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Measuring the Cosmic Microwave Background polarization with the QUaD experiment

M. Bowden[a*], A. N. Taylor[b], K. M. Ganga[c], P. A. R. Ade[a], J. J. Bock[e,f], G. Cahill[g], J. E. Carlstrom[h], S. E. Church[d], W. K. Gear[a], J. R. Hinderks[d], W. Hu[h], B. Keating[f], J. Kovac[f], A .E. Lange[f], E. M. Leitch[h], B. Maffei[a], O. Mallie[a], S. J. Melhuish[a], J. A. Murphy[g], G. Pisano[a], L. Piccirillo[a],C. Pryke[h], B. A. Rusholme[d], C. O'Sullivan[g], K. Thompson[d], M. Zemcov.[a]

[a] School of Physics and Astronomy, Cardiff University, PO Box 913, Cardiff, CF24 3YB;
[b] Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ;
[c] Infrared Processing and Analysis Center, California Institute of Technology, Pasadena, CA 91125;
[d] Department of Physics, Stanford University, Stanford, CA 94305;
[e] Jet Propulsion Labratory, 4800 Oak Grove Dr., Pasadena, CA 91109;
[f] Division of Physics, Math and Astronomy, California Institute of Technology, Pasadena, CA 91125 ;
[g] Experimental Physics Department, National University of Ireland, Maynooth, Co. Kildare, Ireland;
[h] Department of Astronomy and Astrophysics, Department of Physics, Enrico Fermi Lab, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637

ABSTRACT

We look at anticipated science results achievable with QUaD, a ground-based experiment to measure the polarization of the CMB from the South Pole, and describe the features that will enable it to measure this weak polarized signal. We show that QUaD can make a high resolution measurement of the polarization signals on small angular scales. This will lead to tighter constraints on the key cosmological parameters and could also put new limits on the inflationary model.

Keywords: polarization, cosmology, cosmic microwave background, sub-mm telescope

1. INTRODUCTION

The Cosmic Microwave Background (CMB) is a background of radiation originating from a time in the early Universe before the formation of large scale structure . The tiny inhomogeneities in the Universe at this epoch, the seeds for structure formation, produce anisotropies in the radiation field detected today. By measuring the level of these anisotropies on different angular scales it has been possible to use the CMB to test the standard model of cosmology and constrain the parameters with-in this theory. Over the last decade successive generations of experiments have measured the CMB temperature field, culminating in the results of the *WMAP* satellite.[1] By combining these measurements with the data from recent with ground-based experiments measuring the anisotropies on small angular scales, the community is now rapidly approaching the limit of what the CMB temperature field alone can determine about the early Universe. However, the CMB anisotropies are also expected to be linearly polarized. The level of this polarization signal is at least an order of magnitude below the temperature signal and so provides a huge experimental challenge. However, the CMB polarization has recently been detected by the DASI experiment[2] and a new generation of experiments is now pushing towards a sensitive high resolution measurement of the polarization field.

In this paper we describe a ground-based CMB polarization experiment QUaD (QUEST and DASI). This new experiment will install the QUEST (Q and U Extra-galactic Survey Telescope), a high resolution bolometric polarimeter, on the mount of the successful DASI (Degree Angular Scale Interferometer) instrument. QUaD is scheduled to begin taking data in early 2005 and will run for two austral winters. In Section 2 we discuss the motivation for measuring CMB polarization and in Section 3 we describe how QUaD will measure the polarization field from the ground. We discuss the effect of polarized astrophysical foregrounds on the experiment in Section 4 and then finally in Section 5 we go on to predict the expected science results of QUaD.

* E-mail: Melanie.Bowden@astro.cf.ac.uk

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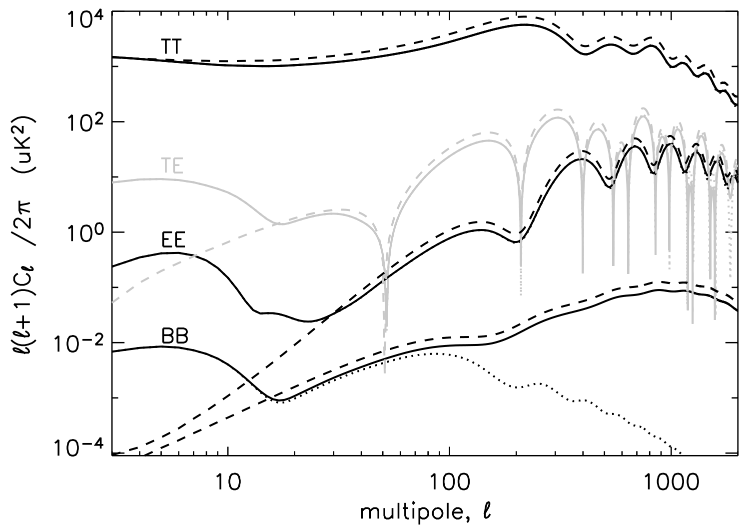

Figure 1. CMB temperature and polarization power spectra. The dashed lines are for a model with no re-ionisation while the dotted lines are for a model with no gravitational lensing. The solid lines include both of theses effects. These spectra have been generated using the CMBFAST code (version 4.2).[5] The lighter line is the correlation between the E-mode and temperature fields.

2. MOTIVATION FOR MEASURING CMB POLARIZATION

The temperature and polarization fields are usually quantified in terms of their angular power spectra (see Fig. 1). These give the size of the anisotropies in the CMB on different angular scales. The tensor polarization field is decomposed into two separate modes, E and B[3].[4] This is similar to the way a vector field is decomposed into gradient-free and curl-free components to give electric and magnetic fields in electromagnetism. Measuring different parts of these polarization power spectra can tell us about different aspects of the physics generating the CMB polarization.

2.1. E-mode acoustic peaks

The CMB is produced at the epoch of recombination. Before this time the Universe can be thought of as a plasma of photons, protons and electrons. The photons are coupled to the electrons electromagnetically and the opposing gravitational pull of over-densities in the underlying matter distribution (caused by gravitational collapse of matter into the intial inhomogeneites) and photon pressure make the density and velocity of this fluid oscillate. When the Universe is cool enough for the protons and electrons to combine to form neutral hydrogen the number of free electrons will drop dramatically so the photons are no longer coupled to the matter. The oscillations in the plasma can be thought of in terms of waves or modes with different wavelengths. At decoupling each mode will be a different phase of its oscillation. This creates a series of acoustic peaks in the CMB temperature power spectrum. There are three distinct effects contributing to the CMB anisotropies: the gravitational redshift a photon experiences when it escapes from an over-density or under-density in the matter distribution, the fluctuations in the photon density at recombination and fluctuations in the velocity of the photons creating a Doppler shift.

The photons are polarized when they scatter off electrons (Thompson scattering). However, before recombination the flux of photons around an electron will be isotropic due to the high electron density. This makes Thompson scattering very frequent so that only photons from close by (and so with the same temperature) will be able to reach the electron. The polarization generated in different directions will cancel out and there will be no net polarization. During recombination photons from further away can reach an electron as the electron density is lower. The inhomogeneities in the early Universe will create an anisotropic radiation field around the electron enabling a net polarization to be produced. In particular if the radiation field has a quadrupole moment the photons will be polarized. The polarization spectra will contain a similar series of acoustic peaks to the temperature spectrum. However, for the temperature spectrum the dominant factor is the density of the photons at recombination, where-as for polarization, the dominant effect is the the Doppler shift due to the velocity of the photons. This means the acoustic peaks will be at different places in the polarization and temperature power spectrum and are generated by subtly different physics.

The measurement of the acoustic peaks in the E-mode spectrum in the predicted positions would therefore provide an important cross-check for the theory used to predict the CMB anisotropies. It will also give new information that can be used to tighten the constraints on the cosmological parameters which influence these acoustic peaks.

2.2. Gravitational wave signal

The inhomogeneities in the early Universe can be split into two distinct types, scalar perturbations and tensor (gravitational wave) perturbations. Scalars will only produce E-mode polarization, where-as tensors can produce both E-modes and B-modes. A detection of the primordial B-mode signal would therefore provide indirect evidence for the existence of large-scale gravitational waves. This would be a huge break though in our understanding of cosmology. The mechanism for producing the initial perturbations in the Universe in still unclear and different theories give different predictions for the level of the tensor perturbations. Inparticular, the measurement of a gravitational wave background at the predicted level is one of the only ways of testing the currently favoured inflationary model for generating the initial perturbations.[6] The B-mode polarization signal will therefore allow us to look further back into the history of the Universe than is possible with any other observation. The important parameter to constrain is the amplitude of this signal as this will determine the ratio of tensor perturbations to scalar perturbations, r.

2.3. Gravitational lensing signal

The anisotropies generated at recombination are called primary anisotropies. The CMB will also contain imprints of processes occurring between recombination and the present day which create secondary anisotropies. For QUaD, the most important of this secondary effects is weak lensing due to the deflection of the CMB photons by the gravitational potential of large scale structure. For the temperature and E-mode spectra, this effect results in a smearing of the acoustic peaks on small angular scales, but the change to the spectra is very small (as shown in Fig. 1). However, lensing will convert a small fraction of the E-mode polarization into B-modes generating a scalar contribution to the B-mode spectrum. This scalar signal will contaminate the gravitational wave signal on small angular scales and needs to be measured precisely in order that it can be removed from the primordial signal.

The lensing signal itself also contains useful information about large-scale structure. This can be used to constrain other cosmological parameters such as the neutrino mass,[7] since this will add to the mass-energy of the universe, altering its expansion history, and suppressing small scale power in the matter power spectrum due to free streaming. The lensing signal will also make the CMB sensitive to the equation of state of the universe as again this will affect the expansion history.

2.4. Re-ionization bump

The CMB is polarized by scattering from free electrons. This can not only occur during recombination, but also at later times when the Universe becomes re-ionized due the formation of the first stars. This generates a polarization signal on large angular scales leading to a bump in the E-mode and B-mode power spectra occurring for $\ell < 30$. By measuring the size of this re-ionisation bump is it possible to determine when the first stars were formed which will provide a huge insight into the evolution of the Universe at a much later epoch than that probed by the primary anisotropies.

3. MEASURING POLARIZATION WITH QUaD

In this Section we discuss the key features that enable QUaD to measure this weak polarized signal. A more detailed discussion of the QUaD instrument is given in Ref. 8. Polarized radiation is characterized by both the polarized intensity, I_p and the angle of polarization χ. In practice, these parameters cannot be measured directly. Instead we measure the two Stokes parameters Q and U, where:

$$Q = I_p \cos 2\chi \quad U = I_p \sin 2\chi \tag{1}$$

In QUaD, the polarized signal is measured by differencing the output of two polarization sensitive bolometers orientated at right angles to each other in each feed. Unpolarized radiation can be decomposed into two equal completely polarized components in orthogonal directions; each PSB is only sensitive to one of these components. Differencing the output of the two bolometers in each feed will therefore leave only the polarized part of the radiation, where the difference, d, is proportional to a linear combination of Q and U:

$$d \propto Q\cos(2\alpha) + U\sin(2\alpha)) \tag{2}$$

where α is the angle between the sky co-ordinate system and the detector co-ordinate system. This means that to measure both Q and U it is necessary to observe each pixel in at least two different orientations. On QUaD this is achieved using rows of feeds along which the PSBs are orientated in different directions. In a single scan each pixel will therefore be observed at different orientations. QUaD also uses a half wave-plate which can be stepped at the end of each scan to rotate the co-ordinate system.

The main problem in observing the CMB from the ground is the atmosphere. Fig. 2 shows a model of the sub-mm transmission of the atmosphere from the ground. The absorption lines are due to water vapour and oxygen. QUaD will look in two frequency bands centred around 100 GHz and 150 GHz which correspond to the regions of the spectrum will high transmission. The atmospheric loading is lower at high dry sites. The South Pole in therefore ideal as it has a low level of water vapour[9] and a low air pressure giving a relatively high effective altitude. However, even at this site, the overall detector sensitivity will be considerabely lower than for a satellite mission. It is therefore better to integrate deeply on a relatively small patch of sky to achieve a high signal to noise ratio in each pixel. The sensitivity of the two QUaD bands is given in Table. 1.

In addition to reducing the instrument sensitivity, the fluctuations in the atmosphere will produce high levels of low frequency noise ($1/f$ noise) in the data stream. In temperature experiments, the effect of atmospheric fluctuations is reduced by chopping the telescope across the sky. For QUaD this is not necessary as differencing the output of the two bolometers in each feed should completley remove any unpolarized radiation. The atmosphere is expected to be unpolarized and so this process will remove nearly all of this common mode signal. It is possible that the two PSBs will have slightly different properities, the important factors are the cross polar leakage and gain. The cross-polar leakage is the fraction of radiation from the 'wrong' component absorbed by each PSB. If this is the same in both bolometers it will just reduce the polarization sensitivity of the feed. However mismatches in the cross polar leakage and the gains of each device will create a common mode leakage into the differenced signal. This problem can be removed if gains and leakages can be measured precisely so that it is possible to weight each signal by the correct amount to remove the common mode signal. This means each device must be well calibrated to determine its response to both total power and polarized signals.

Another problem is that the instrument itself may polarize initially unpolarized radiation as it passes through the telescope optics. This effect has been reduced on QUaD by making the telescope design as symmetric as possible, however it may still be a problem for the feeds on the edge of the focal plane. This instrumental polarization signal will be a small percentage of the total power from atmospheric fluctuations ($\approx 1\%$ at edge of field of view), but is still large compared to the small cosmological signal being measured. QUaD has two levels of modulation which can be used to combat these problems. The telescope can rotate around its optical axis, this will rotate the signal from the sky, but not the instrumental polarization signal and so can be used to characterize the instrumental polarization. Stepping the waveplate will also change the polarization of the radiation so can be used to modulate any polarized signals generated in the optics below the waveplate or during detection.

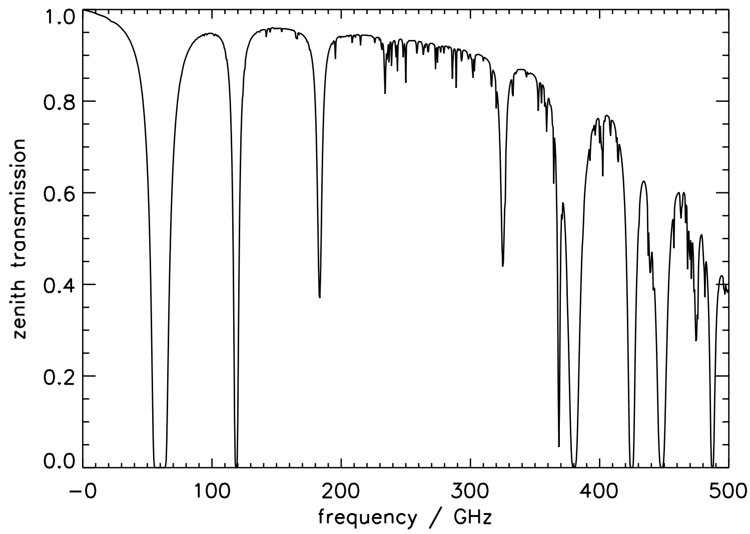

Figure 2. Atmospheric transmission from the South Pole. The absorption lines are due to water vapour (183, 325 and 380 GHz) and oxygen molecules (56,119 and 368 GHz).[10] This model was generated using the AT atmospheric emission program[11] with 0.32 pvw mm water vapour and a base pressure of 657 mbar.

These residual atmospheric fluctuations could still be large at low frequencies and so some high-pass filtering of the timestream may be needed to remove them. This limits the maximum time over which two timestream data points can be compared, as any changes to the CMB signal on long timescales will be filtered out. In turn, this will limit the maximum angular scale on the sky across which different pixels can be compared and so set a minimum value to the range of multipoles across which the polarization power spectra can be measured. This limit will depend on the stability of the atmosphere and on how fast the instrument can scan across the sky. This gives a limit on the minimum multipole that can be measured of $25 \leq \ell \leq 100$,[8] depending on the stability of the atmosphere during the observations. The upper limit on the multipole range which can be covered is determined by the beam size, giving a maximum of $\ell = 2500$.

Table 1. Expected QUaD instrument parameters

Frequency (GHz)	100	150
Number of bolometers	24	38
Angular resolution (arcmin)	6.3	4.2
NET per bolometer (μK$s^{1/2}$)	270	300

4. FOREGROUNDS

The signal from the sky will not only contain a signal from the CMB, but will also contain the radiation from a number of astrophysical foregrounds. In the QUaD frequency bands, the dominant foregrounds will be due to synchrotron emission, vibrating dust and radio point sources. The polarization level in these foregrounds is still debatable as no sensitive polarized measurements have been made at the frequency and resolution required for QUaD. However, this situation should soon change as other experiments will provide polarized maps at CMB frequencies (e.g. Boomerang,[12] WMAP,[13] ARCHEOPS[14]) in the near future. Fig. 3 (left) shows an estimate of the power spectrum of each of these polarized foregrounds across the whole sky. These are based on the "middle of the road" foreground model given in Ref. 15, slightly modified to take into account recent observations[2].[13] The synchrotron radiation dominates the foregrounds at 100 GHz whereas at 150 GHz both vibrating dust and

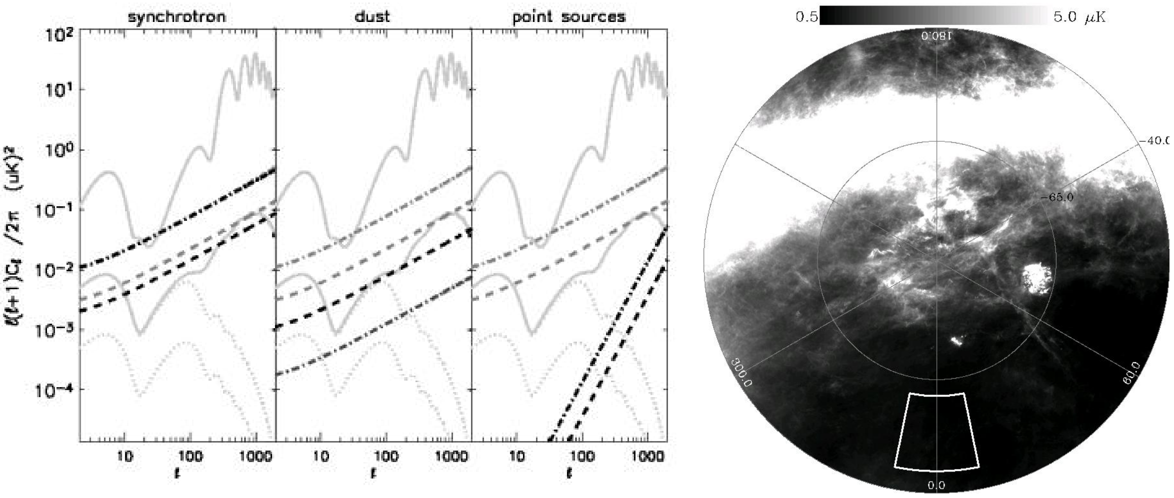

Figure 3. Left: Estimated amplitude of polarized foregrounds compared to the level of the CMB polarization signals (solid light grey lines). The black lines show the foreground models at 100 GHz (dash-dot) and at 150 GHz (dash). For comparison, the total foreground level is also shown on each plot (dark grey) at the same two frequencies.
Right: Equal area-zenithal projection showing the combined foreground levels for dust and synchrotron at 150 GHz in the region of sky accessible to QUaD. The South Pole is at the centre of the plot and a declination of $-45°$ around the perimeter. The right ascension increases anti-clockwise from $0°$ at the bottom. A possible observing region for QUaD with low foreground contamination is shown by the solid lined box.

synchroton radiation are important. The point sources only contribute at very high multipoles. For most of the multipole range of interest for QUaD the EE spectrum dominates over the foregrounds. However, for the smaller BB signal the total contamination is larger than the signal of interest. Foregrounds are therefore likely to be a much bigger problem for B-mode measurements than for the E-modes.

The CMB signal is independent of the wavelength of observation, but the foreground signal is expected to be frequency dependent. It is therefore possible to reduce the total foreground contamination by optimally combining the signal from different frequency channels. This the reason for including both the 100 GHz and 150 GHz bands on QUaD. It may also be possible to use the multi-frequency information to actually remove some of the foreground contamination from the signal.

QUaD will only observe a small region of sky, so this means that an area with low foreground contamination can be targeted. Fig. 3 (right) shows the region of the sky that will be accessible to QUaD from the South Pole and the estimated foreground contamination across this area from dust[16] and synchroton.[17] A possible observing region for QUaD will a low mean foreground amplitude is also shown.

5. PREDICTED SCIENCE RESULTS

In this section we look at the science results achievable with QUaD. This is based on Ref. 18. In all of the calculations we use CMBFAST to generate the model CMB power spectra with the cosmological parameters set to the best fit WMAP values.[19]

5.1. POWER SPECTRUM MEASUREMENTS

The sensitivity to which QUaD will be able to measure the polarization power spectra over different angular scales will depend not only on the raw sensitivity of the instrument, but also on the observing strategy used. For each band in ℓ-space, the error in the measurement of the power spectrum will depend on two factors. The first is the noise per pixel in the map used to construct the power spectrum. If a small area of sky in chosen, this will be low for a fixed observation time, as more time can be spent integrating on each pixel. The second factor is

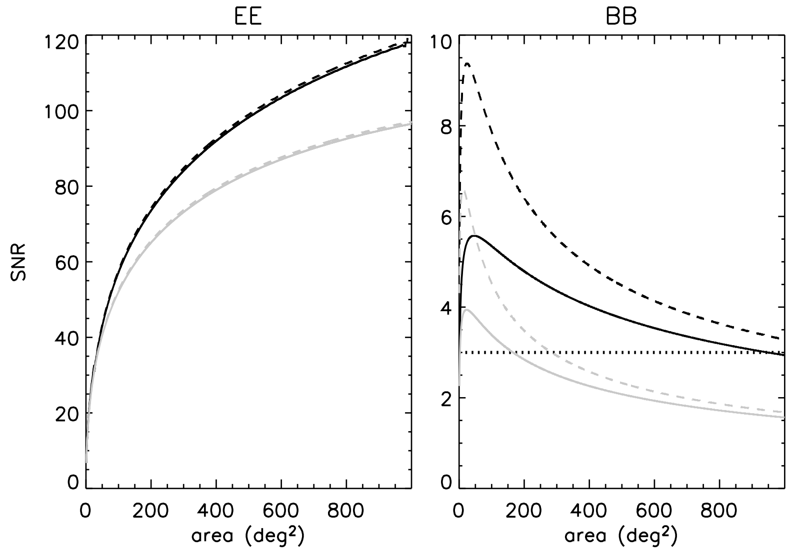

Figure 4. Variation of SNR with survey area for the E-mode (left) and B-mode (right) power spectra for a one year (light) and two year (dark) integration time. The results are shown with (solid lines) and without (dashed lines) foreground contamination.

the number of different measurements that can be made on the angular scales probed by each multipole band. This gives a sample variance which will be lower if a larger area is covered as there will be more measurements for each multipole. The combination of these two conflicting factors gives an error on each band of the power spectrum which depends on the survey area.

The optimal area each power spectrum can be estimated by finding the area giving the highest signal to noise ratio, SNR, for a measurement of the whole power spectrum:

$$\mathrm{SNR} = \sqrt{\sum_{\ell} \left(\frac{\mathrm{C}_{\ell}}{\Delta \mathrm{C}_{\ell}} \right)^2}. \tag{3}$$

where the summation is over the different bands which can be measured. For QUaD, the optimal area is found to be different for the E-mode and B-mode power spectra.[18] For the E-modes the measurement is sample-variance-limited and so a large area is favoured. For the B-modes, the signal is much weaker, and so the survey is detector noise limited, favouring a smaller area. A possible solution to this conflict is to cover an intermediate sized patch of 300 deg^2, as shown in Fig. 4. The calculation has been made both without foregrounds and by including the predicted foreground levels of Section 4 as an extra source of noise. As expected, the foregrounds do not alter the result for the E-mode spectrum, but the SNR for the B-mode signal is increased significantly if the foreground contamination can be removed.

The expected measurement of the polarization power spectra with this survey design is shown in Fig. 5. The error bars include an estimate of the foreground noise which will remain after the signal in the two frequency bands has been optimally combined. This is done by weighting the measurements for each multipole so that the frequency with the lowest foreground contamination has the most weight. QUaD will be able to make a high resolution measurement of the acoustic peaks in the E-mode power spectrum and can also detect the gravitational lensing contribution to the B-mode spectrum. If the gravitational wave contribution to the B-mode spectra is high (a tensor to scalar ratio higher than 0.14) and astrophysical foreground can be removed is could be possible for QUaD to detect the effect of the gravitational wave signal. However, even without this QUaD will still provide a useful upper limit to size of this signal.

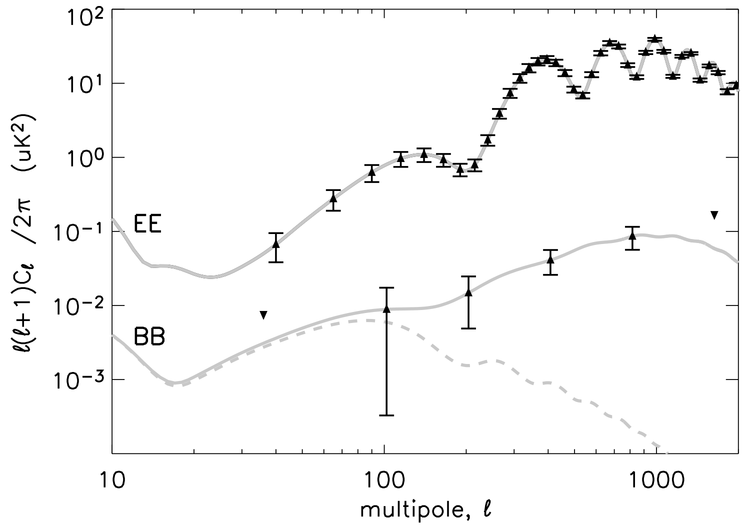

Figure 5. Predicted measurements of the polarization power achievable with QUaD. Error bars show detections above the one-sigma level and free symbols show upper limits. Errors include the estimated contribution from foregrounds.

5.2. CONSTRAINTS ON COSMOLOGICAL PARAMETERS

The data obtained by QUaD will enable an increase in the precision with which cosmological parameters can be measured by the CMB. Fig. 7 shows how well QUaD can measure the key cosmological parameters compared to the satellite mission *WMAP*. These estimates include the minimum variance weighted foreground noise used in the power spectrum estimates. For most parameters, QUaD will give an improvement of at least a factor of two over WMAP. This is mainly due the high resolution measurement of the acoustic peaks in the E-mode spectrum. The only parameter estimates which QUaD cannot improve significantly are the amplitude of the primordial perturbations, A, and the optical depth to the last scattering surface, τ. These parameters are degenerate on all but the largest angular scales and so a satellite mission which can measure the low multipoles in the polarization power spectra is needed to break this degeneracy. The improved upper limit on the gravitational wave B-mode signal increases the precision on the tensor to scalar ratio, r. This precision would be improved by another factor of 3 if it is possible to remove foreground contamination as shown in Fig. 6.

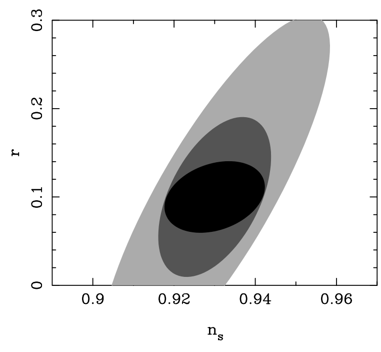

Figure 6. Predicted constraints on inflationary parameters (tensor to scalar ratio, r, and tilt of the scalar power spectrum, n_s) from QUaD. The outer contour shows constraints possible with the 4 yr WMAP data and the middle contour shows the increase in precision by combining QUaD and WMAP results. The inner contour shows the detection possible if foreground contamination can be completely removed.

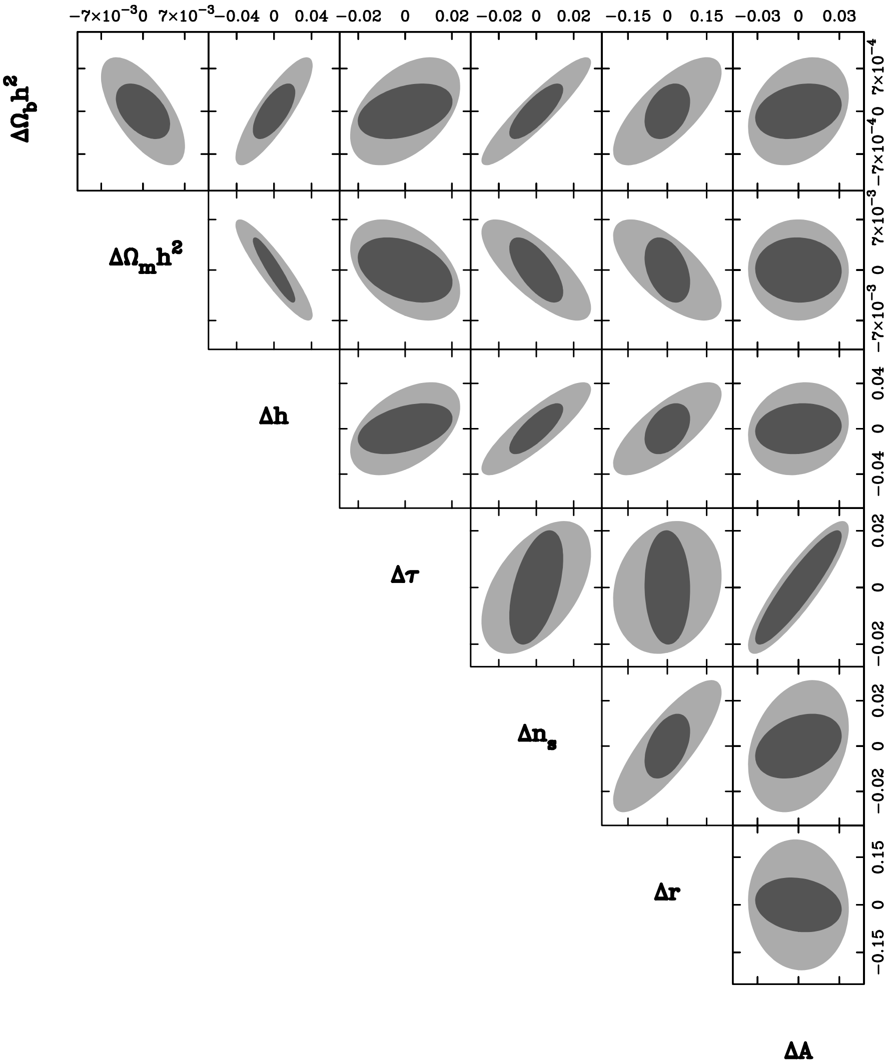

Figure 7. Marginalized relative parameter error constraints ($\Delta \ln L = -1/2$) anticipated for four-year *WMAP* results only (dark) and four-year *WMAP* combined with QUaD (light) for $r = 0.01$ with foregrounds. The projections of the ellipse onto the two axes give the standard errors on each parameter. For a two-parameter 68 per cent confidence region, the ellipses should be scaled by a factor 1.5. The cosmological parameters are the energy density of baryons (Ω_b), the energy density of matter (Ω_b), Hubble constant in units of 100 $\mathrm{kms^{-1}Mpc^{-1}}$ (h), optical depth to surface of last scattering (τ), tilt of the scalar power spectrum (n_s), tensor to scalar ratio (r) and the amplitude of the power spectrum (A).

6. CONCLUSION

By making a deep observation of a relatively small patch of sky QUaD will be able to measure the small scale polarization anisotropy in the CMB with a similar sensitivity to the current generation of satellite experiments. The effects of atmospheric fluctuations are greatly reduced in a polarization experiment as the atmospheric is not linearly polarized. However, systematic effects may contaminate the data with a small fraction of this unpolarized signal. This will reduce the coverage of the polarization power spectra on large angular scales. We have shown that QUaD can make a high resolution measurement of the acoustic peaks in the E-mode power spectrum leading to a increase in precision in the measurement on most of the main cosmological parameters of a factor of two over that obtainable with the *WMAP* satellite. QUaD could also make the first detection of the B-mode signal on small scales from gravitational lensing and will lower upper limits on the amplitude of the gravitational wave B-mode signal. This will lead to tighter constraints on the tensor to scalar ratio, especially if it is possible to reduce the expected level of foreground contamination. QUaD will therefore make a valuable contribution towards constraining the cosmological model.

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