DETECTION OF DEGREE-SCALE ANISOTROPY: A SUMMARY OF ACME ANISOTROPY RESULTS

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ABSTRACT

From 1988 to 1994, the Advanced Cosmic Microwave Explorer (ACME) flew six times on balloons and observed three times from the South Pole. Observing degree-scale anisotropy in the Cosmic Background Radiation over an angular scale from 20 to 120 arc minutes and over a wavelength range from 1 to 12 mm, the ACME experiments have made significant contributions to our understanding of the CBR including the first detection of degree-scale anisotropy at a level of 10–40 ppm, the first measurement of the CBR power spectrum at degree scales and the first evidence for a rise in the power spectrum at sub degree scales.

These results have subsequently been largely corroborated by other experiments. Such measurements allow us to begin to critically test cosmological models in a quantitative fashion and have set the stage for the possibility of measuring a number of critical cosmological parameters in the next generation of experiments. Because of the extreme sensitivities needed (1–10 ppm) and the difficulties of foreground sources, the next generation of measurements will require not only technological advances in detector and measurement techniques, but also multispectral measurements and careful attention to low-level systematic errors as well as an understanding of diffuse galactic and extragalactic emission.

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[*] Parts of this paper are adapted from my IAU 1994 paper.

1 Introduction

The Cosmic Background Radiation (CBR) provides us with a unique opportunity to test cosmological theories in detail. 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, these results can be combined with other measurements of large-scale structure in the universe, such as galaxy surveys, to provide a coherent cosmological model.

Recent measurements of CBR anisotropy have provided us with some exciting results in the last few years. The large-scale anisotropy detected by the COBE satellite allows us to normalize the cosmological power spectrum at long wavelengths. This detection at a level of $\Delta T/T = 10^{-5}$ at 10° gives us crucial information at scales above ten degrees about the primordial fluctuations. The largest scales do not, however, define the subsequent evolution of the CBR structure in the collapse phase after decoupling. In addition, the limited number of sky patches available at large scales, along with the fact that we are only able to sample our local horizon and not the entire universe (cosmic variance), limits the information available from larger scale measurements. Additional measurements must be made at smaller angular scales.

2 CBR Anisotropy Measurements

The temperature of the CBR is currently measured by the COBE to be about 2.73 Kelvin, and hence, 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 foregrounds and backgrounds involved. The obvious regime for CBR measurements is in the microwave and millimeter-wave regions between about 20 and 200 GHz (1.5 to 15 millimeters).

In the microwave region, the primary extraterrestrial 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, multifrequency measurements can distinguish between foreground and CBR fluctuations (provided there is large enough signal to noise).

Figure 1: Relevant backgrounds for terrestrial measurements at the South Pole and at balloon altitudes (35 km) where ACME observes. Representative galactic backgrounds are shown for synchrotron, bremsstrahlung, and interstellar dust emission as well as the various ACME (center) wavelength bands.

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 multifrequency instruments.

At all observation frequencies, extragalactic radio sources are a concern. For an experiment with a collecting area of 1 m^2 (approximately a 0.5° beam at 30 GHz for sufficiently underilluminated optics), a 10 mJy source will have an antenna temperature of 7 μK, which will produce a significant signal in a measurement with a sensitivity of $\Delta T/T \approx 1 \times 10^{-6}$. Extragalactic 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 $\Delta T/T \approx 1 \times 10^{-6}$. In Fig. 2, we show our best estimate for the fraction of sky uncontaminated by the galaxy. There is substantial uncertainty about our understanding of galactic emission so this is only an estimate. However, based on our degree-scale measurements with ACME and the COBE results at large angular scales, we have some confidence that these are reasonable model estimates. One of the secondary measurements to come out of the next generation of CBR measurements will indeed be greatly refined galactic models.

3 Instrumental Considerations

Suborbital 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 six orders of magnitude. In addition to this, the atmosphere will contribute thermal shot noise. At balloon altitudes, atmospheric emission is three to four 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. Underilluminated optical elements and off-axis low blockage designs are typically employed for the task. The sidelobe pattern can be predicted and well-controlled

Figure 2: Galactic model estimates for the fraction of sky uncontaminated below a given level. The model includes synchrotron, bremsstrahlung, and dust emission. The synchrotron model is given for two different spectral indices. Far off the galactic plane (where we are most interested in measuring), the steeper spectral index is more appropriate. The dust model is based on the IRAS 100 micron map combined with our dust data from the mu-Pegasus region.

with single-mode receivers, but appears to be viable for multimode 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 (High Electron Mobility Transistors) or bolometers. A balloon flight obtaining ten hours of data on ten 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 $\Delta T/T = 5 \times 10^{6}$ if 1000 patches were observed with a single detector element. A more ambitious balloon-borne measurement would be a 100-day mission with a focal plane array. With a nine-element array, it is possible to reach a sensitivity per pixel of $\Delta T/T = 5 \times 10^{6}$ on as many as 10^5 pixels in a flight. Such a flight would cover a significant fraction of the sky.

Ground-based measurements from the South Pole are also very promising. The large atmospheric emission (compared to the desired signal level—a 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° 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, makes ground-based observations challenging but so far possible, and in fact, yielding the most sensitive results.

One possible approach to making a precision measurement of the power spectrum is to use an array of very low noise receivers and obtain the necessary integration time by flying a number of long-duration balloons. 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),[1] 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 one-meter, off-axis Gregorian optical system was designed and machined. A lightweight, fully-automated, stabilized, balloon platform capable of directing the one-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 preamplifiers, we progressed to Niobium junctions and a first generation of HEMTs to achieve chopped sensitivities of about 3 mK $\sqrt{\mathrm{sec}}$ in 1986 with a beam size of 0.5° FWHM at 3 mm.

The first flight was in August 1988 from Palestine, Texas. Immediately afterwards, it was shipped to the South Pole for ground-based observations. The results were the most sensitive measurements to date with 60 μK errors per point at 3 mm. The primary advantage of the narrow band coherent approach is illustrated in Fig. 1 where we plot atmospheric emission versus frequency for the 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 ten reduction is possible in the "troughs" in going to a 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 detectors including SIS junctions, direct amplification detectors using HEMTs and bolometers. These remarkable devices developed largely for communication 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

Figure 3: The basic ACME configuration is shown. All of the ACME measurements, both South Pole and balloon borne, use the same basic configuration with the primary change being a different dewar and secondary mirror.

performance is due in large part to the efforts of the NRAO efforts in amplifier design (Pospieszalski, 1990).[2] 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° and 1° FWHM for the 8–12 mm 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 3 shows the basic experiment configuration.

There have been a total of 11 ACME CMB observations/flights from 1988 to 1994. Over 20 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 1.

Date	Site	Detector System	Beam FWHM (deg.)	Sensitivity
1988 Sept	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}) ^{3}He	0.5	12, 2, 5.7, 7.1
1990 Jul	Balloon^{P}	MAX photometer (6, 9, 12 cm^{-1}) ^{3}He	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}) ^{3}He	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

Table 1: CBR measurements made with ACME.

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

P–Palestine, TX
FS–Fort Sumner, NM

5 The ACME-MAX Experiments

During the construction of ACME, a collaboration was formed between our group and the Berkeley group (Richards/Lange) to fly bolometric detectors on ACME (to replace the coherent detectors initially used). 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 three or four bands. Flown from an altitude of 35 km, MAX has had five very successful flights. The first MAX flight (second ACME flight) occurred in June 1989 using ^{3}He cooled (0.3 K) bolometers, and the most recent flight occurred in June 1994 using ADR (Adiabatic Demagnetization Refrigeration) cooled bolometers. All the MAX flights have had a beam size of near 0.5°.

6 Evidence for Structure Prior to COBE

Prior to the COBE launch, ACME had made two flights and one South Pole expedition. Prior to the April 1992 COBE announcement, ACME had flown four times and made two South Pole trips with a total of seven measurements. Our 1988 South Pole trip with ACME outfitted with a sensitive SIS (Superconductor-Insulator-Superconductor) receiver resulted in an upper limit at 0.5° of $\Delta T/T \leq 3.5 \times 10^{-5}$ at 0.5° for a Gaussian sky. This was tantalizingly close to the "minimal predictions" of anisotropy at the time and, as we were to subsequently measure, just barely above the level of detectability. In the Fall of 1989, we had our first ACME-MAX flight with a subsequent flight the next summer (so-called MAX-II flight). Remarkably, when we analyzed the data from this second flight, we found evidence for structure in the data consistent with a cosmological spectrum. This data was taken in a low dust region and showed no evidence for galactic contamination. This data in the Gamma Ursa Minoris region ("GUM data") was first published in Alsop *et al.* (1992)[3] *prior* to the COBE detections. At the time, our most serious concern was of atmospheric stability, so we decided to revisit this region in the next ACME flight in June 1991. In the meantime, ACME was shipped to the South Pole in October 1990 for another observing run, this time with both an SIS detector and a new and extremely sensitive HEMT receiver. At scales near 1°, close to the horizon size, results from the South Pole using the ACME with a HEMT-based detector place an upper limit to CBR fluctuations of $\Delta T/T \leq 1.4 \times 10^{-5}$ at 1.2° (Gaier *et al.*, 1992).[4] This upper limit for a Gaussian autocorrelation function sky was computed from the highest frequency channel. This data set has significant structure in excess of noise but seemed unlikely to be CBR given the spectrum. However, because the data is taken in a step scan and not as a continuous scan, it is not possible to eliminate the possibility that the structure seen is cosmological, since the beam size varies from channel to channel. Under the assumption that the structure seen is cosmological, a four-channel average of the bands yields a detection at the level of $\Delta T/T = 1 \times 10^{-5}$. This is about the same level we measured subsequently in the SP '94 dataset. Analysis of dust and synchrotron maps from the area of the sky surveyed with reasonable spectral indices predict that the signal level observed is not consistent with dust or synchrotron.

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).[5] 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. Again, however, the low frequency synchrotron maps do not show similar morphology and would predict an amplitude that is much smaller ($< 7\ \mu$K). The amplitude is also inconsistent with known dust emission. No evidence for point source contamination was found either. In addition, data taken by our group in 1993/1994 (SP '94) in the same region found a similar amplitude structure that appears cosmological. The Schuster *et al.* data can also be used to set an upper limit comparable to the Gaier *et al.* [4] 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. The relevant measurements just prior to the COBE announcement are summarized in Fig. 4. With apparent detection and good upper limits at degree-scales, what was needed was large-scale normalization. This was provided by the COBE data in 1992, and as shown in Fig. 5, the degree-scale measurements were consistent given the errors involved. Without the large-scale normalization of the COBE data, it was difficult to reconcile the apparently discordant data. However, with the refinement in theoretical understanding and additional data, the pre-COBE data now are seen to be consistent with the post-COBE data.

7 ACME Results

There have been a total of 11 ACME observations/flights from 1988 to 1994. Over 20 articles and proceedings have resulted from these measurements as well as seven Ph.D. theses. ACME-SIS and ACME-HEMT articles by Meinhold and Lubin (1991),[6] Meinhold *et al.* (1992),[7] Gaier *et al.* (1992),[4] Schuster *et al.* (1993),[5] Gundersen *et al.* (1995),[8] and ACME-MAX articles by Fischer *et al.* (1992),[9] Alsop *et al.* (1992),[3] Meinhold *et al.* (1993),[10] Gundersen *et al.* (1993),[11] Devlin *et al.* (1994),[12] and Clapp *et al.* (1994)[13] summarize the results to date.

Significant detection by ACME at 1.5 degrees is reported by Schuster *et al.* (1993)[5] at the 1×10^{-5} level, and by Gundersen *et al.* (1993)[11] at 0.5 degrees

Figure 4: ACME CBR power spectrum data prior to the COBE detection. Theoretical curves are from Steinhardt and Bond (private communication). See Key in Fig. 5 caption.

Figure 5: Recent ACME results (in BOLD) along with results from other groups. Key: a-COBE, b-FIRS, c-Tenerife, d1-SP91 9 pt. 4 channel analysis-Bond ‘93, d3-SP91 9+13 pt. 4 channel analysis-Bond ‘93, d5-SP91 9 pt. Gaier *et al.* ‘92, e-Big Plate, f-PYTHON, g-ARGO, h-MAX4-Iota Dra, i-MAX4-GUM, j-MAX4-Sig Herc, k-MSAM2, l-MSAM2, m-MAX3-GUM, n-MAX3-mu Peg, o-MSAM3, p-MSAM3, q-Wh. Dish, r-OVRO7, s2-SP94-Q, s3-SP94-Ka, t-SP89, u-MAX2-GUM, many from Steinhardt and Bond by private communication.

at the 4×10^{-5} level in adjacent issues of *Astrophys. J. Lett.* The lowest error bar per point of any data set to date is in the Schuster *et al.* [5] 1.5° data with 14 μK while the largest signal-to-noise signal is in Gundersen *et al.* [11] with about a 6 σ detection (at the peak). Recently, Wollack *et al.* (1994)[14] reported a detection at an angular scale of 1.2 degrees of about 1.4×10^{-5} consistent with Schuster *et al.* [5] and using a detector nearly identical to ours. The ACME-HEMT 1994 South Pole (SP '94) data used both Ka- and Q-band HEMT detectors and show a strong detection at a level of about 1.5×10^{-5} (Gundersen *et al.* [1995])[8]. This is consistent with our SP '91 detection in Schuster *et al.* [5], but the addition of a higher frequency band in the SP' 94 experiment gave a much improved discriminator between galactic emission and CMB. At the smaller ACME-MAX scale near 0.5 degrees, the MSAM group also reports detection of a "CBR component" at a level of about 3×10^{-5}. Our recent results from the June 1993 ACME-MAX 4 flight give significant detections at the $3 - 4 \times 10^{-5}$ level at angular scales near 0.5 degrees (Devlin *et al.* [1994][12] and Clapp *et al.* [1994][13]). Additional data from our 1994 Summer ACME-MAX 5 flight is currently in preparation (Lim *et al.* [1995][15] and Tanaka *et al.* [1995][16]).

It is remarkable that over a broad range of wavelengths, most degree-scale measurements report detection at the one to a few $\times 10^{-5}$ level. Even more remarkable is the fact that both ACME degree-scale and COBE-scale detections were published within months of each other (Alsop *et al.* [1992],[3] Smoot *et al.* [1992],[17] Schuster *et al.* [1993],[5] Gundersen *et al.* [1993][11]).

In any case, 1992 and 1993 were historical years in cosmology, and CBR studies in particular. The recent ACME results along with the results of other groups are summarized in Fig. 5. As can be seen from this and the data summarized in Table 2, the ACME data strongly favor a rise in the power spectrum from 1.5 to 0.5 degrees.

8 Future

The next decade promises to yield an enormous amount of cosmological data in CBR studies. We are now at a point, both technologically and in our understanding of the relevant CBR signals and noncosmological backgrounds, that we can seriously contemplate making a precision measurement of the CBR power spectrum. We have strong evidence that we are currently detecting fluctuations.

Publication	Configuration	Beam FWHM (deg.)	$\Delta T/T \times 10^{-6}$ (GACF)**	ℓ	$C_\ell \ell(\ell+1)/2\pi^*$ ($\times 10^{-10}$)
Meinhold & Lubin ‘91	ACME-SIS SP89	0.5	< 35	145	< 8.6
Alsop *et al.* ‘92	ACME-MAX-II (GUM)	0.5	45^{+57}_{-26}	143	$9.6^{+13.7}_{-4.2}$
Gaier *et al.* ‘92	ACME-HEMT SP91	1.5	< 14	58	< 1.5
Meinhold *et al.* ‘93	ACME-MAX-III (μ Peg - upper limit)	0.5	< 25	143	< 2.96
Meinhold *et al.* ‘93	ACME-MAX-III (μ Peg - detection)	0.5	15^{+11}_{-7}	143	
Schuster *et al.* ‘93	ACME-HEMT SP91	1.5	9^{+7}_{-4}	58	$0.76^{+0.80}_{-0.21}$
Bond ‘93	SP91 4 channel $9 + 13$ pt. analysis	1.5		58	$1.06^{+0.83}_{-0.29}$
Bond ‘93	SP91 4 channel 9 pt. analysis	1.5		58	$0.5^{+0.80}_{-0.16}$
Gundersen *et al.* ‘93	ACME-MAX-III (GUM)	0.5	42^{+17}_{-11}	143	$8.5^{+3.0}_{-2.2}$
Devlin *et al.* ‘94	ACME-MAX-IV (GUM)	0.55–0.75	37^{+19}_{-11}	129	$6.1^{+3.9}_{-1.5}$
Clapp *et al.* ‘94	ACME-MAX-IV (Iota Draconis)	0.55–0.75	33^{+11}_{-11}	129	$4.9^{+1.9}_{-1.4}$
Clapp *et al.* ‘94	ACME-MAX-IV (Sigma Hercules)	0.55–0.75	31^{+17}_{-13}	129	$4.3^{+3.0}_{-1.4}$
Gundersen *et al.* ‘95	ACME-HEMT SP94	1		73	$2.14^{+2.00}_{-0.66}$
Gundersen *et al.* ‘95	ACME-HEMT SP94	1.5		58	$1.17^{+1.33}_{-0.42}$
Lim *et al.* ‘94	ACME-MAX-V	0.5	in progress		
Tanaka *et al.* ‘94	ACME-MAX-V	0.5	in progress		

Table 2: Recent ACME degree-scale results.

Extrapolating the ACME-style measurements to a concerted effort either sub-orbital or orbital in nature, it is now feasible to imagine near full sky maps with 10–20 arc-minute resolution with sensitivity per pixel of a few ppm. Such a measurement may allow us to measure the mass density of the universe, the baryon fraction, and other parameters to much better accuracy than we know them today.

9 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. It is now possible to measure CBR polarization to a sensitivity of better than 1 ppm on limited portions of the sky. In the future, this may be a very fruitful area of inquiry, particularly when combined with overlapping anisotropy measurements.

10 Orbital Missions

There are currently several major proposed satellite missions. The European COBRAS/SAMBA proposal is for a combined HEMT and bolometer mission, and would cover from about 1 to 10 mm with resolution varying from about 0.1 to 0.5 degrees depending on the frequency. In the U.S., there are several Mid-Explorer class missions under consideration. These are the Goddard MAP mission and two JPL missions, and the bolometer-based FIRE and HEMT-based PSI missions. There are significant differences in technical and programmatic approaches being taken with the European being a more ambitious, and hence, more costly experiment. The U.S. Mid-Explorer missions are designed with more limited objectives, but at a significantly lower price and possibly shorter time scale. Any of the proposed missions would provide invaluable data that could revolutionize our understanding about early universe physics. Currently, it can be assumed that these missions, if any are selected, will not produce data before the turn of the century, at the earliest, and hence, it is to be anticipated that continued vigorous ground-based and suborbital experiments will continue.

Per pixel sensitivities with suborbital missions in the μK region are now achievable with current and new technologies, HEMTs, and bolometers over hundreds to thousands of pixels and possibly over large portions of the sky. 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. Another approach is a low-cost precursor mission such as the proposed, university-led COFI satellite.

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REFERENCES

[1] P. Lubin *et al.*, Astrophys. J. **298**, L1 (1985).

[2] M. W. Pospieszalski *et al.*, IEEE MTT-S Digest, 1253 (1990).

[3] D. C. Alsop *et al.*, Astrophys. J. **317**, 146 (1992).

[4] T. Gaier *et al.*, Astrophys. J. **398**, L1 (1992).

[5] J. Schuster *et al.*, Astrophys. J. **412**, L47 (1993).

[6] P. R. Meinhold and P. M. Lubin, Astrophys. J. **370**, L11 (1991).

[7] P. Meinhold *et al.*, Astrophys. J. **406**, 12 (1992).

[8] J. O. Gundersen *et al.*, Astrophys. J. **443**, L57 (1995).

[9] M. Fischer *et al.*, Astrophys. J. **388**, 242 (1992).

[10] P. Meinhold *et al.*, Astrophys. J. **409**, L1 (1993).

[11] J. O. Gundersen *et al.*, Astrophys. J. **413**, L1 (1993).

[12] M. Devlin *et al.*, Astrophys. J. **430**, L1 (1994).

[13] A. Clapp *et al.*, Astrophys. J. **433**, L57 (1994).

[14] E. Wollack *et al.*, Astrophys. J. **419**, L49 (1994).

[15] M. Lim *et al.*, in preparation (1995).

[16] S. Tanaka *et al.*, in preparation (1995).

[17] G. F. Smoot *et al.*, Astrophys. J. **396**, L1 (1992).