Measuring the Cosmic Microwave Background Radiation (CMBR) polarization with QUIET

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Summary. — A major goal of upcoming experiments measuring the Cosmic Microwave Background Radiation (CMBR) is to reveal the subtle signature of inflation in the polarization pattern which requires unprecedented sensitivity and control of systematics. Since the sensitivity of single receivers has reached fundamental limits future experiments will take advantage of large receiver arrays in order to significantly increase the sensitivity. Here we introduce the Q/U Imaging ExperimenT (QUIET) which will use HEMT-based receivers in chip packages at 90(40) GHz in the Atacama Desert. Data taking is planned for the beginning of 2008 with prototype arrays of 91(19) receivers, an expansion to 1000 receivers is foreseen. With the two frequencies and a careful choice of scan regions there is the promise of effectively dealing with foregrounds and reaching a sensitivity approaching $10^{-2}$ for the ratio of the tensor to scalar perturbations.

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1. – The status of polarization measurements

The intensity anisotropy pattern of the CMBR has already been measured to an extraordinary precision, which helped significantly to establish the current cosmological paradigm of a flat Universe with a period of inflation in its first moments and the existence of the so called 'Dark Energy' [1]. The polarization anisotropies of the CMBR are an order of magnitude smaller than the intensity anisotropies and provide partly complementary information. The polarization pattern is divided into two distinct components termed E- and B-modes which are scalar (pseudoscalar) fields. The E-modes originate from the dynamics due to the density inhomogeneities in the early universe. The B-modes are caused by lensing of the E-modes by the matter in the line of sight and by gravitational waves in the inflationary period in the very early universe and are expected to be at least one order of magnitude smaller than the E-modes. The status
The current measurements of the E-mode power spectrum are shown, the best fit cosmological model is overlaid.

Fig. 1. – Current measurements of the E-mode power spectrum are shown, the best fit cosmological model is overlaid.

of the E-mode measurements is summarized in Figure 1 from which it becomes obvious that the measurements are consistent with the theoretical model but not yet giving meaningful constraints. Of special importance and interest are the B-modes expected from gravitational waves in the inflationary epoch, since a detection would allow unique access to the very first moments of the Universe. The size of this contribution cannot be predicted by theory, but is parametrized by the tensor-to-scalar ratio, \( r \). Interesting inflationary energy scales of the order of the Grand Unifying Theory (GUT) scale of \( 10^{16} \) GeV correspond to an \( r \) of \( \sim 10^{-2} \), which would give rise to detectable signals of a few \( 10 \) nK. The tiny signal requires unprecedented sensitivity and control of systematics and foregrounds. By now receivers have reached sensitivities close to fundamental limits, so that the sensitivity will only be increased with the number of receivers.

2. – The QUIET Experiment

Recent developments at the Jet Propulsion Laboratory (JPL) led to the successful integration of the relevant components of a polarization-sensitive pseudo-correlation receiver at 90 and 40 GHz in a small chip package. This opened the way to future inexpensive mass production of large coherent receiver arrays and led to the formation of the Q/U Imaging Experiment (QUIET) collaboration. Experimental groups from 12 international institutes \(^1\) have joined the experiment and are working on the first prototype arrays which are planned for deployment for 2008 in Chile. A W-band (90 GHz) array of 91 receivers and a Q-band (40 GHz) array of 19 receivers will be deployed on new 1.4 m telescopes mounted on the existing platform of the Cosmic Background Imager (CBI) in the Atacama Desert at an altitude of 5080 m. It is foreseen to expand the arrays for a second phase of data taking (2010++) to arrays with 1000 receivers. For the expansion it is planned to mount more 1.4 m telescopes on the platform and relocate the 7m Crawford Hill Antenna from New Jersey to Chile to also access small angular scales.

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A sketch of one receiver and its components can be seen in Figure 2. The incoming radiation couples via a feedhorn to an Orthomode Transducer (OMT) and from that to the two input waveguides of the chip package. The chip contains a complete radiometer with High Electron Mobility Transistors (HEMTs) implemented as Monolithic Microwave Integrated Circuits (MMICs), phase shifters, hybrid couplers and diodes. The outputs of the four diodes of the radiometer provide measurements of the Stokes parameters Q and U and fast (4kHz) phase switching reduces the effects of the 1/f drifts of the amplifiers. For 10% of the receivers the OMT will be exchanged by a Magic Tee assembled in a way that the receivers measure temperature differences between neighboured feeds. The signals from the diodes are processed by a digital backend, sampling at 800 kHz with subsequent digital demodulation. This allows unique monitoring of high-frequency noise as well as the production of null-data sets with out-of-phase demodulation giving a valuable check of possible subtle systematics. The receiver arrays together with the feedhorns are assembled in large cryostats and the chip radiometers are kept at 20 K to ensure low noise from the HEMTs.

For a single element a bandwidth of 18(8) GHz and a noise temperature of 45 (20) K is aimed for at 90 (40) GHz, leading to expected sensitivities in Chile of 250 (160) $\mu$K$\sqrt{s}$ per element.

A prototype array of 7 elements with one OMT mounted on top of one chip radiometer is shown on the right hand side of Figure 2. The hexagonal prototype arrays of 91 and 19 elements are being assembled from similar subarrays. The OMTs were built in cost-effective split-block technique and the corrugated horn arrays were produced as platelet arrays where 100 plates with feed-hole patterns are mounted together by diffusion bonding.

The increase in sensitivity is a necessary but not yet sufficient condition for the successful measurement of B-modes as the signal of interest is smaller than the one from astrophysical foregrounds. The diffuse emission (synchrotron, dust) from our galaxy and extragalactic sources produces polarized signals of which the distribution and characteristics are not yet known to the precision required for a full removal. Multifrequency observations are mandatory to study the foreground behaviour and enable the clean extraction of the CMBR polarization anisotropies. QUIET in its observations will use two frequencies which frame the frequency where the contamination from foregrounds in polarization is expected to be minimal, around 70 GHz. Also, it will coordinate the patches to be observed with other polarization experiments to gain additional frequency infor-
Fields were selected in which minimal foreground contamination is expected. The B-modes from gravitational waves will suffer from yet another foreground (which in itself is of scientific interest) which is the lensing of E-modes into B-modes. Using the observations at small angular scales QUIET will be able to determine a lensing correction and, with that, be able to remove that contribution properly.

2.1. Comparison to other Experiments. – While currently ongoing CMBR experiments (BICEP, QUAD) are running with tens of receivers all future experiments are aiming for large arrays with several hundreds of receivers, all of them (but QUIET) using bolometers. Figure 3 visualizes the main parameters of QUIET in comparison to other ongoing and planned CMB experiments (no interferometers are shown). Some of the experiments have their main focus on observations of the Sunyaev Zel’dovich effect (2) (marked accordingly) and not polarization observations, but may still upgrade their detector arrays for polarization sensitivity. The parameters of the future experiments were taken from recent papers and talks about the various efforts, but since some of the technologies are not yet fully established and not all of the experiments are completely funded, it is clear that some of the parameters may change in the course of the production. Both the left and middle plot display beam size versus frequency for the different experiments while the size of the squares indicates different parameters of the experiments. Since some experiments (QUIET, Polarbear) are planned to operate in different phases, they have several squares at the same position. In the left panel the square area is proportional to the total sensitivity of the experiments, which means the smaller the square the more sensitive the experiment. As can be seen the next generation of CMB experiments will achieve the desired level of a few nK sensitivity.

(2) This effect takes advantage of the distortion of the CMBR spectrum from the scattering of the photons in galaxy clusters to study cluster physics and the evolution of the Universe.
Except for the space-based mission Planck and the balloon experiment SPIDER all
ground-based experiments focus their sensitivity on small fractions of the sky. In this way
it is possible to avoid regions of high foreground contamination and also gain a higher
signal-to-noise ratio in the maps, which helps characterizing foregrounds and systematics.
In order to compare the sensitivity on a map the middle figure displays squares which are
in size proportional to the sensitivity in $\mu$K/square degree. The right figure then shows
the corresponding white noise level for the different polarization experiments as a function
of multipole $l$ in comparison to the different polarization power spectra. As can be seen
the white noise power is for Planck a factor of 100 higher than for the ground-based
experiments, which means the noise on a QUIET map is about one order of magnitude
lower than on the maps expected from Planck. The main sensitivity of Planck for the
measurement of B-modes from gravitational waves comes from the reionization peak at
low multipoles of $l$ while the ground-based experiments like QUIET will constrain $r$
from measuring at the maximum of the gravitational wave signal at $l=100$, corresponding to
an angular scale of 2 degrees.

QUIET is complementary to other experiments in many different ways:

- QUIET is the only ground-based effort using coherent receivers and thus dealing
  with different systematics than the bolometric systems.

- It is the only experiment to measure the Stokes parameters Q and U simultaneously
  in one pixel which provides a good handle on several systematic effects.

- The array at 40 GHz complements the high frequencies of the bolometer arrays
  and thus allows to account for the contamination from synchrotron radiation which
dominates at low frequencies.

- By using different telescope sizes QUIET will be able to measure both large and
  small angular scales with the same receivers.

2.2. Science reach. — Already in phase I QUIET will be able to measure the E-
mode spectrum to an unprecedented precision. The expected E- and B-mode power
spectra for the phase II of QUIET with 1000 elements are shown in Figure 4. Only the
Table I. – Expected precision on cosmological parameters in percent. For $\Delta r$ the 5σ upper limit is presented

|     | A    | B    | C    | D    | E    |
|-----|------|------|------|------|------|
| $\Omega_B h^2$ | 6    | 4    | 1    | 1    | 1    |
| $\Omega_M h^2$ | 8    | 7    | 4    | 2    | 2    |
| $\Omega_\Lambda$ | 15   | 14   | 8    | 4    | 3    |
| $\tau$  | 34   | 23   | 14   | 7    | 6    |
| $n_s$  | 4    | 2    | 1    | 1    | 1    |
| $\Delta r$ | 1.35 | 0.021| 0.009| 0.042| 0.009|

A: WMAP  B: WMAP + QUIET Phase I  C: WMAP + QUIET Phase I and II
D: Planck  E: WMAP + QUIET Phase I and II

sensitivity of the W-band (90 GHz) arrays from the 1.4 m telescopes was used assuming that the Q-band sensitivity is used for foreground removal. The results were derived by including several real-data effects: A realistic observing strategy has been simulated and the method used in CAPMAP to remove ground-pickup by mode-removal in single scans has been applied [3, 4]. The simulations also incorporate effects from E-B leakage where the B-mode measurement is degraded due to the E-mode signal leakage into the B-mode spectrum due to the finite size of the observed patch [5]. Additionally, the errors include a marginalization over the power in adjacent $l$-bins and for B-modes also over E power.

The expected precision on cosmological parameters assuming initial adiabatic conditions is summarized in table I. Note that these estimates had been performed before the publication of WMAP results, but do agree well with the published WMAP parameter errors. From the table one can see that QUIET will improve the WMAP parameter errors to a size competitive to the expected precision of Planck. Adding the QUIET measurements to Planck will only bring a small improvement in most of the parameters. However, QUIET will already in phase I be able to constrain the tensor-to-scalar ratio together with Planck to a level significantly smaller than Planck is expected to. Adding QUIET phase II will bring the limit on $r$ down to the level of $10^{-2}$.

3. – Conclusion

We are entering an era where probing GUT scale physics is possible. A number of experiments are in preparation for seeing the signature of inflation in the B-modes. Of these QUIET is the only one using coherent detectors. A convincing discovery of the tiny signal will need consistent measurements from complementary techniques and observing frequencies. Already within the next years QUIET will reach the sensitivity to probe, together with other experiments, interesting levels of $r$.

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