THE BOOMERANG EXPERIMENT

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Abstract.

The BOOMERANG (Balloon Observations Of Millimetric Extragalactic RAdiation and Geophysics) experiment is an international effort to measure the Cosmic Microwave Background (CMB) anisotropy on angular scales of 20' to 4° , with unprecedented sensitivity, sky and spectral coverage. The telescope will be flown from Antarctica by NASA-NSBF with a long duration stratospheric balloon (7-14 days), and is presently scheduled for flight in 1995-1996. The experiment is designed to produce an image of the Cosmic Microwave Background with high sensitivity and large sky coverage. These data will tightly constrain the baryon density, the reionization history, and the formation of large-scale structure in the universe. BOOMERANG will test technologies and return science data that are essential to the design of a future space-borne mission to map CMB anisotropy.

1. The Rationale

Two years of data from the COBE-DMR satellite (Bennet et al., 1994) provide a 10σ detection of the rms CMB anisotropy: $30\,\mu\text{K}$ when observed through a 10° FWHM beam. Many cosmological scenarios are consistent with the COBE measurement. A precise measurement of the power spectrum of CMB anisotropies at smaller angular scales, beyond the resolution of COBE, can distinguish between these scenarios. Angular scales of 1 degree correspond to the largest structures that have been mapped in the current epoch, and thus allow a direct comparison of initial and final conditions. Anisotropies at angular scales < 1° are produced by the Doppler effect, and correspondingly, a "Doppler peak" is expected in the power spectrum. The

amplitude and the position of the Doppler peak probe the baryon density and the reionization history of the Universe.

There is a statistical variance in the power spectra of CMB anisotropy measured by observers located in different regions of the universe. This effect is called Cosmic Variance. Since we can, at best, measure only one manifestation of the statistical ensemble of CMB skies, our ability to constrain theory is ultimately limited by this Cosmic Variance. The COBE-DMR results are presently limited by Cosmic Variance. The Cosmic Variance is smaller at smaller angular scales, because there are a larger number of regions on the sky that can be considered independent samples of the parent distribution. All of the experiments to date (see the review by White et al., 1994) have sampled very limited regions of the sky. The precision with which the amplitude of the power spectrum can be determined by these experiments is thus limited not by Cosmic Variance but by the small size of the sample (Sampling Variance). The precision can be greatly improved simply by increasing the number of pixels that are observed. We have performed a simple simulation to quantify these effects (see de Bernardis et al., 1994, for details). We have used 1000 realizations of CMB anisotropy maps generated in the framework of the CDM model (n=1, COBE-DMR normalization, $\Omega_{\rm B} = 0.05$). We have computed, for each realization, the $\Delta T_{\rm rms}$ measured sampling the sky, and have plotted the results in histograms. We have considered three different experiments: (a) a short balloon flight, similar to present anisotropy experiments, measuring ΔT for 33 sky patches with a beam 40 arcmin FWHM; (b) a long balloon flight, measuring a CMB anisotropy map $10^{\circ} \times 10^{\circ}$ wide with 20 arcmin FWHM ($\simeq 900 \Delta T$ s, as planned for BOOMERANG); (c) a dedicated CMB anisotropy satellite, measuring a larger map with a total of 3600 ΔT (this is a rough estimate of what is possible to do without significant foreground contamination). In the three cases it has been assumed that both detector noise and astrophysical confusion noise are negligible: the spread of the histograms is due only to the combined effect of Cosmic and Sampling Variance. The FWHM of the histograms is $20 \,\mu\text{K}$, $11 \,\mu\text{K}$ and $8\,\mu\mathrm{K}$ in cases (a),(b),(c) respectively. It is evident from these results that experiment (b) can, in principle, make a significant improvement on experiment (a) and can, in fact, come close to what is ultimately possible with an orbital mission. We emphasize that this is the case only if the experiments have adequate sensitivity and frequency coverage to make detector noise and astrophysical confusion noise negligible in the available amount of observing time and sky coverage. We consider Case b) as the design goal for the BOOMERANG experiment. BOOMERANG is designed to minimize galactic foreground confusion by mapping the region of the sky that is least contaminated with galactic foreground emission with unprecedented frequency coverage, from 40 GHz to 450 GHz. BOOMERANG will map a $10^{\circ} \times 10^{\circ}$ region of the sky with better than 0.5 degree resolution and a final



Fig. 1. The same CMB anisotropy simulation, as measured using a present day CMB anisotropy experiment (left) and the BOOMERANG experiment (right). The size of the map is $10^{\circ} \times 10^{\circ}$; the pixel size is 40 arcmin in the case on the left, 20 arcmin for BOOMERANG.

uncertainty/pixel in CMB temperature of about $3 \mu K$. A visual comparison of the same simulated CMB anisotropy map, observed with present day experiments and with BOOMERANG, is shown in Figure 1. The achievable gain in information is evident: while present day experiments can only derive informations on the $rms \Delta T$ in the map, the BOOMERANG experiment will yield detailed information about the topology of the map.

2. Why from Antarctica?

There are two unique features of Antarctic Ballooning which make it very attractive for CMB anisotropy experiments. The first one is the flight duration. Extensive tests made by NASA-NSBF have shown that stratospheric balloons launched from latitudes $\simeq -80^{\circ}$ travel along the meridian, coming back to the launch site in 7 – 20 days. This has to be compared to $\simeq 1$ day flights available from temperate latitudes. The second feature is that the launch campaign is performed during the Antarctic summer (December and January) and a region with very low Galactic dust contrast is available in the anti-sun direction. The region, as it appears in the IRAS Sky Survey Atlas, is at R.A. $\simeq 4.5$ hours, dec. $\simeq -45^{\circ}$, and is roughly 300 square degrees in area. The dust brightness contrast is < 0.2 MJy/sr at $100 \,\mu$ m, the lowest of any region this size. If we use a thermal dust spectrum with $n \simeq 1.5$ and $T_{\rm d} \simeq 21$ K we get a scaling of $\simeq 5 \,\mu$ K/(MJy/sr) in the 4-7 cm⁻¹ band.

This level of contrast in the dust emission corresponds to CMB temperature anisotropy of less than $3\,\mu$ K.

3. The Instrument

The instrument design evolved from the MAX (Fischer et al., 1992), the ARGO (de Bernardis et al., 1990, 1993) and SUZIE (Wilbanks et al., 1994) experiments. The main components of the experiment are 1) an off-axis 1.2 m telescope 2) a 4-band $\times 8$ pixel bolometric receiver 3) an alt-azimuth gondola with reaction wheel pointing capability. The instrument has been specially designed to overcome problems typical of Antarctic ballooning: the long flight duration forces us to use special cryogenic systems; the enhanced cosmic rays flux in polar regions forces us to use special bolometers; the presence of the sun allows us to use solar panels for power supply but also forces us to use multiple sun shields for good thermal performance of the system; the balloon is far from the ground equipement, so special data collection/telemetry systems have to be used, and interactivity with the system is reduced. The concept for the experiment is shown in Figure 2.

Here we can only list some technical highlights of the system:

Bolometers have been developed in Berkeley with "spider web" absorbers, that have very high absorption at mm wavelengths and very low geometrical cross section to cosmic rays (see Bock et al., 1994). The bolometers are AC biased (Wilbanks et al., 1994). The very good low-frequency performance allow electronic differencing between pixels and/or observation in total power mode. This strategy, which is essential for an orbital mission, eliminates the need for a mechanical chopper, and with it problems of microphonics and reliability during the long flight. The bolometers are assembled in four-band photometers, with a total of 8 pixels observing simultaneously the bands $2.5-4 \text{ cm}^{-1}$, $4-7 \text{ cm}^{-1}$, $7-10 \text{ cm}^{-1}$, $13-15 \text{ cm}^{-1}$. The filter bands are defined by resonant metallic meshes developed in London. The first band has been optimized to monitor Galactic free-free, the second and third ones are CMB anisotropy channels, the fourth one is a monitor for thermal emission from Galactic dust. Two pixels in the center of the focal plane observe in a fifth band at $1.2-2.8 \text{ cm}^{-1}$.

The optical system features a 1.3 m, ambient temperature, off-axis parabolic primary, and a re-imaging optics box at 1.6 K, inside the cryostat, composed by an ellipsoidal secondary and a paraboloidal tertiary. Winston concentrators define the acceptance of the 8 photometers. All the 10 photometer beams overlap within 0.1% on the primary mirror, reducing the sensitivity of the system to thermal and emissivity gradients on the primary. The location of the 10 pixels in the sky is sketched in Figure 2: the total power signals can be differentiated during the post flight analysis in any combination, thus obtaining a number of different filter functions with a single experiment.





Fig. 2. The concept of the BOOMERANG detection system. In the box is a sketch of the eight photometric pixels projected in the sky. Each pixel contains four spectral bands.

The bolometers are cooled at 300 mK using a single shot ³He fridge in a long duration ⁴He *cryostat* developed in Frascati and Roma. This consists of a 70 liter liquid N₂ tank and a 40 liter liquid ⁴He tank. Thermal insulation is achieved by supporting all the tanks with Kevlar cords. Aluminized mylar superinsulation is provided between the 300 K and the 77 K stages, while a vapor cooled 35 K shield is mounted between the 77 K and the 2K stages. The hold time of the system is 20 days. The large size of the tanks arises mainly from both the large volume of the photometers array and from the presence of a large focal plane, forcing us to accept the thermal radiation input from a large optical window. The only modulation of the optical signal is achieved by scanning the full gondola in azimuth at approximately one scan/minute. The *pointing system*, developed in Florence and Rome,

is capable of a pointing accuracy of one arcmin, and of a scan speed of 0.5 deg/sec with a power supply of $\simeq 60 \text{ W}$. We use sun sensors (a rough one with 360 deg range and a fine one with 120 deg range) to provide the error signals for the feedback loop controlling the inertia wheels. No moving parts are present in the sensors, again gaining reliability for long duration operations. The *final sensitivity* of the system can be estimated as follows. We assume 10 days of useful data in a 14 days flight; this gives us about 1 hour of observation for each of the 900 pixels in the map if 4 photometric pixels are used. The electrical NEP of the AC biased spider bolometers is of the order of $2 \times 10^{-17} \,\mathrm{W}/\sqrt{\mathrm{Hz}}$, with an overall efficiency of the photometers of $\simeq 10\%$. This translates, in the 4-7 cm⁻¹ band, in a $NET \simeq 150 \mu K / \sqrt{Hz}$ for the thermodynamic temperature fluctuations of a 3 K blackbody. As a result the final sensitivity of the experiment is $\simeq 3 \,\mu \text{K}$ per pixel. Note that each sky pixel is observed by all the photometric pixels in our array: this gives us redundancy and allows us to make important consistency tests in the data set. We are presently building most of the subsystems of the experiment, which is planned for a flight in 1995/1996.

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