Detecting the B-mode Polarisation of the CMB with Cℓover

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We describe the objectives, design and predicted performance of Cℓover, which is a ground-based experiment to measure the faint "B-mode" polarisation pattern in the cosmic microwave background (CMB). To achieve this goal, Cℓover will make polarimetric observations of approximately 1000 deg^2 of the sky in spectral bands centred on 97, 150 and 225 GHz. The observations will be made with a two-mirror compact range antenna fed by profiled corrugated horns. The telescope beam sizes for each band are 7.5, 5.5 and 5.5 arcmin, respectively. The polarisation of the sky will be measured with a rotating half-wave plate and stationary analyser, which will be an orthomode transducer. The sky coverage combined with the angular resolution will allow us to measure the angular power spectra between $20 < \ell < 1000$. Each frequency band will employ 192 single polarisation, photon noise limited TES bolometers cooled to 100 mK. The background-limited sensitivity of these detector arrays will allow us to constrain the tensor-to-scalar ratio to 0.026 at 3σ, assuming any polarised foreground signals can be subtracted with minimal degradation to the 150 GHz sensitivity. Systematic errors will be mitigated by modulating the polarisation of the sky signals with the rotating half-wave plate, fast azimuth scans and periodic telescope rotations about its boresight. The three spectral bands will be divided into two separate but nearly identical instruments — one for 97 GHz and another for 150 and 225 GHz. The two instruments will be sited on identical three-axis mounts in the Atacama Desert in Chile near Pampa la Bola. Observations are expected to begin in late 2009.

1 Introduction

The currently favoured cosmological model predicts that gravity waves produced during a period of cosmological inflation should have imprinted a faint primordial "B-mode" polarisation pattern in the CMB[1,2]. The amplitude of the gravity-wave signal is related to the expansion rate, and hence energy scale[3], during inflation and is therefore not yet predicted by fundamental theory. By precisely characterising the polarization of the CMB, it should be possible to put strong constraints on the various theories of inflation. A discovery of the primordial B-mode signal would be a significant breakthrough for both astrophysics and particle physics, since we would then be probing physics at the 10^{16} GeV scale.

To date, the characterisation of the CMB temperature anisotropy has given the prevailing ΛCDM cosmological model a strong footing[4,5]. This footing was further strengthened when the brighter "E-mode" polarisation signal, which the prevailing model predicted, was recently measured[6,7]. The anticipated B-mode signal has not yet been discovered because the current generation of instrumentation is not sensitive enough to detect it.

In this paper, we describe Cℓover, which is a next-generation CMB experiment that will have sufficient sensitivity to measure the T and E-mode signals and, by searching for a cosmological B-mode signal, measure or constrain the tensor-to-scalar ratio[a] down to $r = 0.026$. This is a factor of 20 lower than the current upper limit from CMB measurements alone[8]. Therefore, the core astrophysical goals of Cℓover are the following: to determine the energy scale of inflation, to improve constraints on a collection of cosmological parameters, to measure a non-primordial gravitaional lensing-induced B-mode signal, and to precisely characterise any polarised Galactic signals such as synchrotron radiation and polarised emission from dust. An overview of Cℓover is given in Section 2, while instrument and observation details are given in Sections 3 & 4.

[a] The tensor-to-scalar ration, r, is proportional to the energy scale of inflation to the fourth power[3].

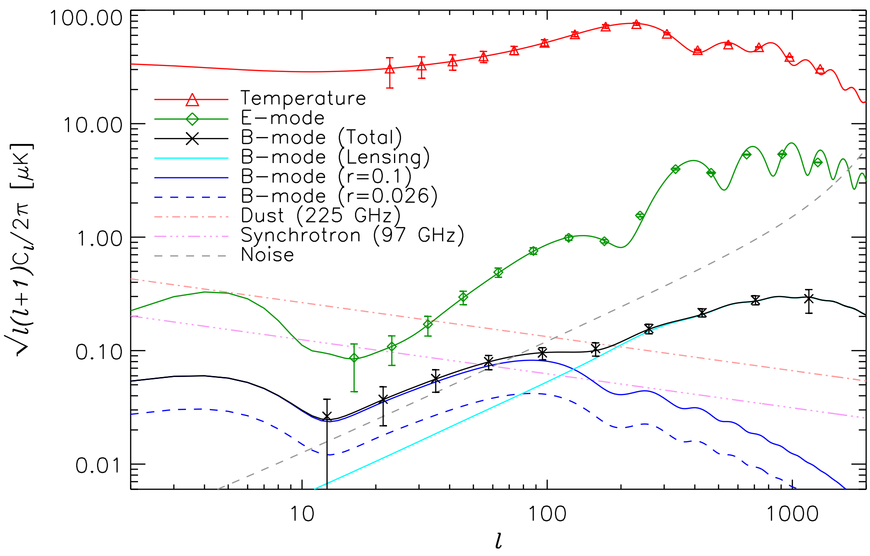

Figure 1: Theoretical angular power spectra for the temperature, E-mode and B-mode signals assuming the ΛCDM cosmological model[9] and $r = 0.1$. The black, B-mode curve comprises a primordial inflationary gravity wave signal and a predicted non-primordial B-mode foreground signal produced by the gravitational lensing of partially polarised CMB radiation as it passed through large-scale structures. The expected performance of Cℓover is overplotted as binned points, with error bars taking into account the atmospheric and instrumental noise for 150 GHz and the sample variance for the Cℓover survey area. For comparison, we plot the power spectra of the forecasted foreground signals in the Cℓover observation regions *before* cleaning, based on polarisation observations and models of unpolarised emission[10,11,12]. These foreground signals include polarised thermal emission from aligned dust grains and polarised synchrotron emission. The dust and synchrotron signals are plotted at 225 and 97 GHz, respectively, to show the worst case scenario. Both signals should be smaller at 150 GHz.

2 The Cℓover Experiment

During two years of operation, Cℓover will make polarimetric observations of approximately 1000 deg^2 of the sky from Pampa la Bola in the Atacama Desert, Chile, which is within the ALMA science preserve. This location was selected because the millimetre-wave transmittance of the atmosphere at the site is among the best in the world for ground-based observatories, primarily due to the high altitude of 4.9 km. The polarimetric observations will be made in spectral bands centred on 97, 150 and 225 GHz with two independent instruments, one for 97 GHz and another for 150 and 225 GHz. The three frequency bands, primarily set by atmospheric transmission windows, are well matched to the 2.7 K CMB blackbody spectrum and are expected to provide sufficient leverage for the spectral removal of the anticipated astrophysical foreground signals. The baseline design of the experiment calls for the use of 576 superconducting transition edge sensors (TES), cooled to 100 mK with a pulse tube cooler, a He-7 refrigerator and a dilution refrigerator[13]. The large number of detector outputs will be multiplexed with a time-domain cryogenic readout. The receivers containing the detectors will be mounted at the focal planes of low cross-polarisation, off-axis compact range antenna reflecting telescopes. The 97 GHz telescope will provide 7.5 arcmin beams on the sky, while the 150/225 GHz telescope will provide 5.5 arcmin beams. The expected instrument NET $\simeq 18\,\mu\mathrm{K}\sqrt{\mathrm{sec}}$ at 150 GHz gives a predicted map sensitivity of around 1.7 μK per 5.5 arcmin resolution element for the Q and U Stokes parameters after a two-year observing campaign. The beam sizes are well matched to the primordial B-mode signal, which dominates the non-primordial B-mode signal below $\ell \simeq 100$ for $r \gtrsim 0.01$, and will allow very good sensitivity to the non-primordial B-mode signal from gravitational lensing (see Figure 1). To mitigate the effect of $1/f$ noise from detector drifts and atmospheric fluctuations, to reject systematic errors and to achieve the best noise performance, Cℓover will use rapid polarisation modulation. This modulation is produced by a rotating achromatic half-wave plate and fixed orthomode transducers, which are the polarisation analysers. Because the B-mode signal is faint, the instrument design outlined above has been advised by detailed cosmological simulations to ensure our results should not be contaminated by spurious instrumental signals[14]. The expected performance of Cℓover is shown in Figure 1, and a model of one of the Cℓover instruments is shown in Figure 2.

3 Instrument Description

Both the C$_\ell$over instruments will use a compact range antenna (CRA), which is composed of a parabolic primary mirror and hyperbolic secondary mirror. Both mirrors are off axis. This optical design gives excellent cross-polarisation performance and low aberrations across a large, flat focal plane[15]. For all focal plane elements, the Strehl ratio is greater than 0.95, and the cross polarisation — including the cross polarisation of the horn — is better than −38 dB. The projected diameters of the primary mirrors are 1.8 and 1.5 m for the 97 and 150/225 GHz instruments respectively. The telescope mirrors will be surrounded by a co-moving baffle lined with millimetre-wave absorber, which will prevent signals in the far side lobes of the telescope from being modulated as the telescope scans.

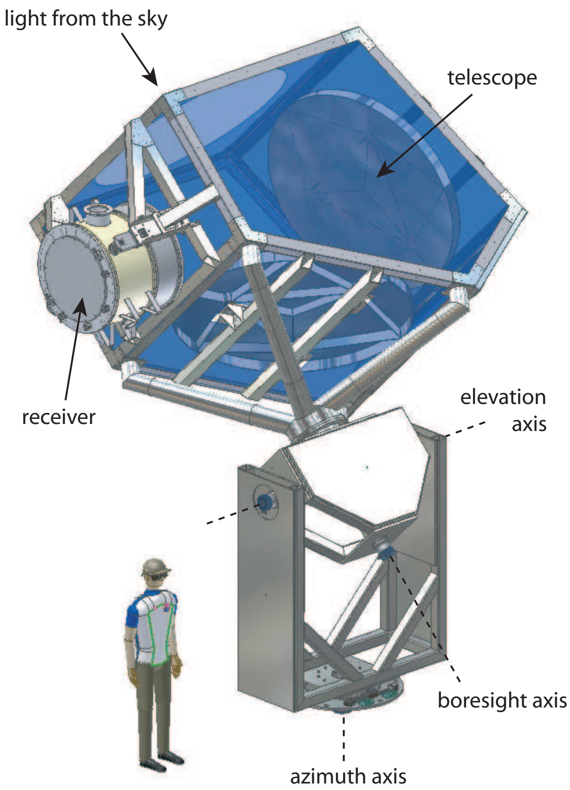

Figure 2: A model of one of the two C$_\ell$over instruments. The three-axis mount also allows the rotation of the entire optical assembly around the telescope boresight. The mirrors are held inside a co-moving baffle (translucent in the figure for clarity). The co-moving baffle is lined with absorber to reduce the effect of side lobes. A counter balance, which is not shown here, will be mounted on the boresight axis on the opposite side of the elevation axis from the telescope. All of the instrument hardware shown here is either built or under construction.

Each array element in the focal plane comprises a profiled corrugated horn, an orthomode transducer (OMT) and two (TES) detectors. The TES detectors are photon noise limited Mo/Cu superconducting bolometers with transition temperatures around 190 mK (430 mK for 225 GHz) and time constants around 0.5 ms[16,17]. In the 97 GHz focal plane the OMT is composed of an electroformed turnstile junction with a circular waveguide input and two rectangular waveguide outputs[18]. Each output waveguide terminates in a microstrip-coupled TES via a finline transition[19]. At 150 and 225 GHz each horn couples to a planar OMT composed of four rectangular probes in a cylindrical waveguide[20]. Outputs from opposing pairs of probes are combined in a microstrip circuit, which terminates in the TES; this design combines the OMT and detectors on a single chip. The focal plane elements are grouped into eight-element modules, and each module is read out with a SQUID multiplexer[21,22,23].

A single achromatic half-wave plate (AHWP) will be mounted approximately 100 mm in front of each focal plane[24,25]. The AHWP is composed of three A-cut sapphire discs at 97 GHz and five discs at 150/225 GHz. The diameter of each disc is approximately 300 mm, and the disc thicknesses are 4.65 mm and 2.43 mm at 97 and 150/225 GHz respectively. The 97 GHz AWHP central disc has a birefringent axis oriented at 59° relative to the outer discs, while the second to fifth crystals in the 150/225 GHz stack are rotated by 29°, 95°, 29°and 0° respectively with respect to the first crystal in the stack. To improve transmission and to minimise spurious polarisation from differential reflection, the AHWP will have a three-layer, broadband anti-reflection coating on the external faces of the stack.

The cryostat and optics are mounted to a common optical assembly, which sits on top of a three-axis mount as shown in Figure 2. The third axis, rotation around the boresight, is necessary for identifying and suppressing systematic errors from instrumental polarisation and for increasing cross-linking.

4 Observation Strategy

C$_\ell$over will observe a total of 1000 deg^2 of the sky. This coverage is divided into the four regions shown in Figure 3, each roughly 20° in diameter. Two of the fields are in the southern sky and two lie along the equator. To control the contribution from the atmosphere each telescope will scan at approximately 0.5 deg/sec in azimuth at a constant elevation. Every few hours, the elevation angle of the telescope will be

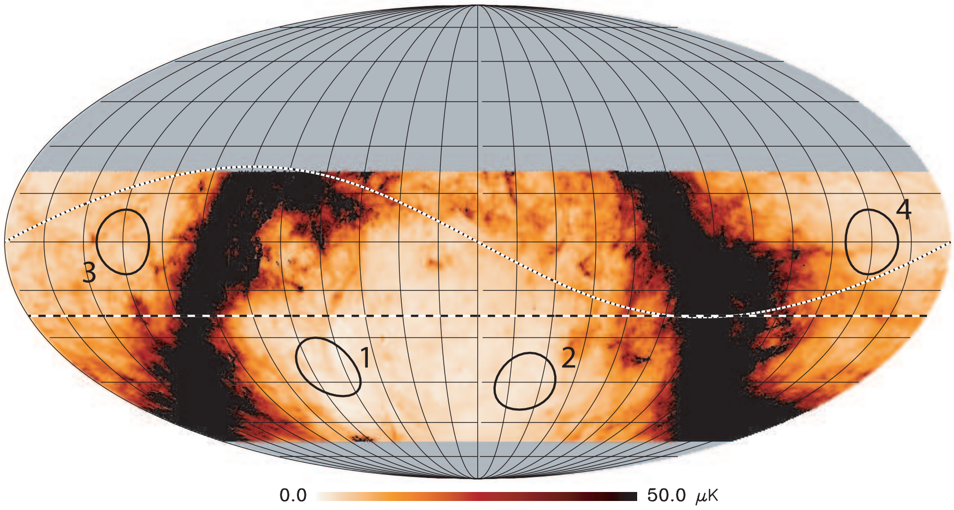

Figure 3: The four observation regions selected for C$_\ell$over, centred on 0430−40, 2230−45, 0900+00 and 1400+00, plotted in equatorial coordinates over a model of the magnitude of the polarised Galactic emission at 225 GHz. The field locations were chosen based on models of the Galactic emission[11,12], and are optimally distributed in RA. These fields are intended to overlap nicely with the survey areas of other B-mode experiments. Also plotted are the zenith declination (dashed) from Pampa la Bola (22° 28′ S, 67° 42′ W) and the ecliptic plane (dotted). Grey areas never rise above 45° from the C$_\ell$over site, which means they are not useful or accessible.

re-pointed to allow for field tracking. During all observations, the AHWP will be rotated continuously at approximately 5 Hz and the telescope will be rotated around its boresight axis periodically. Observations at 97 GHz are expected to begin in late 2009, with 150/225 GHz observations expected from mid-2010.

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References

1. Hu, W., Hedman, M. M., and Zaldarriaga, M. (2003) *Phys. Rev. D* **67**(4), 043004.
2. Seljak, U. and Zaldarriaga, M. (1997) *Phys. Rev. Lett.* **78**(11), 2054.
3. Knox, L. and Song, Y.-S. (2002) *Phys. Rev. Lett.* **89**(1), 011303.
4. Spergel, D. N. et al. (2007) *ApJS* **170**, 377.
5. Hinshaw, G. et al. (2008) *ArXiv e-prints* **0803.0732**.
6. Ade, P. et al. (2008) *ApJ* **674**, 22.
7. Bischoff, C. et al. (2008) *ArXiv e-prints* **0802.0888**.
8. Dunkley, J. et al. (2008) *ArXiv e-prints* **0803.0586**.
9. Komatsu, E. et al. (2008) *ArXiv e-prints* **0803.0547**.
10. Page, L. et al. (2007) *ApJS* **170**, 335.
11. Giardino, G. et al. (2002) *A&A* **387**, 82.
12. Finkbeiner, D. P., Davis, M., and Schlegel, D. J. (1999) *ApJ* **524**, 867.
13. Teleberg, G., Chase, S. T., and Piccirillo, L. (2008) *J. Low Temp. Phys.* **151**(3-4), 669.
14. O'Dea, D., Challinor, A., and Johnson, B. R. (2007) *MNRAS* **376**(4), 1767.
15. Johnson, B. R. et al. (2008) *MNRAS* , in preparation.
16. Audley, M. D. et al. (2008) *Proceedings of the SPIE* **7020**, in press.
17. Audley, M. D. et al. in *Proceedings of the 19th Int. Symp. on Space THz Tech.*, (2008). in press.
18. Pisano, G. et al. (2007) *IEEE Microwave Compon. Lett.* **17**(4), 286.
19. North, C. E. et al. (2008) *MNRAS* , in preparation.
20. Grimes, P. K. et al. (2007) *Electronic Letters* **43**(21), 1146.
21. Battistelli, E. S. et al. (2008) *J. Low Temp. Phys.* **151**, 908.
22. Reintsema, C. D. et al. (2003) *Rev. Sci. Instrum.* **74**(10), 4500.
23. de Korte, P. A. J. et al. (2003) *Rev. Sci. Instrum.* **74**(8), 3807.
24. Pisano, G. et al. (2006) *App. Opt.* **45**(27), 6982.
25. Savini, G., Pisano, G., and Ade, P. A. R. (2006) *App. Opt.* **45**(35), 8907.
26. Górski, K. M. et al. (2005) *ApJ* **622**, 759.