COSMIC MICROWAVE BACKGROUND RADIATION ANISOTROPY STUDIES IN ANTARCTICA

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ABSTRACT

We present the results of two South Pole missions to search for cosmic microwave background radiation anisotropy in the 25-35 Ghz, 26-36 Ghz and 38-45 Ghz ranges, respectively in the summers of 1988/1989, 1990/1991 and preliminary results of the 1993/1994 mission. All the missions were carried out using a Gregorian off-axis, 1 m diameter, 1 m focal telescope and a cooled optical system mounted on top of a stabilized platform: the Advanced Cosmic Microwave Explorer, also known as ACME. For the first mission we used ^{4}He-cooled SIS (Superconductor-Insulator-superconductor) amplifiers operating at a frequency of 90 Ghz at an angular scale of 0.33° and placed a 95% confidence level upper limit of $\Delta T/T \leq 3.5 \times 10^{-5}$ for CBR fluctuations with a Gaussian auto correlation function at a coherence angle of 30'. The second and third missions were accomplished using HEMT (high electron mobility transistor) amplifier based detectors. The receivers operated at 25-35 GHz in the second mission and the measurements set 95% confidence level upper limits of $\Delta T/T \leq 1.4 \times 10^{-5}$ at a coherence angle of 1.2° for a 9-point data set. The 13-point data set measurements yelded a 95% confidence level upper limits of $\Delta T/T \leq 1.6 \times 10^{-5}$ at a coherence angle of 1.5°. The latest, 1993/1994 mission detectors operated in 2 bands: 26-36 GHz and 38-45 GHz. The combined results present a preliminary detection $\Delta T/T \sim 1 \times 10^{-5}$ at a coherence angle of about 1°. Specially the results of the latest mission belong to a new set of very sensitive CBR measurements that detected fluctuations on medium angular scales. Medium angular scale measurements are crucial to the understanding of structure formation processes and will help us discriminate among the many different existing models. Antarctica, due to its unique conditions, is one of the best sites in the world to carry on this kind of science.

INTRODUCTION

The Cosmic Background Radiation (hereafter CBR) was discovered in 1965 (Penzias & Wilson 1965) and is intepreted as the relic radiation of the Hot Big Bang (see, for instance, Dicke et al. 1965, for a historical account or Peebles 1993 for a complete discussion). The early Universe was in thermal equilibrium and consisted of a plasma of matter+radiation with particles and photons being created and annihilated continuously. At the time, Thomson scattering due to free electrons caused the Universe to be opaque to the radiation. As the Universe expandend, the plasma cooled down until it reached the temperature of ~ 4000 K. Free electrons and photons then combined to form the first H atoms, since the radiation field was not hot enough to ionize the atoms any longer. This period is known as the recombination period. As soon as Thomson scattering stopped, the Universe turned into an optically thin medium, allowing free photon propagation. The photons that emerged from what we call the last scattering surface constitute the CBR as we see it today. The matter density has fallen down by many orders of magnitude and we assume there has been no modification in the radiation field since then, except for some local effects like the Sunyaev-Zel'dovich effect (Sunyaev & Zel'dovich 1972). Reionization of the Universe by early stars can erase the primordial fluctuations and create new ones, but constraints set by the COBE satellite results (Wright et al. 1994) indicate this is a very unlikely possibility. Gravitational potential differences between regions on the last scattering surface separated by more than ~ 1° are the probable cause of temperature fluctuations in the CBR (Sachs & Wolfe 1967).

This photon background, produced at a red shift $z \geq 1100$, is a very powerful probe of the physical processes ocurring in the early Universe, and it is the oldest direct source of cosmological information available. There are predictions regarding a "cosmic neutrino background" with a temperature of about 2 K, but it is yet to be detected, leaving the CBR as the primary source of study.

As it is one of the very few "observable" quantities in cosmology, it is important that we characterize it and understand its properties. It is also the best determined cosmological quantity, with an uncertainty in the spectrum determination of less than 1% in the peak, as opposed to an uncertainty of close to a 100% in the Hubble's constant value.

The motivation to study the angular anisotropy in the CBR started almost at the same time as its discovery. It is believed that anisotropies in the temperature radiation field are caused by anisotropies in the matter density distribution. Specially in medium angular scales (around 1° in the sky), CBR fluctuations can tell us a lot about structure formation processes, allowing us to constrain many of the global parameters of the Universe and, at the same time, help us discriminate between the quite large number of structure formation models that exist today.

Astrophysical and atmospheric foregrounds are serious problems to CBR measurements, since one has to deal with contaminants that can be as high as 5 orders of magnitude above the cosmic signal. However, atmospheric emission is reasonably well understood and, in a stable site, can be modeled and extracted from the overall noise without too much hassle.

The South Pole is one of the best sites in the world for CBR studies due to various reasons. The geographical location, (generally) very stable atmosphere during the summer and logistic facilities were important items when the Scott-Amundsen Station was chosen, at the geographic pole, as an option for the ACME missions. Due to the geographic position of the Pole, an experiment can be programmed to continuously track a given source or region in azimuth at constant elevation, corresponding to a continuous tracking in right ascension at constant declination, allowing an easier demodulation of the measured signal. This strategy has the great advantage of permitting the experiment to look at the same amount of atmosphere all the time. As we measure the difference in temperature of 2 patches ~ 2° apart in the sky, a horizontal offset can cause an increase in the "upper" patch temperature due to a larger atmospheric column along the line-of-sight. It is also possible to keep track of the solar trajectory in a much better way, since its path is circular at constant elevation for a given day, reaching its maximum at +23° during the Summer Solstice. As the Sun is a major microwave source, the choice of an adequate observation strategy and the use of baffles and shields can strongly minimize its influence in the measurements.

The very dry weather conditions and the high altitude (~ 3000 m) at the Scott-Amundsen polar station makes it one of the best sites for astronomy in the world. Typical good days of data taking have around 0.3-0.5mm precipitable water vapour content. During the summer the atmospheric conditions are tipically stable for various days at a time. Specially during the last mission (93/94) we had series of ininterrupted observations during over 50 hours. Also, as the telescope sits in a stabilized platform located at 3000 m, the atmospheric contribution is more than 2 orders of magnitude lower than at sea-level sites.

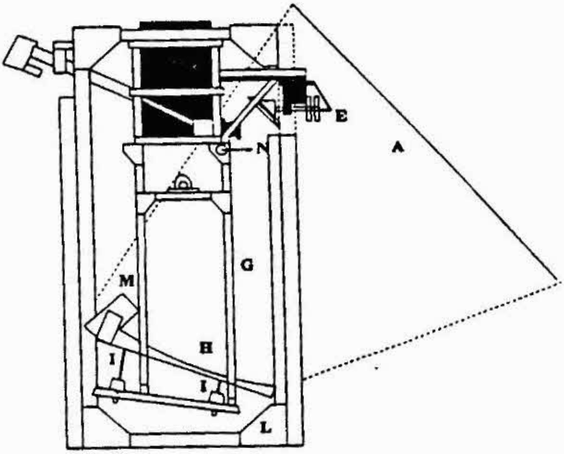

Figure 1 - ACME side view. One can notice the sun shield and field of view delimited by the dash lines. a) Reflecting shields, d) Dewar, e) Secondary mirror nutating system, g) Gondola inner structure, h) Primary mirror, i) Adjustable structure of primary mirror, l) Gondola external structure, m) Stelar sensor, n) Elevation control.

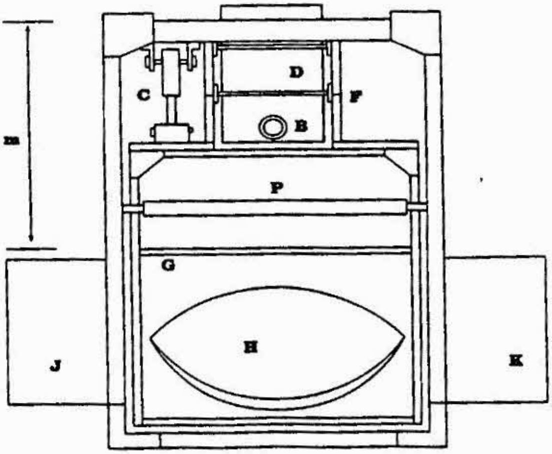

Figure 2 - ACME front view. b) Corrugated scalar horn, c) Linear actuator, d) Dewar, f) Dewar support, g) Secondary inner structure, h) Primary mirror, j) On board electronics/computers, k) Telemetry/Batteries, p) Transversal structure.

Table 1 - ACME results: South Pole and Balloon flights.

Experiment	Coherence angle(°)	Measurement or upper limit
Lubin & Meinhold 1991 (ACME-SIS SP89)	0.33	$\leq 3.3 \times 10^{-5}$ (U.L.)
Alsop et al. 1992 (ACME-MAX-II)	0.33	$\leq 4.5 \times 10^{-5}$ (U.L.)
Gaier et al. 1992 (ACME-HEMT SP91)	1.2	$\leq 1.4 \times 10^{-5}$ (U.L)
Schuster et al. 1993 (ACME-HEMT SP91)	1.2	$\leq 0.8 \times 10^{-5}$ (U.L.)
Gundersen et al. 1993 (ACME-MAX-III)	0.42	$4.2^{+1.7}_{-1.1} \times 10^{-5}$
Meinhold et al. 1993 (ACME-MAX-III)	0.42	$1.5^{+1.1}_{-0.7} \times 10^{-5}$
Clapp et al. 1994 (ACME-MAX-IV)	0.41	$3.3^{+1.1}_{-1.1} \times 10^{-5}$; $3.1^{+1.7}_{-1.3} \times 10^{-5}$
Devlin et al. 1994 (ACME-MAX-IV)	0.41	$3.5^{+3.3}_{-1.4} \times 10^{-5}$
Gundersen et al. 1995 (ACME-HEMT SP94)	1.2	$3.4^{+1.2}_{-0.7} \times 10^{-5}$

Obs: Adapted from Lubin (1994). Results from theoretical papers are not included.

THE MISSIONS

The gondola used in all of the three missions was basically the same structure, known as the **ACME** gondola. It is described in detail in Lubin, Meinhold and Chingcuanco (1990) and Meinhold et al. (1993). Briefly, it consists of an off-axis Gregorian, 1-m diameter, 1-m focal lenght primary mirror, an elipsoidal secondary mirror and all the system is stabilized with a flywheel, a gyroscope and magnetometers. Figures 1 and 2 show ACME in side and front views. It was designed to be a compact configuration, optimized to fit the limitations and structure requirements for balloon flights.

ACME first mission was a flight in 1988 on board a stratospheric balloon and soon afterwards the telescope was packed and sent to Antartica for the 1988/1989 summer. The first mission consisted of SIS amplifiers cooled down to 3.5 K inside a dewar and operating at 90 GHz. The antenna FWHM was 30' and the sensitivity obtained was 4.3 mK√Hz. We made first difference measurements of 10 patches of the sky at constant declination, chopping sinusoidally with a 1.4° peak-to-peak throw. Several strips were measured to different sensitivities yelding 43 hours of godd data. The details of this mission were published by Meinhold and Lubin (1990), and we will present the results and discuss their implications in the next section.

The next mission took place in the 90/91 summer and the main difference compared to the first was the substitution of SIS mixers by HEMT detectors. The cryogenic requirements were basically the same, with the amplifiers cooled down to 6 K. They operated in the frequency range from 25-35 GHz, in 4 bands of 2.5 GHz. The antenna FWHM was $1.65^{\circ} \pm 0.1^{\circ}$ at 27.7 GHz, and the sensitivity achieved was around 1.8 - 4.5 mK/√Hz. We did step scans at 6 (constant) declinations subtracting patches 2.1° apart in the sky, in the same way as Meinhold and Lubin. This mission generated two data sets published by Gaier et al. (9-point set, 120 hours out of 500 total) and Schuster et al. (13-point set, 64 hours out of 500). The 13-point set presents the smallest error bar per pixel, to date, in any angular scale.

After the success of the previous missions and the announcement of the COBE satellite results, a third mission was planned aiming to detect fluctuations in medium scales (~ 1°). A new set of HEMT detectors was adapted to the ACME gondola in 2 frequency bands: 26-36 GHz (Ka-band) and 38-45 GHz (Q-band). The sensitivity achieved was better than 1 mK/√Hz. We performed 3 sets of observations, each consisting in a $20^{\circ} \times 1^{\circ}$ strip on the sky and employed a 3° peak to peak sinusoidal, single difference chop. The first two observations used a receiver which operated at 3 equal bands between 38 and 45 GHz with a FWHM beam which varied from 1° to 1.15°. The third observation overlapped the second observation and used a receiver which operated at 4 equal bands between 26 and 36 GHz with a FWHM beam which varied from 1.25° to 1.7°. More details regarding the 93/94 mission can be found in Gundersen et al. (1995).

THE RESULTS

Significant results were achieved in each of the missions. The first and second missions happened in the pre-COBE era and did not actually detected fluctuations in the CBR. However, the results of Meinhold and Lubin (1990), Gaier et al. (1992) and Schuster et al. (1993) reported some of the most stringent upper limits for detections of fluctuations at the time. A real measurement was done in the third mission (Gundersen et al. 1995) and is one of the various claims of detections in medium angular scale after COBE. Table 1 presents most of those upper limits and results from 1990 to date. Analysis of the data sets by theoreticians have helped to set limits for structure formation model parameters (Holtzman 1989; Bond et al. 1991; Srednick et al. 1994; Bunn et al. 1994) and to make a better estimate of the CBR power spectrum (Wright et al. 1994).

Upper limits and detections obtained by the ACME-SP series have been used, along with other positive results, to try to determine a coherent model for structure formation. All of its results agree with most versions of the cold dark matter (hereafter CDM) model and are consistent with the COBE numbers. If the source of fluctuations is really primordial and the fluctuations themselves are Gaussian, the published data are consistent with CDM scenarios normalized to the COBE results and put strong constraints in the model parameters (Bond et al. 1991; White, Scott and Silk 1994; Steinhardt et al. 1994).

Figure 3 shows the CBR power spectrum for a variety of CDM, texture and cosmic string models using most of the medium and large angular scale results available to date. Despite some points sit off the curve, one can see that CDM gives the power spectrum fit as a function of the spherical harmonics multipoles covered by each experiment. An important conclusion that can be drawn from this graph is the remarkable agreement (to a few x 10^{-5} level) of results in a wide range of frequencies, coming from different technologies, different angular scales and observing different sky patches. One can imagine that agreement of different experiments in the same angular scale might be caused by sistematic errors or unknown extragalactic point sources. However, the agreement between them and COBE (which maps the whole sky, probes regions that are NOT causally connected at the decoupling time, in a completely different angular scale) can only be justified by a cosmic conspiracy.

The ACME-SP missions were designed to measure structure in the Rayleigh-Jeans part of the spectrum (~ 20-90 GHz) and from 0.5° to 1° which are also in reasonable agreement with a CDM power spectrum model. A slight disagreement can be seen, for instance, between ACME-MAX and MSAM, but we hope it will be clarified soon. It is never too late to remark the importance of statistical and sampling errors in this kind of measurements and analysis. Their understanding is of paramount importance when comparing different data sets or data sets and theory.

FUTURE PERSPECTIVES AND CONCLUSION

It is still early to say that the problem of structure formation is solved and we are happy to announce the ultimate model. We are, nevertheless, marching towards the solution and the contribution of medium scale experiments is crucial to clarify the situation. CDM can, for the time being, be considered the paradigma for structure formation, although some other models like hot dark matter (also known as HDM), barionic dark matter (or BDM), textures and cosmic strings can not be entirely ruled out yet.

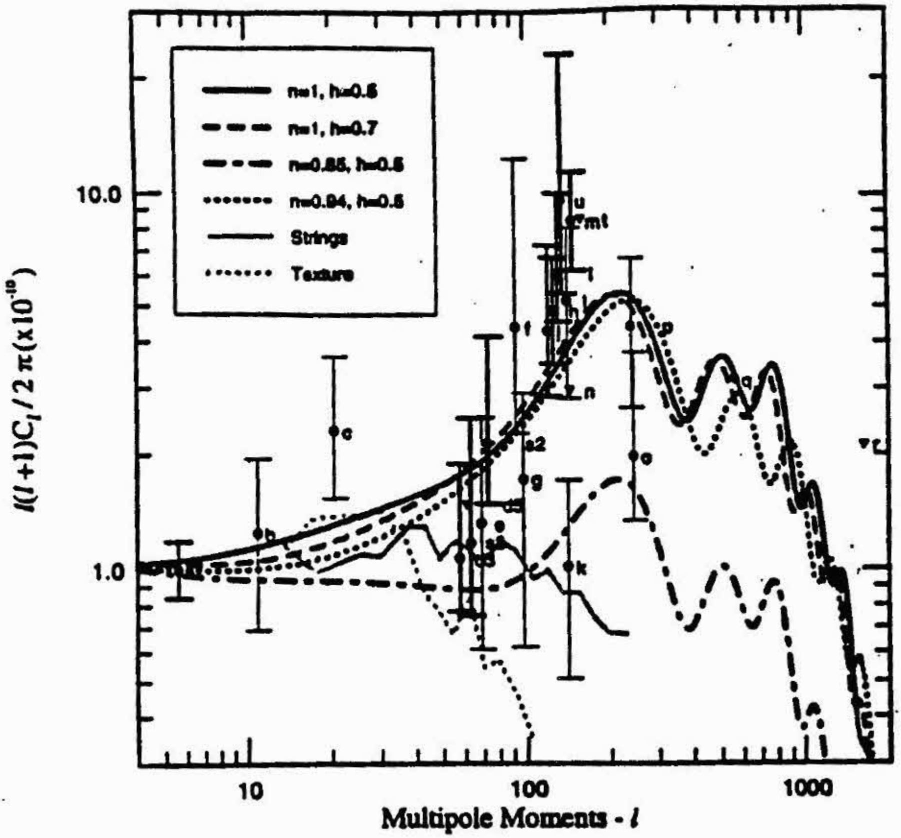

Figure 3 - Recent results from CBR experiments in various angular scales, including ACME-SP. Key: a- COBE, b- FIRS, c- Tenerife, d1-SP91 (9 pt. 4 channel analysis=Bond 93), d3-SP91 (9+13 point 4 channel analysis-Bond 93), d5-SP91 9 pt. Gaier et al. 92, e- Big Plate, f- Phyton, g- Argo, h- MAX4-Iota Drac, i- MAX4-GUM, j- MAX4-Sigma Her, k- MSAM2, l- MSAM2, m-MAX3-GUM, n- MAX2-mu Peg, o- MSAM3, p- MSAM3, q- White Dish, r-OVRO-7, s2-SP94-Q, s3-SP94-Ka, t-SP89, u- MAX2-GUM (Adapted from Lubin 1994 and Steinhardt private communication).

Detector limitations appear to be a bottleneck for more sensitive measurements, since HEMTs and bolometers (also used for CBR measurements) are quickly getting close to the their quantum limit. Presently the quantum limit is one order of magnitude below the best detection level. The next step in improving the quality of CBR anisotropy measurements is to use small arrays of detectors and this is being planned for several experiments. For the present level of sensitivities, an array flown on a balloon or used at a South Pole mission could reach sensitivities of 1 μK/pixel for ~ 100 pixels in time scales of a few weeks. A clear discussion of detector technologies and limitations can be found in Lubin (1994). We should also stress that while better detectors are being developed, studies of low-level foreground emission must also result in more complete models, specially regarding the nature of Galactic emission. Once we have these tools in hands and learn more about the nature of the structure we want to observe, the choice of sensitivity for a given angular scale will come up in a clearer way.

ACME measurements made at the South Pole have played an important role along the transition from upper limits to actual temperature fluctuations detections. Following this line, there is a new experiment being designed at UCSB to replace ACME. It is called ACE (Advanced Cosmic Explorer) and will be completed by late 1996-early 1997. There are plans to fly ACE on board of a stratospheric balloons and circunpolar flights are being considered as part of a strategy to make a map of CBR anisotropy in degree angular scales.

We see this field as one of the most exciting in Cosmology these days. In the last three years we have seen a boom of new results and technologies, and our understanding of the cosmic structure formation is reaching a much higher level, with experimentalists and theoreticians converging to the same approach and, so to speak, "talking in the same language". The knowledge obtained so far is very high if compared to the financial investiments and we gained both theoretical insights and experimental training that we lacked just a few years ago. CBR polarization is also a related area that seems to be very promising and potentially can tell us a lot about the reionization theory, scalar and tensor gravity wave modes and large scale geometry effects. In short, this field of Cosmology has shown itself a rich source of interesting physics. From our own experience there is still a lot to be learned in the next years and we are sure ACME and ACE will be around to contribute.

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