degree, close to the horizon size, results from the South Pole using the ACME (Advanced Cosmic Microwave Experiment) with a High Electron Mobility Transistor (HEMT) based detector place an upper limit to CBR fluctuations of $\Delta T/T \leq$

1.4×10^{-5} at 1.2° (Gaier et al. 1992). This data set has significant structure in excess of noise but was unlikely to be CBR given the spectrum. A conservative upper limit for a Gaussian autocorrelation function sky was computed from the highest frequency channel. A four channel average of the bands yields a detection at the level of $\Delta T/T = 1 \times 10^{-5}$.

Additional analysis of the 1991 ACME South Pole data using another region of the sky and with somewhat higher sensitivity shows a significant detection at a level of $\Delta T/T = 1 \times 10^{-5}$ (Schuster et al. 1993). The structure observed in the data has a relatively flat spectrum which is consistent with CBR but could also be Bremsstrahlung or synchrotron in origin. This data sets an upper limit comparable to the Gaier et al upper limit, but can also be used to place a lower limit to CBR fluctuations of $\Delta T/T \geq 8 \times 10^{-6}$, if all of the structure is attributed to the CBR. The 1σ error measured per point in this scan is 14 μK or $\Delta T/T = 5 \times 10^{-6}$. Per pixel, this is the most sensitive CBR measurement to date at any angular scale and will be used later in a discussion of systematics for possible future experiments from sub-orbital platforms. Recent measurements by the Princeton Big Plate experiment using a detector and beam size very similar to Gaier et al. (1992) and Schuster et al. (1993) but with a different chopping scheme, has found detection at levels consistent with the Schuster et al. 1993 results but in a completely different region of the sky and at lower galactic latitude (Wollack et al. 1994).

At scales near 0.5°, balloon-borne and South Pole based experiments have made very sensitive measurements. In 1988-89 the ACME experiment oufitted with a sensitive SIS (Superconductor - Insulator - Superconductor) detector set an upper limit of $\Delta T/T \leq 3.5 \times 10^{-5}$ at 0.5° for a Gaussian sky. Further refinements using sensitive bolometers on ACME resulted in the joint UCSB-UCB ACME-MAX balloon-borne experiment which has now had four successful flights. One scan (the μ Peg scan) resulted in an upper limit of $\Delta T/T \leq 2.5 \times 10^{-5}$ (Meinhold et al. 1993). This particular scan is notable in that it contained a strong detection of dust as well. After subtraction of the dust component a residual detection consistent with a CBR thermal spectrum remains at a level of $\Delta T/T = 1.5 \times 10^{-5}$. A scan from another region of the sky (the GUM scan) during the same flight resulted in a detection consistent with a CBR spectrum with an amplitude $\Delta T/T = 4.2 \times 10^{-5}$ (Gundersen et al. 1993). An ADR cooled bolometer based receiver has also been recently flown on MAX (June 1993) resulting in three deep CBR scans. One of the scans, the GUM scan, resulted in a detection consistent with that we previously saw with MAX in Alsop et al. (1992) and Gundersen et al. (1993). This data is presented in Devlin et al. 1994. The other two scans are reported in Clapp et al. 1994 and give $\Delta T/T = 3.1 \times 10^{-5}$ for the Sigma Hercules scan and $\Delta T/T = 3.3 \times 10^{-5}$ for the Iota Draconis region for a Gaussian autocorrelation function with a coherence angle of 0.5 degrees. Recent results from the Goddard-Chicago-Princeton MSAM (Medium Scale Anisotropy Measurement) balloon experiment using a beam size also near 0.5 degree also shows evidence of a possible CBR structure at the few $\times 10^{-5}$ level using a multi-wavelength He-3 cooled bolometric detector (Cheng et al. 1993).

At scales smaller than 0.1°, the results have come from ground-based radio telescopes. No significant CBR detections have been reported and current upper limits to fluctuations are $\Delta T/T \leq 1.8 \times 10^{-5}$ at 5 arcminutes and at 1 arcminute.

Theoretical arguments predict CBR on intermediate and large angular scales at a level $\Delta T/T \approx 1 \times 10^{-5}$. Different models predict a variety of power spectra. Recent arguments about foreground emission suggest that a per pixel sensitivity of $\Delta T/T \leq 1 \times 10^{-6}$ (3 μK) may be required to separate foreground contaminants from true CBR signals at a level where the power spectrum can be determined. (An order of magnitude more sensitivity may be required to do this separation well.) This number will be important for later discussions of future experiments.

It is clear from the existing results that in order to fully map out the primordial fluctuation spectrum, more data are needed. By taking advantage of rapidly evolving technology, and building low noise receivers at several frequencies using single detector elements at first, and then in focal plane arrays it should be possible to reach the required sensitivity in the next five years.

2. CBR ANISOTROPY MEASUREMENTS

The spectrum of the cosmic background radiation peaks in the millimeter-wave region. Figure 1 shows a plot of antenna temperature vs. frequency, demonstrating the useful range of CBR observation frequencies and the various backgrounds involved. The obvious regime for CBR measurements is in the microwave and millimeter-wave regions.

In the microwave region, the primary extra-terrestrial foreground contaminants are galactic synchrotron and thermal bremsstrahlung emission. Below 50 GHz, both of these contaminants have significantly different spectra than CBR fluctuations. Because of this, multi-frequency measurements can distinguish between foreground and CBR fluctuations (provided there is large enough signal to noise).

Above 50 GHz, the primary contaminant is interstellar dust emission. At frequencies above 100 GHz, dust emission can be distinguished from CBR fluctuations spectrally, also using multi-frequency instruments.

At all observation frequencies, extra-galactic radio sources are a concern. For an experiment with a collecting area of $1\mathrm{m}^2$ (approximately a 0.5° beam at 30 GHz for sufficiently under-illuminated optics), a 10 mJy source will have an antenna temperature of 7.3 μK, which will produce a significant signal in a measurement with a sensitivity of $\Delta T/T \approx 1 \times 10^{-6}$. Extra-galactic radio sources have the disadvantage that there is no well known spectrum which describes the whole class. For this reason, measurements over a very large range of frequencies and angular scales are required for CBR anisotropy measurements in order to achieve a sensitivity of $\Delta T/T \approx 1 \times 10^{-6}$.

3. INSTRUMENTAL CONSIDERATIONS

Sub-orbital measurements differ from orbital experiments in at least one important area, namely our terrestrial atmosphere is a potential contaminant. A good ground-based site like the South Pole has an atmospheric antenna temperature of 5 K at 40 GHz, for example. For a measurement to reach an error of $\Delta T/T \approx 1 \times 10^{-6}$, the atmosphere must remain stable over 6 orders of magnitude. In addition to this, the atmosphere will contribute thermal shot noise. At balloon altitudes, atmospheric emission is 3-4 orders of magnitude lower and much less of a concern. In addition, the water vapor fraction is extremely low at balloon altitude. Satellite measurements avoid this problem altogether. Another consideration for CBR anisotropy measurements is the sidelobe antenna response of the instrument. Astronomical and terrestrial sources away from foresight can contribute significant signals if the antenna response is not well behaved. Under-illuminated optical elements and off-axis low blockage designs are typically employed for the task. The sidelobe pattern can be predicted and well controlled with single-mode receivers, but appears to be viable for multi-mode optics as well. Even with precautions, sidelobe response will remain an area of concern for all experiments.

Most of the measurements discussed in the previous section were limited by receiver noise when atmospheric seeing was not a problem. It is possible to build receivers today with sensitivities of 200-400 μK $-\sqrt{s}$ using HEMTs or bolometers. A balloon flight obtaining 10 hours of data on 10 patches of sky, for example, could achieve a 1 σ sensitivity of 6.7 μK or $\Delta T/T = 2.5 \times 10^{-6}$ *per pixel* using one such detector.

To map CBR anisotropy with a sensitivity of $\Delta T/T = 1 \times 10^{-6}$ requires more integration time, lower noise receivers or multiple receivers. A 14-day, long duration balloon flight launched from Antarctica could result in a per pixel sensitivity of $\Delta T/T = 5 \times 10^{7}$, if 10 patches could be observed with a single detector element or $\Delta T/T = 5 \times 10^{-6}$ on 1000 patches as another example.

Measurements from the South Pole are also very promising. The large atmospheric emission (compared to the desired signal level - few million times larger!) is of great concern and based upon actual experience, even in the best weather, there is significant atmospheric noise. Estimated single difference atmospheric noise with a 1.5 degree beam is about 1 mK$\sqrt{s}$ at 30 GHz during the best weather. This added noise, as well as the overall systematic atmospheric fluctuations, make ground-based observations challenging but so far possible, and, in fact, yielding the most sensitive results.

Another approach to the problem is to use very low noise receivers and obtain the necessary integration time by flying long duration balloons. These receivers can be tested from ground-based observing sites like the South Pole. Should the long duration balloon effort prove inadequate, the only means toward the goal of mapping CBR anisotropy at this level may be a dedicated satellite. Again, the receivers on such a satellite would have to be low noise. The minimal cryogenic requirements for HEMT amplifiers make them an obvious choice for satellite receivers, but bolometric receivers using ADR coolers or dilution refrigerators offer significant advantages at submillimeter wavelengths.

4. HISTORY OF THE ACME EXPERIMENTS

In 1983, with the destruction of the 3 mm mapping experiment (Lubin et al. 1985), we decided to concentrate on the relatively unexplored degree scale region. Motivated by the possibility of discovering anisotropy in the horizon scale region where gravitation collapse would be possible and with experience with very low noise coherent detectors at balloon altitudes, we started the ACME program. A novel optical approach, pioneered at Bell Laboratories for communications, was chosen to obtain the extreme sidelobe rejection needed. In collaboration with Robert Wilson's group at Bell Labs, a 1 meter off-axis primary was machined. A lightweight, fully-automated, stabilized, balloon platform capable of directing the 1 meter off-axis telescope was constructed. As the initial detector we chose a 3 mm SIS receiver. Starting with lead alloy SIS junctions and GaAs FET pre-amplifiers we progressed to Niobium junctions and a first generation of HEMTs to achieve chopped sensitivities of about 3 mK $\sqrt{\text{sec}}$ in 1986 with a beam size of 0.5 degrees FWHM at 3 mm.

The first flight was in August 1988 from Palestine, Texas. Immediately afterwards, ACME was shipped to the South Pole for ground-based observations. The results were the most sensitive measurements to date (at that time) with 60 μK errors per point at 3 mm. The primary advantage of the narrow band coherent approach is illustrated in Figure 1 where we plot atmospheric emission versus frequency for sea level, South Pole (or 4 km mountain top) and 30 km balloon altitudes. With a proper choice of wavelength and bandpass, extremely low residual atmospheric emission is possible. (Total < 10 mK. The differential emission, over the beam throw, is much smaller.) Another factor of 10 reduction is possible in the "troughs" in going to 40 km altitude. The net effect is that atmospheric emission does not appear to be a problem in achieving μK level measurements, if done appropriately.

Subsequently, ACME has been outfitted with a variety of detector including direct amplification detectors using HEMT (High Electron Mobility Transistor) technology. These remarkable devices developed largely for communications purposes are superb at cryogenic temperatures as millimeter wavelength detectors. Combining relatively broad bandwidth (typically 10-40%) with low noise characteristics and moderate cooling requirements (including operation at room temperature) they are a good complement to shorter wavelength bolometers allowing for sensitive coverage from 10 GHz to 200 GHz when both technologies are utilized. The excellent cryogenic performance is due in large part to the efforts of the NRAO efforts in amplifier design (Pospieszalski 1990). We have used both 8-12 mm and 6-8 mm HEMT detectors on ACME, these observations being carried out from the South Pole in the 1990 and 1993 seasons. The beam sizes are 1.5 degrees and 1 degree FWHM for the 8-12 and 6-8 mm HEMTs respectively. Units using both GaAs and InP technology have been used. The lowest noise we have achieved to date is 10 K at 40 GHz, this being only 3.5 times the quantum limit at this frequency. These devices offer truly remarkable possibilities. Figure 2 shows the basic experiment configuration.

5. THE MAX EXPERIMENT

During the construction of ACME, a collaboration was formed between our group and the Berkeley group (Richards/Lange) to fly bolometric detectors on ACME. This fusion is called the MAX experiment and subsequently blossomed into the extremely successful Center for Particle Astrophysics' CBR effort. Utilizing the same basic experimental configuration as other ACME experiments, MAX uses very sensitive bolometers from about 1-3 mm wavelength in 3 or 4 bands. Flown from an altitude of 35 km, MAX has had four very successful flights. The first flight occurred in June 1989 using ^{3}He cooled (0.3 K) bolometers, and the most recent flight occurred in June 1993 using ADR (Adiabatic Demagnetization Refrigeration) cooled bolometers. All the MAX flights have had a beam size of near 0.5 degrees.

6. RESULTS

There have been a total of ten ACME observations/flights from 1988 to 1993. Over twenty articles and proceedings have resulted from these measurements as well as seven Ph.D. theses. A summary of the various observations is given in Table I.

ACME articles by Meinhold & Lubin (1991), Meinhold et al. (1992) , Gaier et al. (1992), Schuster et al. (1993), and ACME-MAX articles by Fischer et al. (1992), Alsop et al. (1992), Meinhold et al. (1993), Gundersen et al. (1993), Devlin et al. 1994 and Clapp et al. 1994 summarize the results to date.

Significant detection by ACME at 1.5 degrees is reported by Schuster et al. (1993) at the 1×10^{-5} level and by Gundersen et al. (1993) at 0.5 degrees at the 4×10^{-5} level in adjacent issues of *ApJ Letters*. The lowest error bar per point of any data set to date is in the Schuster et al. 1.5° data with 14 μK while the largest signal to noise signal is in Gundersen et al. with about a 6 σ detection (at the peak) Recently Wollack et al. (1993) report a detection at an angular scale of 1.2 degrees of about 1.4×10^{-5} consistent with Schuster et al. and using a detector nearly identical to ours. At 0.5 degrees, the MSAM group reports detection of a "CBR component" at a level of about 2×10^{-5} but with "point like" sources that are being reanalyzed and which may contribute additional power. Our most recent results from the June 1993 ACME-MAX flight give significant detections at the $3 - 4 \times 10^{-5}$ level at angular scales near 0.5 degrees.

It is remarkable that over a broad range of wavelengths that most degree scale measurements report detection at the one to a few $\times 10^{-5}$ level. Even more remarkable is the fact that both degree scale and COBE scale detections were published within six months of each other (Smoot et al. 1992, Schuster et al. 1993, Gundersen et al. 1993).

In historical retrospective, the degree scale detection in the Gamma Ursa Minoris region ("GUM data") was first published in Alsop et al. (1992) **prior** to the COBE detections. In any case, 1992 and 1993 were historical years in cosmology and CBR studies in particular. The ACME degree scale results are summarized in Table II.

7. GOALS FOR THE FUTURE

We adopt as a long term goal the measurement of CBR anisotropy to a level of 1 micro-Kelvin per pixel. A near term goal of mapping a large number of pixels to 10 micro-Kelvin per pixel would also be highly desirable. This is somewhat but not completely arbitrary as recent analysis indicates that such (1 micro-Kelvin per pixel) sensitivity may be needed to allow good multi-parameter galactic subtraction. A word of warning is appropriate here. The galactic and extra-galactic backgrounds are not well understood at the levels and wavelengths needed. The same is true of our understanding of the actual signals we are attempting to find. Different physics scenarios in the early universe if known *a priori* would yield different search and experimental configurations. We are groping for the light here and any such search will be a modified random walk with frequent turns in direction after hitting the cosmic lamp posts. It will be amusing to review this ten years from now. It is believed that much of the current theoretical ideas will be well tested with such a sensitivity over an angular range of a few tenths of a degree to about ten degrees. The very large and small angular scales should not be totally neglected either, however, as evidenced in that even with the COBE DMR results after 4 years of data, many (most) of the pixels in the sky maps will not be galactic limited or even show a significant galactic signal. Another large scale anisotropy experiment with perhaps a 3 degree beam and a sensitivity 10 times better than COBE should allow a near background limited measurement at the large angular scales.

An important reference point to consider is that 1 micro-Kelvin is about an order of magnitude smaller than the currently most sensitive experiments. This comparison is important in what follows as we will discuss the future experiments in terms of the current experiments and indicate the magnitude of the needed improvements and the viability of these being accomplished. Keep in mind that in the past decade CBR anisotropy experiments have improved their sensitivity by about an order of magnitude as well. In what follows we will take a "devil's advocate" position to assume a worst case analysis that all of the presently measured signals are due to various systematic errors.

8. ATMOSPHERE

For coherent detectors, atmospheric emissions of a few Kelvin at the South Pole and milliKelvin or less at balloon altitudes. For incoherent detectors, similar emission at lower altitudes though usually substantially larger at balloon altitude due to the broad bandwidths. Note that the gain is going from the South Pole or mountain top to balloon altitudes is about a factor of $10^3 - 10^4$ reduction in emission.

For ground-based measurements, weather is definitely a problem. Typically, at sea level and lower altitude sites, the number of "good" days can be quite limited. For example, the many year experience at Owens Valley was that perhaps only a few handfuls of days per year were suitable. Experience at the South Pole indicates that in a typical summer season, perhaps 30% of the days are usable. Other ground-based sites, such as Mauna Kea, are also usable. If we assume all of the structure in the recent South Pole experiments is of atmospheric origin, then reducing the atmosphere by two orders of magnitude (going to balloon altitudes) should suffice. There is no evidence that atmospheric emission limit the current experiments except as the amount of "good" days available, however there are viable solutions (balloons) if this is a fundamental limitation for some experiments.

9. GALACTIC EMISSION

Understanding the emission from our galaxy both as diffuse and compact sources is of utmost concern for CBR anisotropy experiments as it is expected (and already is) to be problematic. Emission from charged particles in the complex galactic magnetic fields as well as collisions between charged particles as well as interstellar dust is complicated and not well enough understood to assess its full impact. Here again we draw on actual data. A variety of experiments from centimeter wavelengths to the millimeter and submillimeter bolometric experiments show regions where at least at the $\Delta T/T \sim 10^{-5}$ level galactic emission is not overwhelming (but may be present) in the "best" regions. Significant debate and uncertainty remains as to the best wavelength range to make measurements in. Most groups have adopted multiple wavelength measurements to allow the discrimination of galactic from cosmological sources due to the different spectral nature of the signals. Planned and existing experiments covering a factor of 2-3 in wavelength are typical.

10. EXTRA-GALACTIC SOURCES

For most of the beam sizes being discussed extragalactic sources are essentially point sources (sub beam size). Many extragalactic sources can be distinguished easily on the basis of their spectrum, but relatively flat spectra sources are known to exist. Most sources, however, do not have spectra that are well characterized at centimeter and millimeter wavelengths. This is going to be a challenging problem for CBR experiments requiring careful broad wavelength design and most likely follow up ground-based measurements. Fortunately, besides the spectral discrimination, the morphological (point source like) characteristic of extra-galactic sources will be very helpful. This is an area where much closer coordination is necessary with ground-based radio and submillimeter telescopes.

11. SIDELOBE ISSUES (OFF AXIS RESPONSE)

The response of the beam includes contributions from directions other than the target direction. Problematic sources of pickup include atmospheric emission (especially near the horizon where it can be quite large), solar and lunar emission, galactic (plane) and generally the most important being terrestrial earth emission. A simple calculation shows for a 0.5 degree experiment that rejection of the order of $10^{13} - 10^{14}$ is desired *if* we want the total radiometric emission picked up on the back lobe (earth) to be less than 1 μK. This is a formidable requirement on any antenna system, indeed one that is very difficult to even measure. It is also an unduly pessimistic requirement. Here again we are guided by actual experience and current data. Again, doing a worst case analysis, if we assume that all the structure seen in the recent South Pole and balloon experiments is due to earth sidelobe pickup, we conclude that another factor of 10^2 is needed to get the desired goal of 1 μK. A factor of 10^2 should be available with modest redesign and additional ground shields. Going to a balloon or low earth orbit does not help here (unless it is atmospheric sidelobe contamination that is the concern). Going to a multi-AU orbit (trajectory) does help greatly here since the earth subtended solid angle becomes much less.

12. DETECTOR LIMITATIONS - PRESENT AND FUNDAMENTAL

Detectors can be broadly characterized as either coherent or incoherent being those that preserve phase or not, respectively. Masers, SIS and HEMTs are coherent. Bolometers are incoherent. SIS junctions can also be run in an incoherent video detector mode. Phase preserving detectors inherently must obey an uncertainty relationship that translate into a minimum detector noise that depends on the observation frequency, the so called quantum limit. Incoherent detectors do not have this relationship but are ultimately limited by the CBR background itself. At about 40 GHz, these fundamental limits are comparable. Current detectors are not at these fundamental limits, though they are within an order of magnitude for both HEMTs and bolometers when used over moderate bandwidths. Here we include all effects including coupling efficiencies. Currently both InP HEMTs and ADR and ^{3}He cooled bolometers exhibit sensitivities of under 500 μK sec$^{1/2}$. This assumes no additional atmospheric noise, true at balloon altitudes. For ground-based experiments at the South Pole, atmospheric noise is significant however.

Significant advances have been made in recent years in detector technology with effective noise dropping by over an order of magnitude over the past decade. With moderate bandwidths the fundamental limits for detectors are about a factor of 5 below the current values, so fundamental technology development is to be highly encouraged for both coherent and incoherent detectors.

With current detectors, achieving 1 μK sensitivity requires roughly one day per pixel for a single detector. This is appropriate for detector limited not atmospheric limited detection. This would be appropriate for balloon altitudes.

Small arrays of detectors are currently planned for several experiments. This should allow μK per pixel sensitivity over, say, 100 pixels in time scales of a few weeks, suitable for long duration ballooning or polar observations. If the fundamental detector limits could be achieved, the effective time would drop to about a day. Factors of 2-3 reduction in current detector noise are not unreasonable to imagine over the next five years, and if they could be achieved, the above time scale would drop to less than a week. Multiple telescopes are also possible. If we are willing to accept a goal of 3 μK per pixel (1 part per million of the CBR) instead of 1 μK then roughly 10 times as many pixels can be observed for the same integration time allowing significant maps to be made from balloon-borne detectors. A 10 μK error per pixel measurement would allow 100 times as many pixels to be measured in the same time. As we learn more about the structure of the CBR and about the nature of low level foreground emission the choice of sensitivity for a given angular scale will become clearer.

13. SPECTRUM MEASUREMENTS

The spectrum of the CBR has been extremely well characterized by the COBE FIRAS experiment in the millimeter wavelength range. However, in the range of about 1-100 GHz, where interesting physical phenomenon may distort the spectrum, much work remains to be done; particularly, at the longest wavelengths. Fortunately, the atmospheric emission is quite low over much of this range from both good ground-based sites and extremely low at balloon altitudes. Galactic emission and sidelobe contamination are of primary concern at the longest wavelengths, but it is expected that a number of ground-based and possibly balloon-borne experiments will be performed and should be encouraged.

A recent balloon-borne experiment, Schuster and Lubin (1994), is an example of what might be done in the future from balloon spectrum experiments. With all cryogenic optics and no windows, this experiment measured $T = 2.71 \pm 0.02$ K at 90 GHz with negligible atmospheric contamination ($\sim$ a few mK) and no systematic corrections. Errors of order 1 mK should be obtainable. The basic configuration could be extended to longer wavelengths where much remains to be done. In particular coherent measurements at 10 - 50 GHz from a balloon could be done. Such experiments are now being explored.

14. POLARIZATION

Very little effort has been directed towards the measurement of the polarization of the CBR compared to the effort in anisotropy detection. In part, this is due to the low level of linear polarization expected. Typically, the polarization is only 1-30% of the anisotropy and depends strongly on the model parameters. This is an area which in theory can give information about the reionization history, scalar and tensor gravity wave modes and large scale geometry effects. In the future, this may be a very fruitful area of inquiry.

15. TO SPACE

The question of whether or not a satellite is needed to get the degree scale "answer" is complex. There is no question that the measurements can be done from space and given sufficient funding this is the preferable way. It is unclear at this time what the limitations from sub-orbital systems will be and vigorous work is planned for sub-orbital platforms over the next decade. The galactic and extragalactic background problem remains the same for orbital and sub-orbital experiments. The atmosphere can be dealt with, particularly from balloon-borne experiments, with careful attention to band passes. Per pixel sensitivities in the μK region are achievable with current and new technologies, HEMTs, and bolometers over hundreds to thousands of pixels. The major issue will be control of sidelobes and getting a uniform dataset. Ideally full sky coverage would be best and this is one area where a long term space based measurement would be ideal. In the control of sidelobe response a multi AU orbital satellite would be a major advance. This advantage is lost for near Earth orbit missions, however. By the end of the millennium, degree scale maps over a reasonable fraction of the sky at the 10^{-6} level should be possible from balloons and the ground. The potential knowledge to be gained is substantial, and I can think of few areas of science where the potential "payoff" to input (financial and otherwise) is so high.

16. ACKNOWLEDGEMENTS

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TABLE I

CBR Measurements With the UCSB ACME Platform

Date	Site	Detector System	Beam FWHM (deg)	Sensitivity
1988 Sep	Balloon[P]	90 GHz SIS receiver	0.5	4 mK $s^{1/2}$
1988 Nov-1989 Jan	South Pole	90 GHz SIS receiver	0.5	3.2
1989 Nov	Balloon[FS]	MAX photometer (3, 6, 9, 12 cm^{-1}) ^3He	0.5	12, 2, 5.7, 7.1
1990 Jul	Balloon[P]	MAX photometer (6, 9, 12 cm^{-1}) ^3He	0.5	0.7, 0.7, 5.4
1990 Nov-1990 Dec	South Pole	90 GHz SIS receiver	0.5	3.2
1990 Dec-1991 Jan	South Pole	4 Channel HEMT amp (25-35 GHz)	1.5	0.8
1991 Jun	Balloon[P]	MAX photometer (6, 9, 12 cm^{-1}) ^3He	0.5	0.6, 0.6, 4.6
1993 Jun	Balloon	MAX photometer (3, 6, 9, 12 cm^{-1}) ADR	0.55-0.75	0.6, 0.5, 0.8, 3.0
1993 Nov-1994 Jan	South Pole	HEMT 25-35 GHz	1.5	0.8
1993 Nov-1994 Jan	South Pole	HEMT 38-45 GHz	1.0	0.5
1994 Jun	Balloon	MAX photometer (3, 6, 9, 14 cm^{-1}) ADR	0.55-0.75	0.4, 0.4, 0.8, 3.0

Sensitivity does not include atmosphere which, for ground-based experiments, can be substantial.

P - Palestine, TX
FS - Fort Sumner, NM

TABLE II

Recent ACME Degree Scale Results

Publication	Configuration	Beam FWHM (deg)	$\Delta T/T \times 10^{-6}$
Meinhold & Lubin 91	ACME-SIS	0.5	<35
Alsop et al. 92	ACME-MAX (GUM)	0.5	45^{+57}_{-26}
Gaier et al. 92	ACME-HEMT	1.5	<14
Meinhold et al. 93	ACME-MAX (μ Peg - upper limit)	0.5	<25
Meinhold et al. 93	ACME-MAX (μ Peg - detection)	0.5	15^{+11}_{-7}
Schuster et al. 93	ACME-HEMT	1.5	9^{+4}_{-2}
Gundersen et al. 93	ACME-MAX (GUM)	0.5	42^{+17}_{-11}
Devlin et al. 94	ACME-MAX (GUM)	0.55-0.75	37^{+19}_{-11}
Clapp et al. 94	ACME-MAX (Iota Draconis)	0.55-0.75	33^{+11}_{-11}
Clapp et al. 94	ACME-MAX (Sigma Hercules)	0.55-0.75	31^{+17}_{-13}

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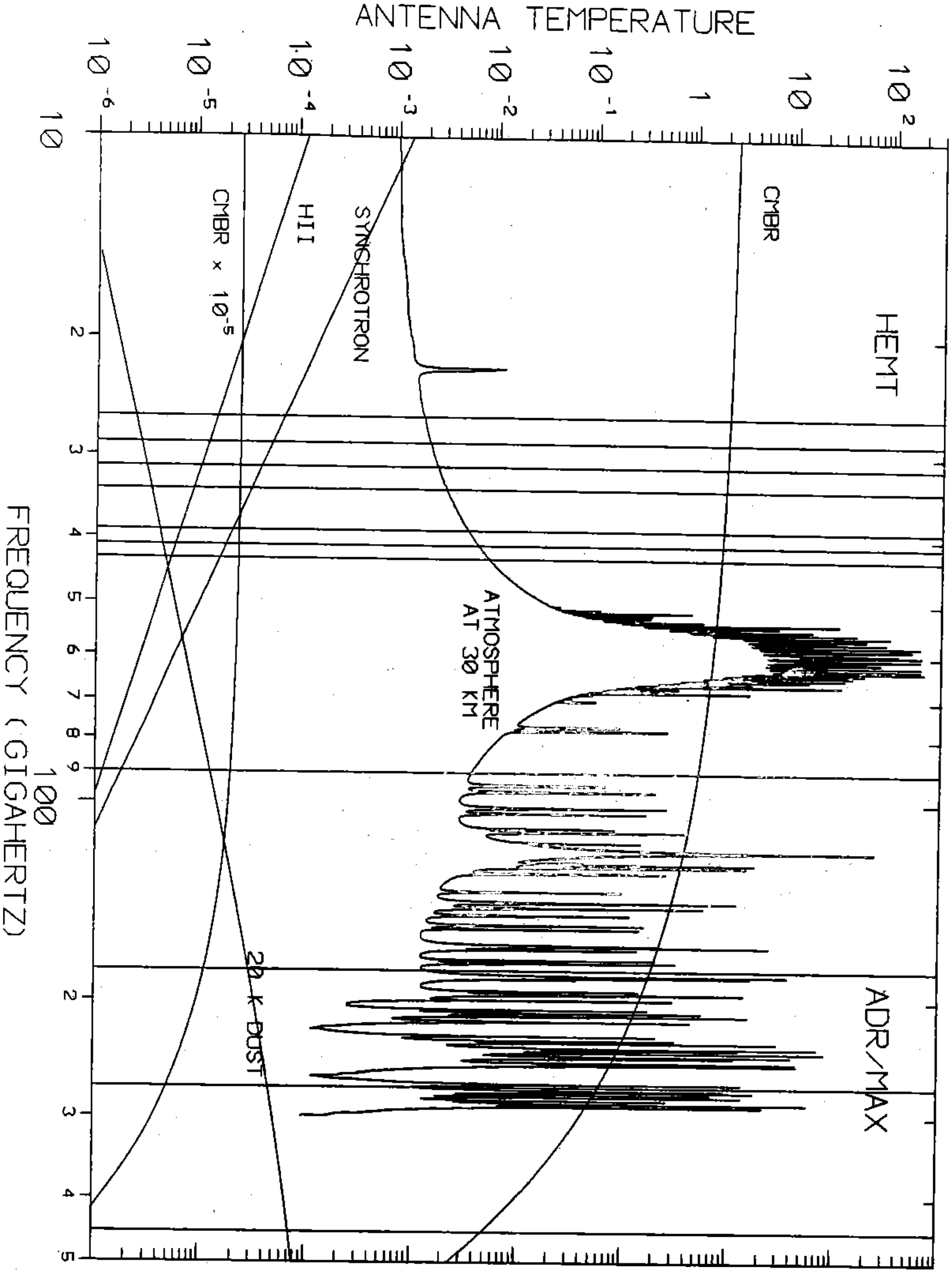
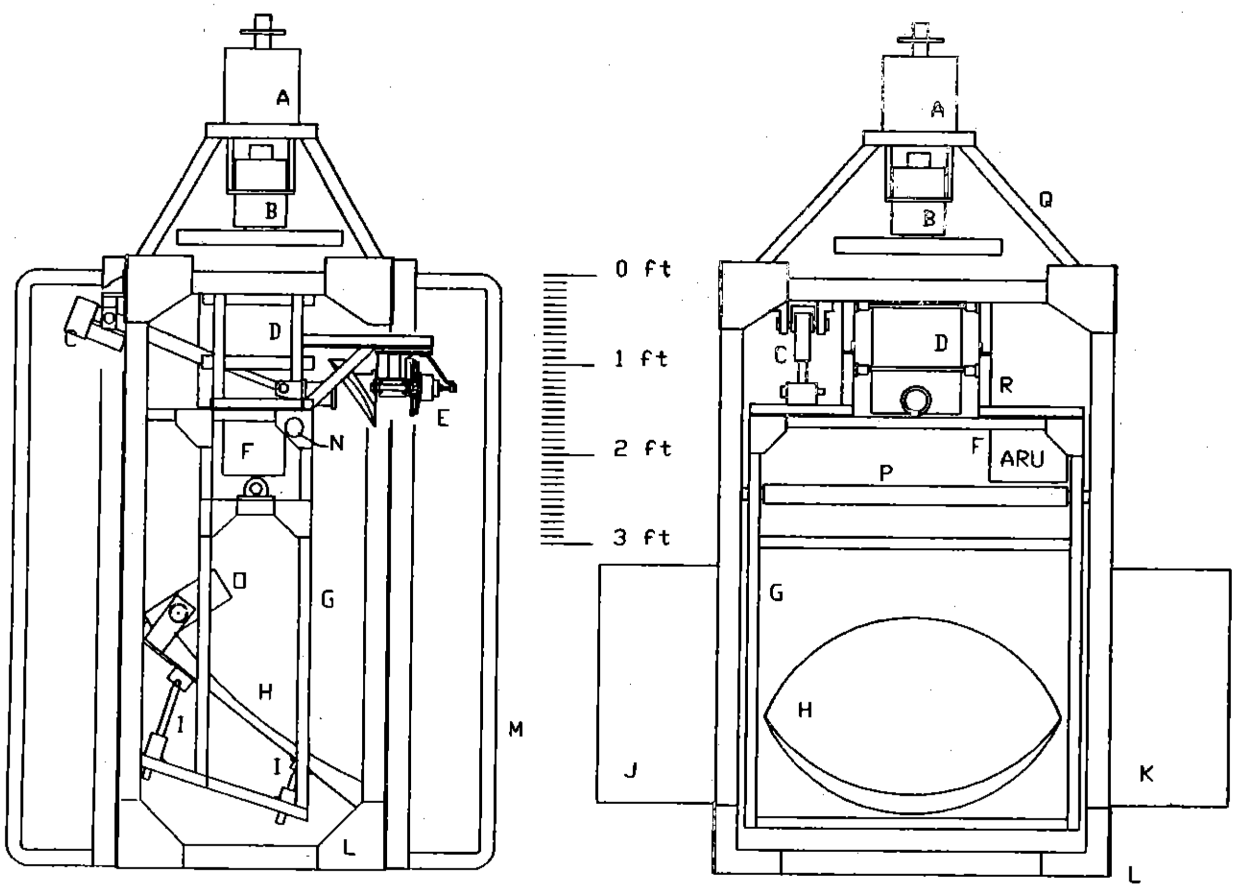
FIGURE CAPTIONS

Figure 1: Atmospheric and galactic emission as a function of frequency

Figure 2: The ACME stabilized telescope


ANTENNA TEMPERATURE
FREQUENCY (GIGAHERTZ)
HEMT
ADR/MAX
CMBR
SYNCHROTRON
HII
CMBR × 10^-5
ATMOSPHERE AT 30 KM
20 K DUST



(A) RCUBE
(B) Reaction Wheel
(C) Linear Actuator
(D) Dewar
(E) Nutation System /Secondary mirror
(F) ARU gyroscope
(G) Secondary Frame
(H) Off Axis Parabolic Mirror
(I) Adjustable Mirror Mount
(J) Electronics/Computer
(K) Telemetry/Batteries
(L) Main Frame
(M) Roll Bars
(N) Clinometer
(O) CCD Camera
(P) Main Elevation Shaft
(Q) Top Spider Frame
(R) Dewar Mount

* Magnetometer inside Box (J)