QUBIC, a bolometric interferometer to measure the B modes of the CMB

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Measuring the B modes of the CMB polarization fluctuations would provide very strong constraints on inflation. The main challenge in this measurement is the treatment of systematic effects. CMB observations with imagers and interferometers, subject to very different systematics, are complementary in this respect. Interferometry provides direct access to the Fourier transform of the sky signal. In bolometric interferometry, the interference pattern produced by the sky through a few hundred horns is imaged on a bolometer array. Several such modules are needed to achieve the required sensitivity. We will describe QUBIC, a merger of the US and European MBI and BRAIN collaborations. QUBIC is a polarized bolometric interferometer to be deployed in 2011-2012.

1 CMB polarization

The CMB polarization results from the local quadrupole in the distribution of last scattered photons. One can separate the polarization patterns in the sky according to their parity: even parity $E$ modes, and odd parity $B$ modes. For reasons of symmetry, scalar primordial fluctuations only produce $E$ modes, whereas tensor perturbations (gravity waves) produce both $E$ and $B$ modes, therefore detection of $B$ modes means detection of gravity waves.

Inflation In most inflationary models the dominant scalar fluctuations are adiabatic and the level of $E$ modes can be inferred from the level of temperature fluctuations, as has been observed in the WMAP observations. In contrast, the Tensor/Scalar ratio $r = T/S$ is not known but depends on the rate of production of primordial gravitons which is related to the energy scale of inflation by $r \simeq 0.1 \left( \frac{E_{\text{infl}}}{10^{14} \text{GeV}} \right)^4$. At the moment, $r$ is only bounded above by the temperature power spectrum: $r < 0.33$. The best upper bound from upper limits on polarization $B$ modes is weaker

2 $B$ mode detection

$B$ modes are at least ten times weaker than $E$ modes but could be much smaller. Therefore, to measure them we need i) very high sensitivity, ii) extremely good control of systematics and iii) an efficient and reliable foreground subtraction. To make sure that $B$ modes have really been
detected, several converging observations with different systematics and different foreground subtraction methods would be beneficial.

Two techniques have so far been used to measure the CMB polarization fluctuations: 

Imagers: this technique has been the most commonly used. It provides excellent sensitivity, in particular if one uses bolometers which allow to reach the photon noise limit. The forthcoming bolometer arrays will allow to detect very low level CMB polarization fluctuations. However it suffers from several kinds of systematics: i) Telescope induced systematics (beam, polarization angles, ground pick up); ii) polarization measurements requires taking differences between detectors, which is a source of intercalibration errors; iii) as the sky image is obtained from its time ordered scanning by a narrow beam, time variations of the atmosphere emissivity and transparency are critical.

Heterodyne interferometry is the first technique to have detected CMB polarization. In interferometry, i) no front optics is necessary; ii) no differences between detectors are needed to measure polarizations; iii) interferometry directly observes the Fourier transform of the sky within the beam, and therefore is not sensitive to time variations of the atmosphere. However, in heterodyne interferometry the noise is dominated by the amplification noise, which does not allow reaching the photon noise limit. Moreover it seems technically difficult to measure the numerous baselines needed to reach the sensitivity required for $B$ mode detection.

Bolometric interferometry may combine the advantages of both techniques

3 Bolometric interferometry

In bolometric interferometry, bolometers do not see the sky directly but they see the interference pattern produced by the sky through an array of horn antennas. The signal collected by each horn is separated into its two orthogonal polarization components, one of the polarization is rotated by $90^\circ$ so that they can interfere, and each channel is appropriately phase shifted. The signals from all different channels are combined in a beam combiner to produce the interference pattern. The combined signals illuminate a bolometer array. Bolometric interferometry is an additive interferometry which means that the visibility, the Fourier transform of the sky signal, must be separated from the total bolometer output. This can be done by modulating the phase shifts.

The difficulty is to separate the $2N(N-1)$ complex visibilities corresponding to all pairs of the $N$ input horns and 2 polarizations. When $N$ is large, an electronic solution to this problem is desperately complex. This is the reason why we turned to an optical solution.

The Quasi Optical Interferometer (QOI) The principle of the QOI is the following (see figure 1): the signal from each polarization and each horn is re-emitted by $2N$ back horns, and the interference pattern of the back horns is collected by a bolometer array on the focal plane of an internal telescope. Thus, all parallel rays re-emitted by all back horns in the same direction reach the bolometer array on the same pixel. The additional geometrical phase shifts create the interference pattern.

As has been shown in two dedicated papers, the real and imaginary part of all visibilities can be separated in an optimal way using time sequences of phase shift modulations.

Sensitivity Compared to an imager with the same number of input channels, the sensitivity of a bolometric interferometer is roughly worse by a factor 2, as can be seen on figure 2a. This is the price to pay for better or in any case different systematics. A detailed comparison has been published.
The US and European collaborations MBI and Brain have decided to join their efforts and build a large interferometer, QUBIC, aimed at measuring the $B$ modes of the CMB. A possible configuration would be as follows: 6 modules, each equipped with 144 input horns, ($\simeq 10000$ baselines) and 288 back horns in a compact square array and a focal plane of $\simeq 900$ Transition Edge Sensors. The primary beams would have a FWHM of $\sim 14^\circ$. To check for foreground contamination we would have 3 frequency channels: 90, 150 and 220 GHz, with 25% bandwidth. The cryogenics would involve a 4K pulse cooler for each module and a 100-300 mK dilution unit for the focal plane. The multipole range would be approximately $25 \leq \ell \leq 150$. Such an instrument would allow to reach $r \sim 0.01$ in one year of continuous operation at DOME C in Antarctica. The expected QUBIC sensitivity compared to some other ongoing or planned experiments is displayed in figure 26.

**Present status and tentative schedule:** Before merging into QUBIC in 2009, the Brain and MBI collaboration worked independently.

**The Brain collaboration** has launched two site testing (atmosphere, logistics) path finder campaigns at Dome C during the antarctic summers of 2006 and 2007, and a winter-over campaign is scheduled starting during the antarctic summer 2009

**The MBI collaboration** has built a four horn prototype interferometer, MBI-4, and taken data in 2007 and 2008. Fringes have have been observed with MBI-4.

**The QUBIC collaboration** intends to deploy a first module of QUBIC, possibly at DOME C, in 2011/2012. The goal is to complete the full QUBIC instrument by 2014 at the latest.

**References**

1. M. R Nolta et al. Five-year Wilkinson Microwave Anisotropy Probe observations: Angular power spectra. *The Astrophysical Journal Supplement*, 180:296, Feb 2009.
2. QUAD collaboration - M. L Brown et al. Improved measurements of the temperature and polarization of the CMB from QUAD. *arXiv*, 0906.1003, Jan 2009.
3. H. C. Chiang et al. Measurement of CMB polarization power spectra from two years of BICEP data. *arXiv*, 0906.1181, June 2009.
4. J. M. Kovac, E. M. Leitch, C. Pryke, J. E. Carlstrom, N. W. Halverson, and W. L. Holzapfel. Detection of polarization in the cosmic microwave background using DASI. *Nature*, 420:772, 2002.
5. P. Timbie et al. The einstein polarization interferometer for cosmology (EPIC) and the millimeter-wave bolometric interferometer (MBI). *New Astronomy Reviews*, 50(11-12):999–1008, Dec 2006.
6. R. Charlassier, J. -Ch. Hamilton, É Bréédle, A. Ghribi, J. Kaplan, M. Piat, and D. Prêle. An efficient phase-shifting scheme for bolometric additive interferometry. *A&A*, 497:963, 2009. arXiv:0806.0380.
7. P. Hyland, B. Follin, and E. F. Bunn. Phase shift sequences for an adding interferometer. *MNRAS*, 393:531–537, February 2009.
8. Hamilton, J.-C. and Charlassier, R. and Cressiot, C. and Kaplan, J. and Piat, M. and Rosset, C. Sensitivity of a bolometric interferometer to the cosmic microwave background power spectrum. *A&A*, 491:923, 2008.
(a) Sensitivity of a bolometric interferometer compared with an imager and an heterodyne interferometer. Thick curves: noise only; thin curves include cosmic variance with $r \sim 0.1$.

(b) QUBIC sensitivity compared with Ebex, Clover and Planck.

Figure 1: The Quasi Optical Interferometer

Figure 2: Sensitivity (sample+instr. noise) to Tensor to Scalar ratio