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Precision CMB Measurements from Long Duration Stratospheric Balloons: Towards B-modes and Inflation

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Abstract. Observations of the Cosmic Microwave Background (CMB) have played a leading role in establishing an understanding of the structure and evolution of the Universe on the largest scales. This achievement has been enabled by a series of extremely successful experiments, coupled with the simplicity of the relationship between the cosmological theory and data. Antarctic experiments, including both balloon-borne telescopes and instruments at the South Pole, have played a key role in realizing the scientific potential of the CMB, from the characterization of the temperature anisotropies to the detection and study of the polarized component. Current and planned Antarctic long duration balloon experiments will extend this heritage of discovery to test theories of cosmic genesis through sensitive polarized surveys of the millimeter-wavelength sky. In this paper we will review the pivotal role that Antarctic balloon borne experiments have played in transforming our understanding of the Universe, and describe the scientific goals and technical approach of current and future missions.

Keywords. Cosmology, Cosmic Microwave Background, Ballooning, Polarimetry, Cryogenic Detectors

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The cosmic microwave background radiation represents a uniquely powerful laboratory for probing topics in fundamental physics ranging from cosmology to particle physics. The spectrum and the statistical properties of the anisotropy in the temperature and polarization of the CMB rely almost exclusively on the primordial initial conditions and well understood physics in the linear regime (Kamionkowski 1999, Kamionkowski & Kosowsky 1999, Scott 1999). As a result, modeling uncertainties have played a negligible role in the interpretation of the increasingly powerful observational data, allowing for unambiguous tests of competing cosmological theories and imposing tight constraints on the parameters that describe them (Samtleben *et al.* 2007, Komatsu *et al.* 2011, Larson *et al.* 2011, Challinor 2012).

Following the discovery of CMB temperature anisotropies by the DMR instrument on the COBE satellite, studies of the CMB focused on the characterization of the angular power spectrum of these fluctuations (Wright *et al.* 1992, Smoot *et al.* 1992). The statistical properties of these extremely faint fluctuations, having amplitudes of a few hundred μK, encode a rich set of information about the contents and the evolutionary history of the Universe; cosmological theories make specific predictions regarding the shape of the power spectrum of the intensity and polarization fluctuations on the sky. Figure 1 shows a few example power spectra corresponding to qualitatively different cosmological models, all of which were consistent with observations prior to 1999 (see Figure 2).

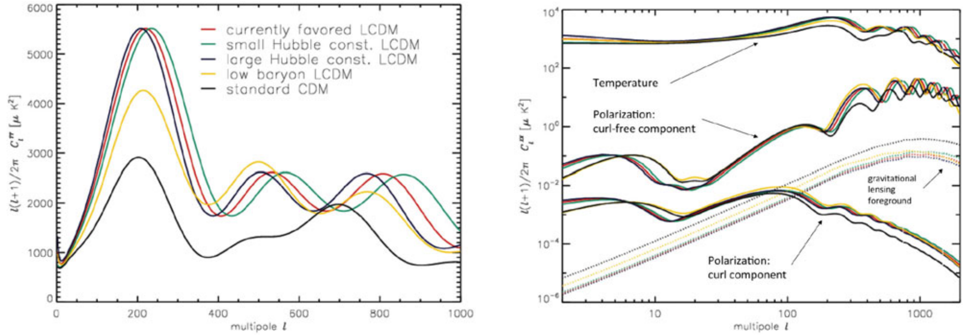

Figure 1. *At left*, the power spectra of temperature fluctuations corresponding to a range of cosmological models, all of which were consistent with the data available circa 1999. *At right*, the corresponding temperature (above, at several thousand μK^2) and polarization (both E-mode and B-mode) spectra, displayed on a log plot to illustrate the amplitude of the polarized component relative to the already faint temperature anisotropies.

CMB fluctuations on the sky represent a single realization of a Gaussian random process; observational data are used to infer the underlying power spectrum from which our realization is drawn. Cosmological models are tested and model parameters determined from these estimates through Bayesian inference. The experimental challenge of extracting this information is framed by the required instrumental sensitivity, sky coverage, control of systematics and the ability to disentangle the cosmological signal from that of the astrophysical foregrounds.

CMB temperature anisotropies

Boomerang was a pioneering balloon borne instrument designed to image the CMB temperature fluctuations, with fidelity to angular scales ranging from 5° to 20′ (Lange *et al.* 1996). The experiment employed two innovations that enabled a dramatically improved millimeter-wavelength imaging capability relative to contemporary instruments. The first of these were the cryogenic bolometric detectors at the heart of the receiver. These devices, cooled to a third of a degree above absolute zero, provided an instantaneous sensitivity limited only by the thermal radiation of the backgrounds. These "spider web" bolometers, named after their web-like silicon nitride structure, were designed to minimize the suspended heat capacity and the cross section to cosmic ray particles (Lange *et al.* 1995), allowing the devices to take full advantage of the capabilities afforded by the second of these innovations: the Antarctic long duration balloon platform.

From the point of view of atmospheric opacity and stability, Antarctica is arguably the best site in the world to perform observations at millimeter and far-infrared wavelengths with terrestrial telescopes (Burton *et al.* 1994, Storey *et al.* 1998, Battistelli *et al.* 2012); a review of South Pole based CMB experiments can be found elsewhere in these proceedings (Halverson 2012). In addition to the favorable conditions of the lower atmosphere, the stability of the stratospheric circumpolar winds during the Austral summer offers a unique capability for long duration balloon (LDB) flights (Gregory 2006). Stratospheric balloons launched from the ice shelf near McMurdo Station now routinely provide in excess of a week of observation in a near-space environment (Gregory & Stepp 2004).

Boomerang launched on December 29, 1998 from Williams Field, on the ice shelf approximately 10 km from McMurdo Station. Prior to 1998, many experiments had made statistically significant detections of anisotropy over a range of angular scales (e.g.

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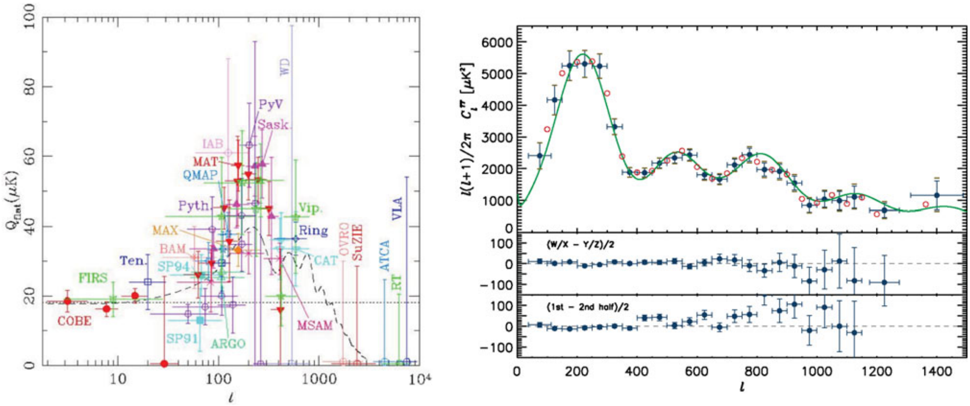

Figure 2. *At left*, the status of measurements of the angular power spectrum of the CMB, circa 1999 (Scott 1999). A number of experiments had detected significant levels of anisotropy, including hints of a peak near a multipole, $\ell \sim 200$, corresponding to angular scales of one degree. *At right*, the final angular power spectrum (upper panel), and corresponding null tests (lower two panels), derived from the Boomerang data (de Bernardis *et al.* 2000, Ruhl *et al.* 2003, Jones *et al.* 2006a). The characteristic scale of the features evident in Figure 3 result in a corresponding series of harmonic peaks in the power spectrum.

Netterfield *et al.* 1995, Torbet *et al.* 1999), but no single instrument had imaged the CMB with high signal-to-noise over a large area of the sky, providing a definitive characterization of the shape of the CMB power spectrum. The state of the measurement of the angular power spectrum circa 1999 is shown in Figure 2, reproduced with permission from Scott (1999).

The raw sensitivity and high fidelity of the Boomerang data provided an unambiguous measure of the CMB temperature anisotropy from super horizon scales, sampling primordial density fluctuations, to the harmonic peaks resulting from oscillations in the photon-baryon fluid prior to decoupling, while also clearly showing the expected suppression of power on small scales (above a multipole $\ell \gtrsim 900$) resulting from the combination of projection effects and Silk damping (photon diffusion) on small scales. This was the first single experiment to clearly measure all three of these distinct features in the CMB temperature anisotropy.

The scientific impact of the data from the 1998 Antarctic flight was extraordinary. For the first time, when combined with measurements of the Hubble constant and the expansion history via observations of supernovae, there was a clear determination that the geometry of the Universe was Euclidean, and that it consists of a surprising mix of Dark Energy ($\sim 70\%$), Dark Matter ($\sim 30\%$) and only trace amounts of familiar baryonic matter (de Bernardis *et al.* 2000). Within weeks of the publication of these data, the results from North American flight of the Maxima experiment were released, broadly confirming the Boomerang result (Hanany *et al.* 2000). While the value of these parameters have since been determined with greater precision, the ΛCDM model established by Boomerang's first Antarctic LDB flight remains the "Standard Model" of Cosmology (Lange *et al.* 2001).

CMB polarization

Following the successful characterization of the bulk features of the CMB temperature power spectrum, experimental groups directed their efforts toward the detection and characterization of the extremely faint polarized component of CMB. Polarization in the

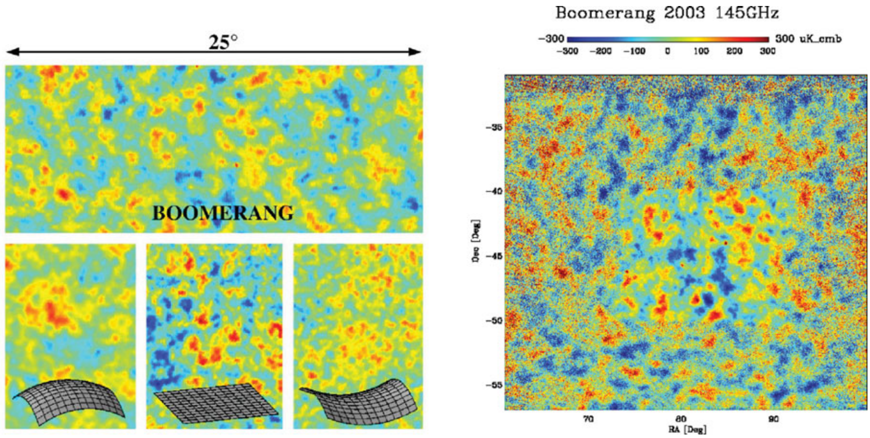

Figure 3. *At left*, the characteristic angular size of the CMB temperature fluctuations encodes the angular diameter distance to the surface of last scattering. A measure of this scale, together with a measure of the Hubble constant, constrains the topology of space-time to be closed (bottom left panel), Euclidean (bottom middle panel) or open (bottom right panel). The top panel shows the data from Antarctic long duration balloon flight of Boomerang in 1998 (Netterfield *et al.* 2002, Ruhl *et al.* 2003). Together with the data from the Maxima experiment, which imaged a much smaller portion of sky (Hanany *et al.* 2000), the data from the 1998 LDB flight provided the first resolved images of the CMB, and with it an unambiguous measure of the apparent angular size of the sound horizon corresponding to the epoch of last scattering. *At right*, the Boomerang temperature map derived from the data obtained in the 2003 long duration balloon (LDB) flight (Jones *et al.* 2006a). The integration time was distributed between a central deep field, and a shallow field covering roughly 10x more area, resulting in the apparent non-uniformity of the noise. The central deep field has approximately the same resolution and signal to noise as that achieved by the *Planck* HFI. Unlike the data in the left panel, this image has had no spatial filtering applied to highlight the small scale structure in the CMB.

CMB is generated by several processes. Thomson scattering in the optically thin plasma present during the epoch of recombination is generated by quadrupole anisotropies in the ambient radiation field. Quadrupoles induced from scalar perturbations, as are expected from primordial density fluctuations, produce a curl-free vector field (the "E-mode") with an amplitude a few percent of temperature anisotropy. Quadrupoles produced from tensor perturbations, such as gravitational waves from inflation, contribute a non-zero curl (the "B-mode").

In the context of the most simple inflationary theories, the amplitude of this component is simply related to the energy scale of the theory underlying the strong-electroweak phase transition and is not expected to exceed an rms level of a few hundred nano-Kelvin. On angular scales smaller than a degree, gravitational lensing of the CMB E-mode induces a B-mode signature even in the absence of a primordial component (Rees 1968, Kosowsky *et al.* 1999).

Based on mature technologies and insensitive to atmospheric emission, coherent interferometric receivers represented the most sensitive and robust technology for microwave polarimetry available at the time. The first statistical detection of a diffuse E-mode signal, later confirmed to have the angular spectrum expected from the CMB, was achieved at the South Pole in with DASI, a 30 GHz interferometer (Leitch *et al.* 2002, Kovac *et al.* 2002).

Coherent receivers, including both interferometric (DASI, CBI) and quasi-total power detectors (CAPMAP, WMAP) remained the technology of choice for the first generation of CMB polarization experiments. However, moving beyond detection to the precise

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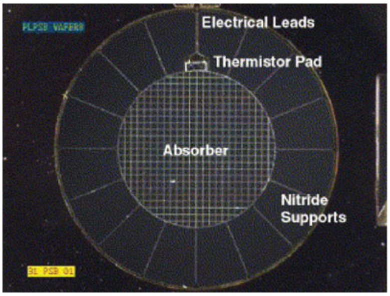

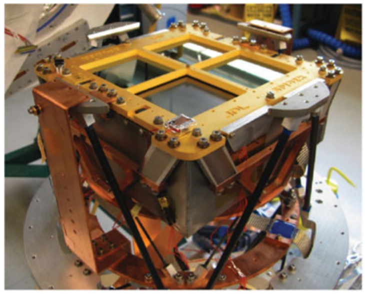

Figure 4. *At left*, a polarization sensitive bolometer, as employed in the 2003 flight of Boomerang, Bicep, QUaD and the *Planck* HFI instrument (Jones *et al.* 2003). *At right*, one of *Spider*'s six large format arrays of 512 antenna-coupled detectors (Bonetti *et al.* 2012).

characterization of CMB polarization required a dramatic increase in system sensitivity over the range of frequencies relevant to the CMB and Galactic foregrounds, 30 to 300 GHz.

At frequencies above 60 GHz, the noise performance of receivers based on coherent amplification are less competitive with incoherent (bolometric) techniques due to the quantum limit associated with phase sensitive amplification. This is particularly true for the low background cryogenic bolometers flown in space and on stratospheric balloons, which are limited in sensitivity only by the photon noise resulting from the 3 K cosmic background radiation (Lange *et al.* 2002).

Despite the advantages in raw sensitivity, and unlike their coherent analogues, traditional bolometric detectors are intrinsically insensitive to polarization.† However, the extreme sensitivity requirements of the B-mode science motivated a concerted effort to develop massively scalable bolometric receivers that would preserve the favorable polarimetric capabilities of the coherent systems.

Antarctic ballooning again played a leading role in both the technical development and scientific discovery of the next generation of CMB experiments. Indeed, just three months after the end of the first Antarctic Boomerang flight, the Caltech group proposed an ambitious program of technology development that would enable new discoveries from the South Pole, Antarctic LDB flights and ultimately on space missions.

The plan of work was to develop and fly two new technologies; polarization sensitive bolometers (PSBs) and large-format arrays of antenna-coupled bolometers (Lange *et al.* 1999). Having reached fundamental limits to the sensitivity of a given detector, massively scaling the number of detectors in a focal plane was the only way to realize the necessary increase in system sensitivity.

The first of these, polarization sensitive bolometers, saw first light on Boomerang in the 2003 Antarctic LDB campaign. They were later duplicated in larger numbers in the Bicep and QUaD experiments, and ultimately flew in the High Frequency Instrument (HFI) on the *Planck* spacecraft (Jones *et al.* 2003, 2007, 2006b; Takahashi *et al.* 2010). In addition to unprecedentedly sensitive images of the unpolarized CMB anisotropies, the data from the 2003 flight of Boomerang provided the first measurements of the CMB EE and TE power spectra made with a bolometer as well as at frequencies above 30 GHz (see Figure 5; Jones *et al.* 2006a, Piacentini *et al.* 2006, Montroy *et al.* 2006, MacTavish *et al.* 2006).

† Prior to the 2003 flight of Boomerang, no attempt had been made to perform CMB polarimetry with bolometers since the pioneering effort of Caderni *et al.* (1978).

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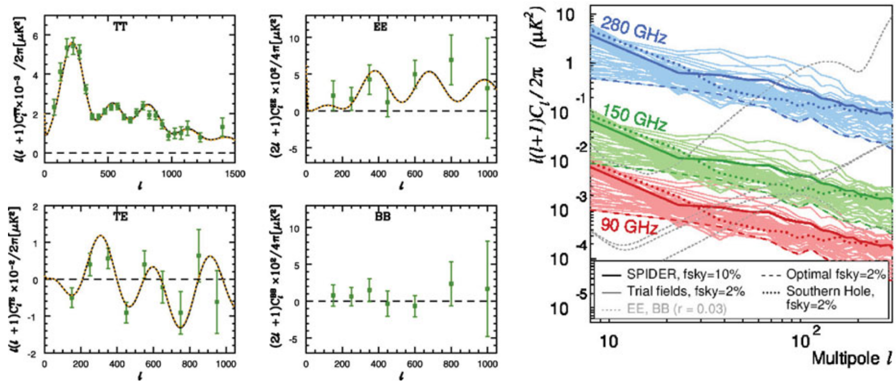

Figure 5. *At left*, the power spectrum of the CMB temperature and polarization anisotropies as measured by Boomerang during the January 2003 Antarctic LDB flight (MacTavish *et al.* 2006). *At right*, an illustration of the expected *minimum* amplitude of polarized Galactic emission (at these frequencies, primarily thermal dust emission) relative to the expected levels of the cosmological B-mode (shown in dotted lines for both the E- and B-modes. On scales larger than a few degrees, the Galactic foreground emission is likely to dominate the cosmological signal, requiring exquisite measurements over a range of frequencies to discriminate the two. For more discussion, see Fraisse *et al.* (2011).

The second of these, large format arrays of antenna-coupled detectors, are being developed for the Spider Antarctic LDB mission as well as South Pole based telescopes, and have only recently seen first light (Kuo *et al.* 2006, Fraisse *et al.* 2011, Brevik *et al.* 2010). Since the antenna, filter and detector can all be lithographed on a single wafer, antenna-coupled detectors are massively scalable. Whereas the number of detectors grew from eight PSBs in Boomerang, to dozens of PSBs in Bicep/QUaD and HFI, over two thousand background-limited detectors will fly on Spider.

Several groups, including UC Berkeley, NIST, ANL, GSFC and Caltech/JPL are now fielding innovative and complementary array technologies that provide the sensitivity, frequency coverage and control of systematics required to realize the scientific potential of CMB polarization (Hubmayr *et al.* 2012, McMahon *et al.* 2012, George *et al.* 2012, Westbrook *et al.* 2012, Aubin *et al.* 2010). EBEX and Spider represent the near future of Antarctic LDB CMB experiments. The two experiments are highly complementary, employing different technologies while probing complementary angular scales and electromagnetic frequencies. EBEX will field 1400 TES detectors spanning 150–400 GHz, covering 1% of the sky with 8′ resolution. Spider will fly 2400 detectors between 95 and 220 GHz, covering 10% of the sky with 30′ resolution. The EBEX Antarctic LDB experiment, which has deployed as of this writing, is the first highly multiplexed transition edge sensor (TES) array to have flown on a balloon (Reichborn-Kjennerud *et al.* 2010). Together, these Antarctic LDB experiments will constrain the B-mode CMB polarization at angular scales ranging from 30° to 10′, providing tight constraints on the shape of the B-mode power spectrum.

The future

Antarctic long duration balloon flights have played a pivotal role in the technological and scientific achievements in the CMB community during the last fifteen years, and remain at the leading edge of the search for the signature of inflation in the CMB. The benefits of the near-space environment provided by the stratospheric balloon platform include:

• Dramatically increased raw sensitivity – two to three times the best acheived from terrestrial telescopes at 90–150 GHz.

• The ability to extend frequency coverage above 150 GHz without significant degradation in performance due to atmospheric continuum emission

• Sensitivity to angular scales roughly five times larger than possible from the ground

• Access to 10% of the full sky near the Southern Galactic Pole that is relatively free from Galactic emission

The extremely low signal-to-background of the B-mode science requires not only massive scaling of background-limited detector arrays, but also new levels of systematic control. The community has developed a variety of creative solutions for both, but continued support of the development of detectors *and* polarimetric systems will be required as the next generation of experiments push orders of magnitude beyond the sensitivity of the first generation of CMB polarization experiments.

Galactic foregrounds will pose a significant, if not dominant, challenge in observational efforts to detect and characterize the cosmological B-mode signal. Disambiguation of the Galactic and cosmological signals will require sensitive surveys in closely spaced frequency bands spanning 60 to 400 GHz.

In addition to serving as a proving ground for space technologies, the balloon program provides an unparalleled training ground for the young scientists who will facilitate future space missions. Having been central to the successes of the past fifteen years, the Antarctic LDB program is poised to continue that tradition through the next decade.

Acknowledgements

The dramatic achievements of the past fifteen years, both technical and scientific, are the result of the combined efforts of an extraordinarily vibrant, talented and competitive community of researchers. This summary has been narrowly focused on the role played by Antarctic Long Duration Balloons in the development of the field, and in no way presumes to provide a comprehensive survey of contribution of the broader CMB community to the field. The author would like to acknowledge the support of the David and Lucille Packard Foundation, NASA grant NNX12AE95G, NSF award ANT-1043515 and the CSBF, and to thank the organizers of the IAU General Assembly for their efforts and hospitality.

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