DEGREE SCALE ANISOTROPY:
CURRENT STATUS

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1. ABSTRACT

The Cosmic Background Radiation gives us one of the few probes into the density perturbations in the early universe that should later lead to the formation of structure we now observe. Recent advances in degree scale anisotropy measurements have allowed us to begin critically testing cosmological models. Combined with the larger scale measurements from COBE we are now able to directly compare data and theory. These measurements promise 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 is in a true discovery mode. Our own group has been involved in a series of eleven experiments over the last six 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. The recent data from these and other measurements will be reviewed as well as some of the challenges and potential involved in these and future measurements.

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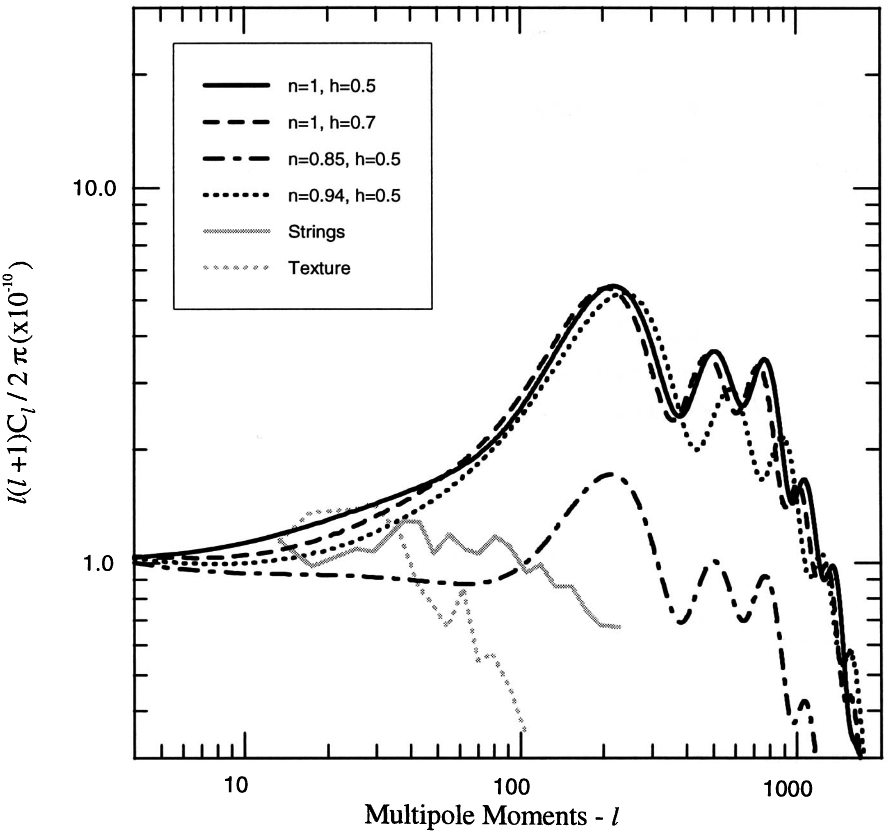

Figure 1. **Theoretical CBR Power Spectrum (model results from P. Steinhardt and R. Bond, private communication for a $Q_{rms-ps} = 18\mu K$)**

2. Introduction

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. The large scale anisotropy detected by the COBE satellite allows us to normalize the cosmological power spectrum at long wavelengths. The COBE detection at a level of $\Delta T/T = 10^{-5}$ at 10° gives us crucial information at scales above 10 degrees about the primordial fluctuations. The

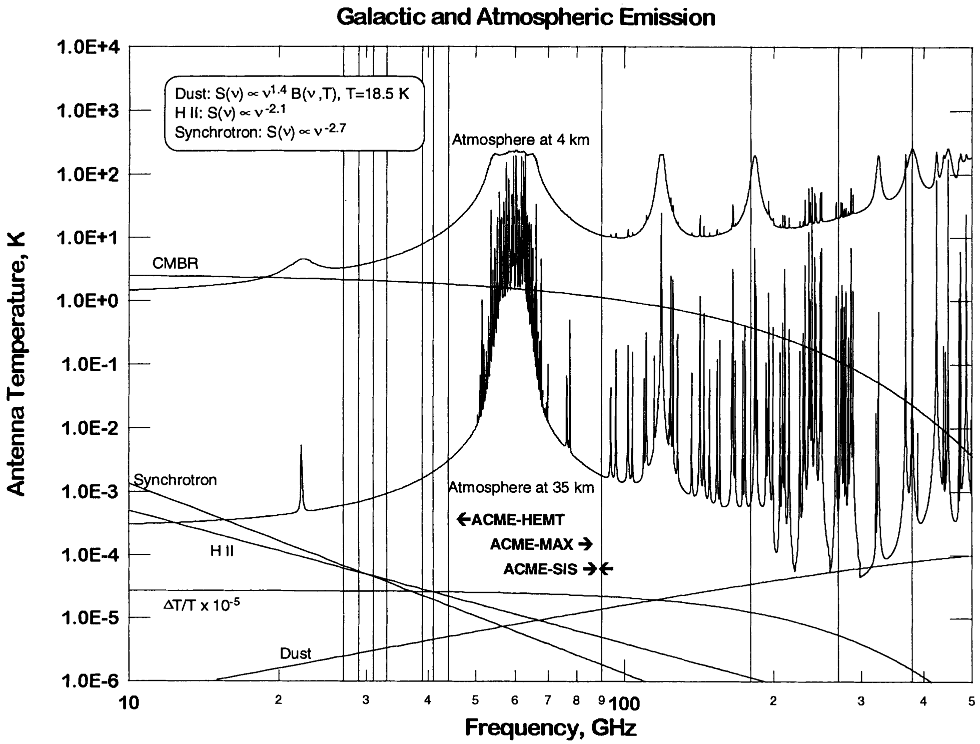

Figure 2. Relevant backgrounds for terrestrial measurements at the South Pole and at 35 Km where ACME observes. Representative galactic backgrounds are shown for synchrotron, Bremsstrahlung and interstellar dust emission as well as the various ACME (center) wavelength bands.

largest scales do not however define the subsequent evolution of the CBR structure in the collapse phase after decoupling. In addition due to 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. As an example Figure 1 shows the power spectrum expected in a number of models.

3. CBR Anisotropy Measurements

The spectrum of the cosmic background radiation peaks in the millimeter-wave region. Figure 2 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). For example, Figure 2 shows the ACME 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 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 about 10 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 $\Delta T/T \approx 1 \times 10^{-6}$.

4. 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 to be discussed are 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. Multiple detectors obviously help here.

Measurements from the South Pole are also very promising. The large atmospheric emission (compared to the desired sensitivity level - few million times larger!) is of great concern and based upon our 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 will be a dedicated satellite. Again, the receivers on such a satellite would have to be low noise. The minimal cryogenic requirements for HEMT (High Electron Mobility Transistor) amplifiers make them an obvious choice for satellite receivers, but bolometric receivers using ADR coolers or dilution refrigerators offer significant advantages at submillimeter wavelengths.

5. 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 using 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 preamplifiers we progressed to Niobium junctions and a first generation of HEMTs to achieve chopped sensitivities of about 3 mK $\sqrt{s}$ 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 2 where we plot atmospheric emission versus frequency for sea level, South Pole (or 4 km mountain top) and 35 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 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. Detectors 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 eleven ACME observations/flights from 1988 to 1994. Over twenty articles and proceedings have resulted from these measurements as well as seven Ph.D. theses. A summary of the various

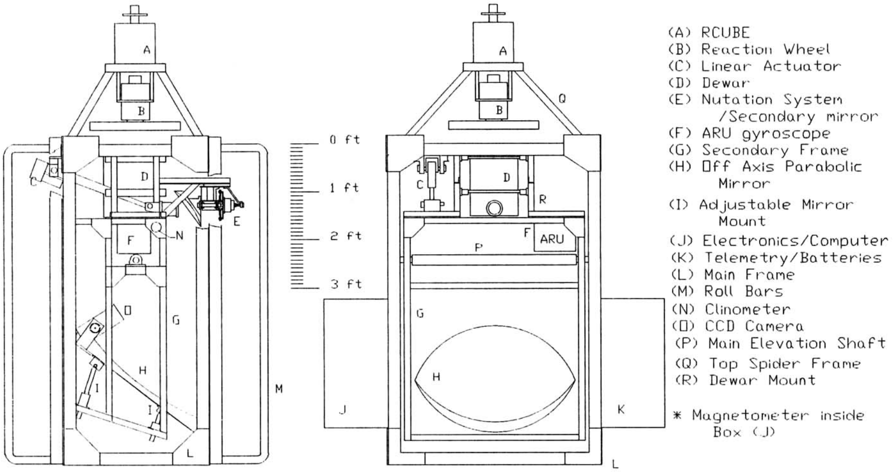

Figure 3. Basic ACME configuration

observations is given in Table I.

TABLE 1. CBR Measurements made with ACME

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}) ^{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[P]	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[P]	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

6. 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 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 degrees.

7. 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 92 COBE announcement, ACME had flown four times and made two South Pole trips for 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 of $\Delta T/T \lesssim 3.5 \times 10^{-5}$ 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 was data taken in a low dust region and showed no evidence for galactic contamination. The data in the Gamma Ursa Minoris region ("GUM data") was first published in Alsop et al. (1992) **prior** to the announcement of 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 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 placed an upper limit to CBR fluctuations of $\Delta T/T \leq 1.4 \times 10^{-5}$ at 1.2° (Gaier et al. 1992). This data set has significant structure in excess of noise with a spectrum that was about 1.4σ from flat (Gaier 1993). This upper limit for a Gaussian autocorrelation function sky was computed from the highest frequency channel. Since 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 $\Delta T/T \simeq 1 \times 10^{-5}$ (Bond 1993). Interestingly, this is about the same level seen in another SP 91 scan (see next) as well as that observed in the nearly same region of sky observed in the SP 94 data (Gundersen et al. 1995).

Additional analysis of the 1991 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 also 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. Combining these two scans in a multichannel analysis results in a detection level slightly above 1×10^{-5} (Bond 1993). The relevant measurements just prior to the COBE announcement are summarized in Figure 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 Figure 5, the degree scale measurements were consistent with COBE given the errors involved. Without the large scale normalization of the COBE data, it was hard to reconcile the apparently discordant data. However, with the refinement in theoretical understanding and additional data, the pre-COBE ACME data now are seen to be remarkably consistent with the post-COBE data.

8. Results

There have been a total of eleven ACME observations/flights from 1988 to 1994. ACME articles by Meinhold & Lubin (1991), Meinhold et al. (1992), ACME-HEMT articles by Gaier et al. (1992), Schuster et al. (1993), Gundersen et al. (1995) and ACME-MAX articles by Fischer et al. (1992, 1995), 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

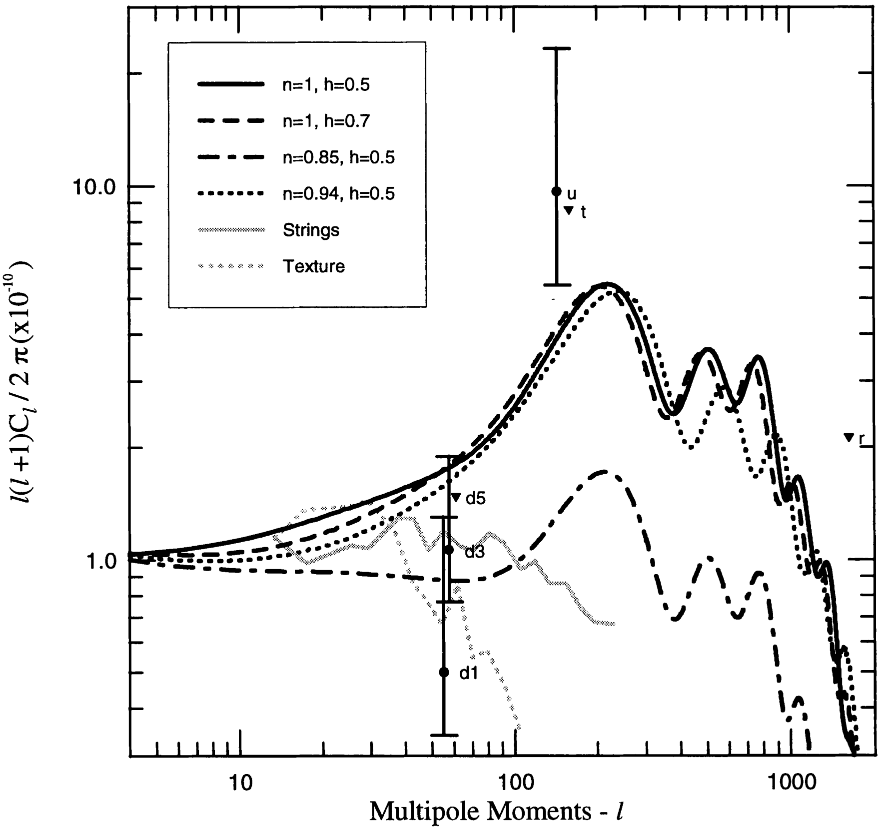

Figure 4. ACME CBR Power Spectrum data prior to the COBE detection. Theoretical curves are from Figure 1. See KEY in Figure 5 caption.

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.(1993) with about a 6 σ detection (at the peak). Recently Wollack et al. (1993) reported a detection at an angular scale of 1.2 degrees of about 1.4×10^{-5} consistent with Schuster et al., Gaier et al. and the combined 9 + 13 pt. analysis using a detector and beam size nearly identical to ours. Remarkably this result is taken in a completely different region of the sky and at lower galactic latitude and yields similar results. A conspiracy to yield comparable results in very different parts of the sky from point sources or sidelobe spill over is always possible. When one takes into account the similar level of the COBE detection at larger scales it would seem to require multiple conspiracies however. Additional data taken at the South Pole by ACME in 1993/94 ("SP94" data) in a region of the sky close to the SP91 area but with additional HEMT detectors from 25 - 45 GHz in seven bands

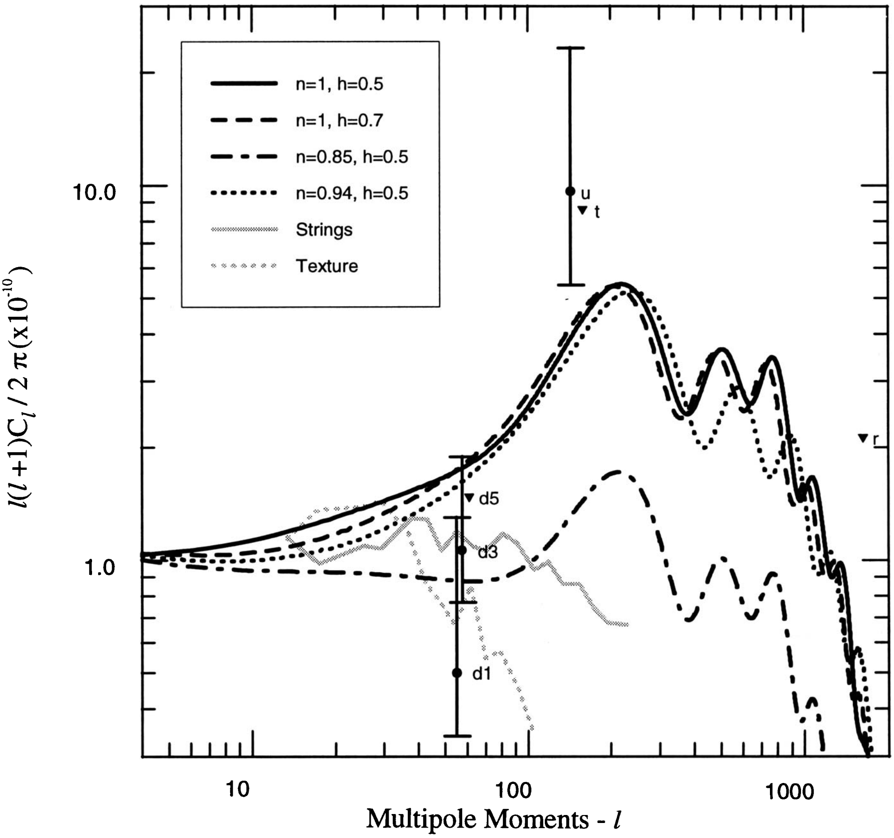

Figure 5. Figure 5: Recent ACME Results (in BOLD) along with results from other groups. Key: a-COBE, b-FIRS, c-Tenerife, d1-SP91 9 pt. 4 channel analysis-Bond 93, d3-SP91 9+13pt 4 channel analysis-Bond 93, d5-SP91 9 pt. Gaier et al. 92, e-Big Plate, f-PYTHON, g-ARGO, h-MAX4-Iota Dra, i-MAX4-GUM, j-MAX4-Sig 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, private communication.

and with beam sizes from 1.0 - 1.7 degrees FWHM, yield results consistent with a CDM model (and others) normalized to COBE. The SP94 data are consistent with the SP91 results (Gundersen et al. 1995) as shown in Figure 5. 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 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.

The most recent ACME-MAX data have been in low dust regions so that no subtraction of dust was needed. In one scan, the μ-Pegasi region, there was enough dust to provide a good calibration of high galactic latitude interstellar dust emission (Meinhold et al. 1993). Interestingly, the residual "CBR component" was anomolously low compared to the other regions surveyed. Whether this is indicative of other issues, such as non-gaussian fluctuations, or is just due to limited sampling statistics is unclear at this time.

The most recent ACME-MAX flight in June 1994 included two more low dust regions and a revisit of the μ-Pegasi region. The data is currently being analyzed (Lim et al. 1995, Tanaka et al. 1995).

It is remarkable that over a broad range of wavelengths, very different experiments using a variety of technologies and observing in different parts of the sky report degree scale detection at the one to a few $\times 10^{-5}$ level. ACME, in particular, has now been used to measure structure from 25 - 250 GHz and from 0.4 - 2 degrees that is in reasonably good agreement with a CDM power spectrum model. The agreement of the ACME-HEMT data with other experiments (notably Big Plate at Sasskatoon) up to ℓ of about 75 is very good, as can be seen from Figure 5. At 0.5 degree scales (ℓ about 150) the agreement of ACME-MAX and MSAM data is marginal and will hopefully be clarified soon. It is important to keep in mind that the statistical and sampling errors need to be taken into account in any comparison between data sets and between data and theory.

In any case, 1992 and 1993 were clearly historical years in cosmology and CBR studies in particular. The ACME results along with the results of other groups are shown in Figure 5. As can be seen by comparison to Figure 4 which was the data prior to COBE, the pre- and post-COBE data are reasonably consistent given the errors. The deluge of theoretical results and scrutiny that followed COBE was a boon for degree scale results giving us a theoretical insight we lacked just a few years ago. The current ACME degree scale results are summarized in Table II.

9. 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

TABLE 2. Recent ACME Degree Scale Results

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		

* from P. Steinhardt & R. Bond, priv. communication. 1σ errors, upper limits are 95%
** GACF=Gaussian Autocorrelation Function - Upper limits and error bands are 95%

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 s$^{1/2}$. This assumes no additional atmospheric noise, true at balloon altitudes. For ground-based experiments, even 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 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.

10. Spectrum Measurements

A related area of interest that could yield interesting cosmology in the next few years is the long wavelength spectrum. Although 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 et al. (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. The BLAST (Balloon Absolute Spectrometer)-ARCADE (Absolute Radiometer for Cosmology, Astrophysics, and Diffuse Emission) experiment, a joint UCSB-Goddard balloon borne experiment will attempt to exploit the low atmospheric emission available from balloon altitudes using coherent HEMT detectors in the 10-30 GHz range. Accuracies of under 1 milliKelvin may be feasible. This will allow extremely sensitive measurements of long wavelength distortions in the CBR should they exist. Since the spectral deviation rises rapidly at long wavelengths as does the galactic emission from synchrotron radiation, measurements in the 5-20 GHz range will be particularly useful.

11. Polarization

Very little effort has been directed towards the measurement of the polarization of the CBR compared to the effort in direct 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 (Steinhardt 1994). 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 particularly at degree angular scales.

12. 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 definitely 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. European efforts such as SAMBA and COBRAS and US efforts such as PSI, MAP and FIRE are examples of possible future space based efforts. A low cost precursor mission such as the university led COFI satellite is an example of an economical approach to proving HEMT technology in space for a possible future effort. 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.

13. Acknowledgements

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