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The POLARBEAR Cosmic Microwave Background Polarization Experiment

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Abstract The POLARBEAR cosmic microwave background (CMB) polarization experiment has been observing since early 2012 from its 5,200 m site in the Atacama Desert in Northern Chile. POLARBEAR's measurements will characterize the expected CMB polarization due to gravitational lensing by large scale structure, and search for the pos-

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sible B-mode polarization signature of inflationary gravitational waves. POLARBEAR's 250 mK focal plane detector array consists of 1,274 polarization-sensitive antenna-coupled bolometers, each with an associated lithographed band-defining filter and contacting dielectric lenslet, an architecture unique in current CMB experiments. The status of the POLARBEAR instrument, its focal plane, and the analysis of its measurements are presented.

Keywords Cosmic microwave background · CMB polarization · Millimeter-wave

1 Introduction

From its discovery to the present, a series of more detailed measurements of the cosmic microwave background, including its primary temperature anisotropy and E-mode (curl-free) polarization, have helped refine our models of the universe [1,2]. Many current cosmic microwave background (CMB) experiments, including POLARBEAR, are focused on characterizing the B-mode (divergence-free) polarization component of the CMB.

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At large angular scales, B-mode polarization is predicted to have been generated by primordial gravitational wave tensor perturbations during inflation [3]. The strength of these tensor perturbations is dependent on the shape of the inflationary potential as well as the energy scale of inflation, but it is expected to peak on an angular scale of 2°. Detection of this B-mode polarization would be direct evidence supporting the inflationary paradigm, and would help to constrain the parameter space of inflationary models [4].

Although tensor perturbations are the only primordial source of B-mode polarization, B-modes are also created at later times by weak gravitational lensing of the CMB by large scale structure. This lensing mixes E and B-modes, creating B-mode polarization that has recently been detected on small angular scales [5]. Lensing B-modes can give information about the large scale structure that generated them, as the lensing effect is sensitive to the formation of structure at early epochs. POLARBEAR's observation fields overlap with optical and infrared galaxy surveys, and cross-correlation with these data sets will leverage their redshift information for a more complete picture of the lensing effect.

2 Instrument Overview

Reaching the sensitivity necessary to measure the CMB's B-mode polarization requires significant advances in detector technology. POLARBEAR uses a unique 637 pixel lenslet-coupled focal plane, integrated with a large field of view telescope and cold reimaging optics, and observing in a single 38 GHz wide spectral band centered at 148 GHz. This section gives a brief overview of the instrument. The design and development of the POLARBEAR experiment have been described in detail in previous proceedings [6–8].

POLARBEAR is mounted on the Huan Tran Telescope (HTT), built by VertexRSI[1], which is an off-axis Gregorian design that satisfies the Mizuguchi–Dragone condition. This optical design has a large diffraction limited field of view of 2.3°, along with low sidelobe response and low cross polarization, meeting the systematic requirements for POLARBEAR's science goals [9,10]. The primary mirror is a 2.5 m monolithic piece of cast aluminum, precision machined to 53 μm rms surface accuracy, with a lower-precision guard ring extending to 3.5 m diameter. The primary produces a 3.5 arcminute FWHM beam at 148 GHz. The secondary mirror is 1.4 m, with baffling enclosing it and the receiver window to block scattered light.

The transition edge sensor (TES) detectors are designed to operate at 0.25 K, where thermal carrier noise becomes subdominant compared to expected thermal background loading noise from the Chilean atmosphere. The bolometers have a design noise equivalent temperature (NET) of 500 $\mu K_{CMB}\sqrt{s}$. The cryogenic receiver, shown in Fig. 1, has a cumulative optical efficiency of 37 %, including contributions from the focal plane, aperture stop, lenses, and filters [6]. A two-stage pulse tube refrigerator[2] providing continuous cooling power at 50 and 4 K. A three-stage helium sorption

1 http://www.gdsatcom.com/vertexrsi.php

2 http://www.cryomech.com

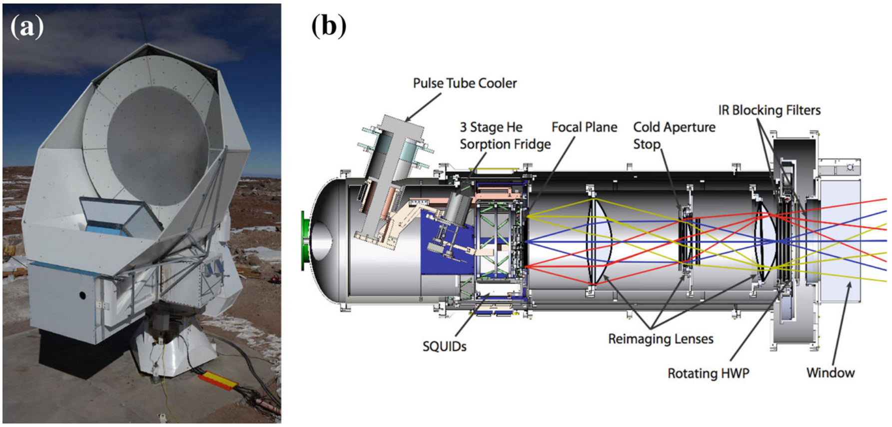

Fig. 1 **a** The Huan Tran Telescope. **b** A cross-sectional drawing of the POLARBEAR cryogenic receiver with major components identified (Color figure online)

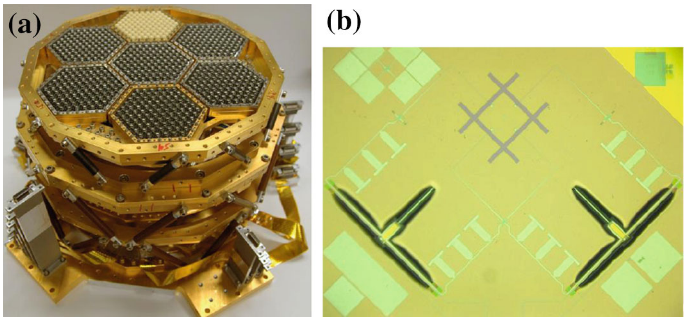

Fig. 2 **a** POLARBEAR's complete focal plane including lenslets, support structures and wiring. One array module has white alumina instead of silicon lenslets. **b** A single pixel, with two TES detectors and slot antenna (Color figure online)

fridge[3] provides two cooling stages at 0.35 and 0.25 K, with a hold time greater than 30 h.

The focal plane, shown in Fig. 2, consists of seven modular arrays of antenna-coupled transition edge sensor (TES) detectors, each with 192 detectors. An individual pixel, shown in Fig. 2, consists of two Al/Ti bilayer TES detectors, coupled to orthogonal polarizations of the dual-polarized slot antenna, with on-chip band-defining filters [7]. Each pixel is paired with a beam-forming, anti-reflection coated lenslet [11]. Fluctuations in optical power are converted to changes in current in the voltage-biased TES detector, and this current is read out using superconducting quantum interference devices (SQUIDs). Reading out large arrays of detectors requires signal multiplexing in order to reduce thermal loading on the cold focal plane, as well as to reduce the cost, size, and complexity of cryogenic wiring and other cold readout components. POLARBEAR uses frequency-domain multiplexing [12] with a multiplexing factor of eight.

3 http://www.chasecryogenics.com

3 Instrument Performance

POLARBEAR is located at the James Ax Observatory, at an altitude of 5,200 m on Cerro Toco in the Atacama desert in Chile and achieved first light in January 2012. This site was chosen for its dry, stable weather, with precipitable water vapor (PWV) less than 1.5 mm for over 50 % of the year. This corresponds to a sky brightness in the POLARBEAR design band of $15K_{RJ}$ at an elevation angle of 60°.

Calibration is key to understanding the instrument's performance, and POLARBEAR uses both hardware and astrophysical calibration sources. Calibration data for relative detector response is taken every hour during observations. The relative detector response is measured using a 3 min observation of a variable frequency chopped thermal source located behind an aperture in the secondary mirror, with an effective temperature of 0.03 K. Relative detector response is also measured using fast elevation scans that vary detector response due to the changing line-of-sight air mass, spanning 3° of elevation and approximately 0.5 K of sky temperature modulation. The relative detector response is used to calculate a differential timestream for the response of the two orthogonally oriented detectors within one pixel. This timestream can be used to measure the Q or U Stokes parameters while suppressing the unpolarized atmospheric signal.

The large fraction of the sky available to POLARBEAR means that many astrophysical sources can be observed. Planets like Jupiter and Saturn are bright point sources, so observations of these planets map the structure of the beams. Each detector beam's size, ellipticity, and offset from boresite can be measured using planets. Figure 3 shows a coadded map made from active detectors observations of Saturn. The measured median FWHM beam size is 3.5 arcminutes, with a median ellipticity of 0.05 [6]. Planet observations can also be used to determine detector yield and NET, which vary with atmospheric conditions. The total number of active detectors is 1,015, the typical operating yield during observations is about 900 detectors, and the median detector NET is 550 $\mu K\sqrt{s}$. Another important astrophysical calibrator for POLARBEAR is Taurus A, a supernova remnant in the Crab Nebula. Taurus A has a well-known polarization angle, caused by synchrotron emission [13], and is used to calibrate detec-

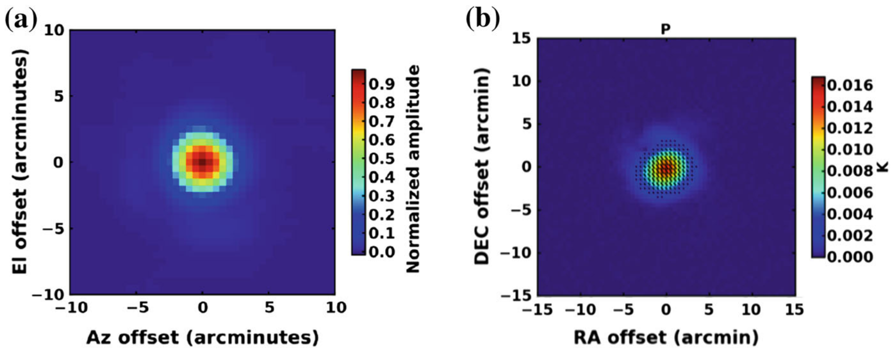

Fig. 3 **a** Coadded angular response of observations of Saturn. **b** Intensity and polarization map of Taurus A (Color figure online)

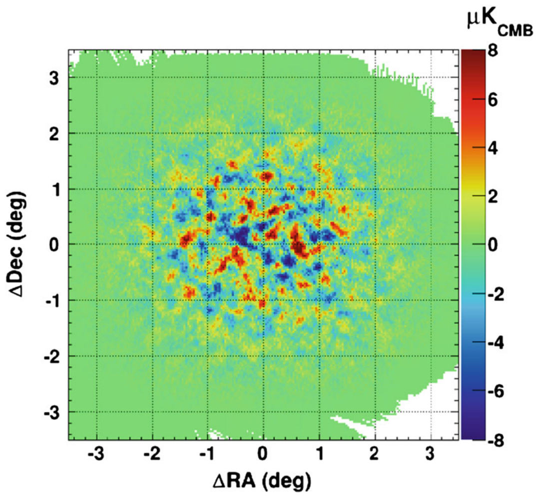

Fig. 4 Preliminary first season E-mode polarization map for one of three observation patches, with approximately 1,700 h of observation time (Color figure online)

tor polarization angles. Figure 3 shows a coadded temperature map of Tau A with the resulting polarization $P = \sqrt{Q^2 + U^2}$ and polarization angle of the source.

The POLARBEAR collaboration is not examining B-mode polarization results until the instrumental and data quality studies using other indicators are complete. Shown in Fig. 4 is the E-mode polarization for one of three sky patches observed by POLARBEAR. A preliminary map depth for this patch has been calculated, which is 5 μK_{CMB}-arcminute for polarization.

4 Future Plans

POLARBEAR is in its second season of observations, and the POLARBEAR collaboration is currently analyzing the first season of data. Upgrades to the project are also underway, with two additional telescopes, known as the Simons Array, and the next-generation dichroic receiver, POLARBEAR2 [14] under construction.

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