The Atacama B-mode Search: an experiment to measure the polarization of the cosmic microwave background at large angular scales

S. T. Staggs[1], J. Appel[1], H.-M. Cho[2], W. D. Duncan[2], T. Essinger-Hileman[1], J. Fowler[1], M. Halpern[3], K. D. Irwin[2], T. A. Marriage[4], M. D. Niemack[2], L. Page[1], L. P. Parker[1], S. Pufu[1], K. Visnjic[1], K. W. Yoon[2], Y. Zhao[1]

[1]Physics Department, Jadwin Hall, Washington Rd, Princeton University, Princeton, NJ 08544-0001, USA
[2] National Institute of Standards and Technology, Mail Stop 814.03, 325 Broadway, Boulder, CO 80303, USA
[3] Department of Physics & Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC, V6T1Z1, Canada
[4] Department of Astrophysical Science, Peyton Hall, Princeton University, Princeton, NJ 08544-1001, USA

E-mail: staggs@princeton.edu

Abstract. The Atacama B-mode Seach (ABS) is a new experiment to probe the inflationary epoch in the early universe by measurng the patterns of polarization anisotropy in the cosmic microwave background (CMB) at large angular scales. The polarization of the CMB observed on the celestial sphere can be described with a tensor field. Gravitational waves from inflation, if it occurred, lead to a pseudoscalar component of that tensor field, which is quantified versus angular wavenumber as B-modes [1, 2]. ABS is designed to measure the CMB polarization over a wide frequency band at 145 GHz, using novel detectors optimized for polarization, fabricated at NIST. The detectors are bolometers, based on transition-edge sensors (TES), coupled to feedhorns. ABS features a large focal plane array of detectors illuminated by two $\approx$ 60 cm mirrors cooled to 4 K. The incoming polarization of the CMB is rotated with a warm half-wave plate (HWP) at the dewar aperture. ABS will make observations at a high-altitude site in the Atacama Desert of Chile.

1. Introduction

The possibility of detecting the imprint of gravitational waves from an inflationary epoch in the B-mode polarization of the cosmic microwave background (CMB)[1, 2] has stimulated a number of teams to develop experiments aimed at characterization of the large-scale CMB B-modes. The set of experiments spans a variety of detector technologies, optical configurations, and experimental techniques, and ABS occupies its own niche. Features particular to ABS include its compact all-reflective primary optical system in an entirely cryogenic configuration, its warm half wave plate (HWP) which modulates the polarization before the radiation reaches other optical elements, and its use of new detectors fabricated at NIST.

Table 1. Experimental Parameters in Annapolis Conference Format

Parameter	Value	Units
Angular resolution	30	arcminutes
Frequency Coverage	145	GHz
Sky Coverage	800	square degrees
Multipole Coverage	25 – 200	
Polarization Modulation[0]	Warm HWP	
Location	Ground (Chile)	
Instrument NEQ[0]	15	μK s$^{1/2}$
Status	Funded	

[0] The HWP is in front of all optical elements.
[0] Here calculated for 200 detectors each with two bolometers of sensitivity ≈ 300 μK s$^{1/2}$. This sensitivity is extrapolated from NEP measurements in the dark of prototype parts.

2. Overview

ABS is designed for rapid deployment. The entire experiment is built inside a standard 20 ft shipping container with a modified roof which opens to allow the telescope to observe the sky. Before it ships to Chile, ABS will be tested in essentially its final configuration. The ABS instrument is small. The cryostat housing the telescope and detectors is about 1 m tall and 1 m in diameter, and mounts on a modest az-el mount designed for azimuth scans at fixed elevation(s).

The 200 dual-polarization detectors in the initial configuration of ABS operate at 150 GHz. The instrument will measure the sky polarization with $\approx 30'$ beams over about 800 square degrees. Further experimental parameters are given in Table 1.

If the scalar-to-tensor ratio r of the primordial fluctuations is near 0.1, then extrapolations based on WMAP and the FDS map [3] indicate that the B-modes will be larger than foreground emission in the region of sky targeted by ABS [4]. We are designing ABS to have the sensitivity to detect such B-modes with a few months of observations.

3. Optics

The ABS telescope is an optimized crossed-Dragone [5] system; the primary and secondary mirror are each about 60 cm in diameter, making them small enough that they could be (and were) machined in a university machine shop. Figure 1 includes a ray trace of the optical system. The focal plane permits 200 300 mK corrugated feedhorns in a 20°-diameter field of view. The 2.5 cm-long feedhorns are also machined in a university machine shop. The full optical response has been computed from the geometric theory of diffraction; the resulting beams at the extreme edges of the focal plane are also shown in Figure 1. To minimize the impact of the small beam asymmetries at the focal plane edges, the polarization axes of each detector will be optimally oriented, with one axis approximately radial.

A rotating ambient-temperature sapphire HWP at a stop at the entrance to the telescope (and the cryostat) modulates the polarization before it enters the telescope. The HWP diameter is 33 cm. A prototype was built and tested in Chile [6].The HWP is anti-reflection coated and has less than 1.5% emission. Nonetheless the ≈ 4 K thermal emission is a significant source of loading, an acceptable penalty for the simplicity of its operation.

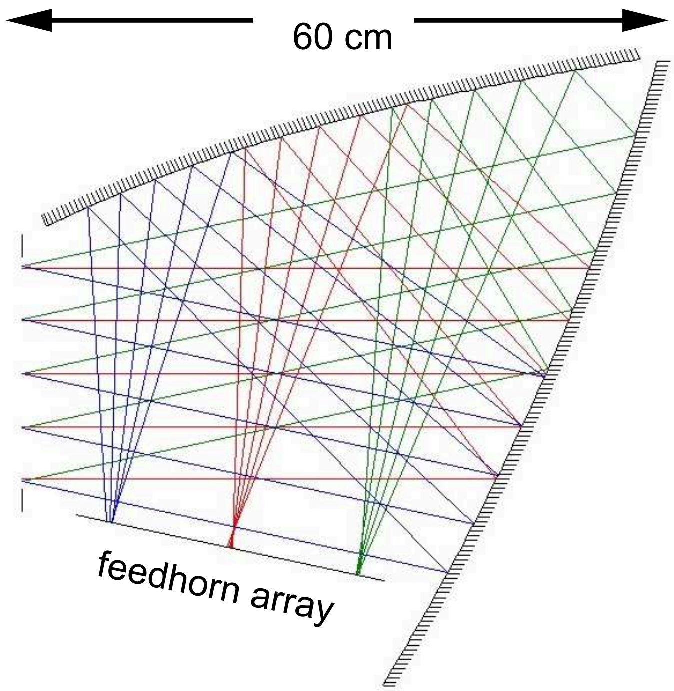

Figure 1. Ray-trace of telescope..

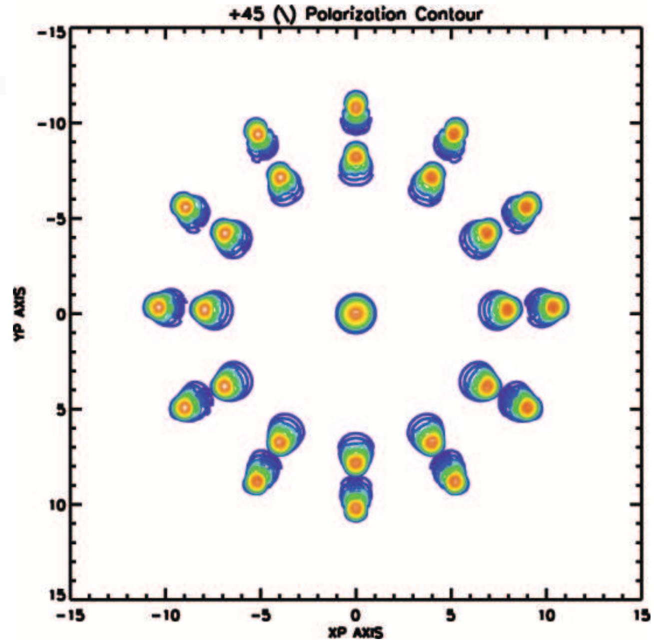

Figure 2. Contours for the beams of selected horns from the 200-horn focal plane array. Shown are slices through the beams at 45° to the E-planes.The x and y axes are in degrees, and the 3 dB contour has diameter $\approx 30'$.

4. Detectors

ABS will field-test newly designed detectors optimized for polarimetry. These detectors, fabricated at NIST and described in [7], comprise pairs of transition edge sensor (TES) bolometers coupled to planar orthomode transducers (OMTs) via coplanar waveguide (CPW) filters. The design was inspired by work done at Goddard Space Flight Center [8]. The detectors are the result of a design-and-test collaboration among NIST, the University of Chicago, the University of Colorado, and Princeton.

5. Systematics

All CMB experiments are designed with mitigation of systematic errors in mind, and ABS is no exception. The placement of the HWP before other optical components, the scanning and the sky rotation provide needed layers of modulation. At the request of the Annapolis CMB Systematics Conference organizers, we summarize our largest concerns thus far. First, unpolarized foregrounds can give rise to apparent polarization if the bandpasses of the filters on the detector differencing pairs are poorly matched. However, thus far, the filters appear to be well-matched, as might be expected since they are fabricated together; moreover sky rotation and comparison of signals from multiple detectors mitigate this effect. A second concern is that beam asymmetries remaining even after the detector axes are optimally placed lead to spurious polarization signals from the unpolarized atmosphere. Again, sky rotation and comparison of signals from detectors around the focal plane provide mitigation. Finally, we cannot rule out the possibility of troublesome systematic effects in the warm HWP until we have done further testing.

6. Conclusions

The ABS experiment is well underway and can be rapidly deployed to Chile. It is designed to detect primordial B-modes if their amplitudes are in the higher part of the range predicted by inflationary theories. ABS will provide a first field test of new NIST detectors and of a compact all-reflective cryogenic telescope, among other design concepts which might be used in an eventual satellite aimed at making the definitive CMB polarization measurements.

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References

[1] Seljak, U. and Zaldarriaga, M., "Signature of Gravity Waves in the Polarization of the Microwave Background," PRL 78, 2054, 1997.

[2] Kamionkowski, M., Kosowsky, A., and Stebbins, A., "A Probe of Primordial Gravity Waves and Vorticity," PRL 78, 2058, 1997.

[3] D. Finkbeiner, M. Davis, D. Schlegel, Extrapolation of Galactic Dust Emission at 100 Microns to Cosmic Microwave Background Radiation Frequencies Using FIRAS, Ap.J, 524, 867, 1999.

[4] Dunkley, J., Amblard, A., Baccigalupi, C., Betoule, M., Chuss, D., Cooray, A., Delabrouille, J, Dickinson, C., Dobler, G., Dotson, J., Eriksen, H. K., Finkbeiner, D., Fixsen, D., Fosalba, P., Fraisse, A., Hirata, C., Kogut, A., Kristiansen, J., Lawrence, C., Magalhaes, A. M., Miville-Deschenes, M. A., Meyer, S., Miller, A., Naess, S. K., Page, L., Peiris, H. V., Phillips, N. , Pierpaoli, E., Rocha, G., Vaillancourt, J. E., and Verde, L, "CMBPol Mission Concept Study: Prospects for polarized foreground removal," ArXiv, 0811.3915.

[5] Tran, Huan; Lee, Adrian; Hanany, Shaul; Milligan, Michael; Renbarger, Tom, "Comparison of the crossed and the Gregorian Mizuguchi-Dragone for wide-field millimeter-wave astronomy," App. Opt. 47, 103, 2008

[6] J. Lau, "CCAM: A Novel Millimeter-wave Instrument Using a Close-Packed TES Bolometer Array," Ph.D. thesis, Princeton University, 2007.

[7] Yoon, K. W., Beall, J. A., Cho, H.-M., Doriese, W. B. , Duncan, W. D., Irwin, K. D., Schmidt, D.R., Ullom, J. N., Becker, D. T., Halverson, N. W., Hilton, G. C., 'Design and development of a large-format TES array for CMB polarimetry', Proceedings, ASC 2008, in preparation.

[8] Wollack, E., private communication.