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QUEST: A Ground-Based mm-Wave Telescope for CMB Polarization Studies

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Abstract

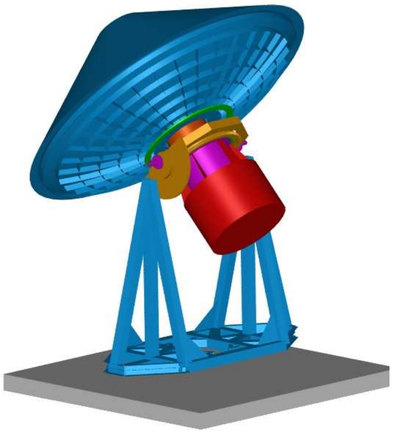
The cosmic microwave background (CMB) is predicted to exhibit two forms of polarization structure, each encoding important cosmological information. Advances in telescope design and detector sensitivity will allow these phenomena to be mapped in the next few years. QUEST (Q and U Extra-galactic Sub-mm Telescope) is a new experiment, due to start observing in early 2004, dedicated to CMB polarization studies. The telescope is a ground-based, 2.64-m Cassegrain which will be equipped with an array of 31 polarization-sensitive bolometer pairs split between 100 and 150 GHz observation. The instrument includes several features that will be critical for the removal of systematic effects such as a rotating achromatic waveplate and axisymmetric rotatable optics. QUEST is designed to produce a high signal-to-noise measurement of at the EE signal and the lensed BB polarization structure given current theoretical predictions.

1.1 Introduction

The cosmic microwave background radiation is the relic thermal radiation from the creation of the Universe, released about 300 000 years after the Big Bang. The background has three observable properties, which in order of declining signal strength are; frequency spectrum, spatial brightness anisotropies and spatial linear-polarization anisotropies. The polarization structure is commonly split into two separate forms as the two linear StokeŠs parameters Q and U combine on the spherical sky in a tensor, which, by analogy with electromagnetism, is usually decomposed into the gradient E, and a curl B term. The presence of E-mode polarization has only recently been confirmed at the expected signal level of a few μK (Kovacs et al., 2002).

The E and B modes each encode different information about the Universe. The E power spectrum is dominated by contribution from Thomson scattering of the emission from local thermal quadrupoles on the last scattering surface, and is thus almost completely determined by the temperature power spectrum. The differences however are important in breaking degeneracies and increasing the precision by which cosmological parameters can be recovered.

Excitingly B mode polarization can be caused by primordial gravitational waves which would allow the energy-scale of inflation to be reconstructed. The level of this signal is not yet constrained, though at best is at least an order of magnitude beneath that of the E-modes. Yet more seriously the gravitational lensing of the E-mode signal by foreground structure can also produce a B signal, revealing the power spectrum of the intervening dark matter



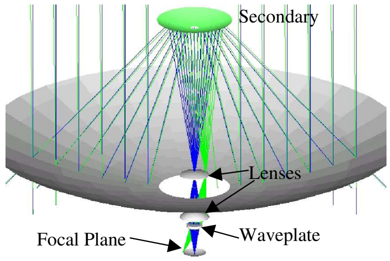


Fig. 1.1. Left: Schematic of the QUEST telescope. The telescope is a typical alt-az with an extra rotation about the optical axis using a bearing housed in the section color-coded gold. Right: Layout of the QUEST optical system

Table 1.1. *The specification of the QUEST telescope. The quoted sensitivity includes the amplifier, photon-shot and wave-noise terms, and 1mm PWV at the Chajnantor site.*

Telescope			
	Size of primary mirror (m)	2.64	
	Total field of view (deg)	1.5	
	Pointing accuracy (arcmin, reconstructed)	0.1	
Receiver			
	Frequency band (GHz)	100	150
	Number of feeds (two bolometers per feed)	12	19
	Angular resolution (arcmin)	6.3	4.2
	Bandwidth (percent)	25	25
	End-to-end optical efficiency	0.4	0.4
	System temperature inc. atmosphere (K)	26	26
	NET per bolometer (μK s$^{-\frac{1}{2}}$)	300	350

but also contaminating recovery of any gravitational-wave signal. This lensing signal peaks at around ℓ of 1000 and needs to be quantified before a detection of the gravitational-wave B-mode signal can be claimed.

1.2 The QUEST Telescope

QUEST is a purpose-built telescope dedicated to CMB polarization, scheduled to be on site in late 2003 and on air at the beginning of 2004. The telescope itself is Cassegrain (fig. 1.1) and is equipped with a large-format polarization-sensitive bolometer (PSB) array. The overall specification and sensitivity of the telescope are shown in Table 1.1. The impor-

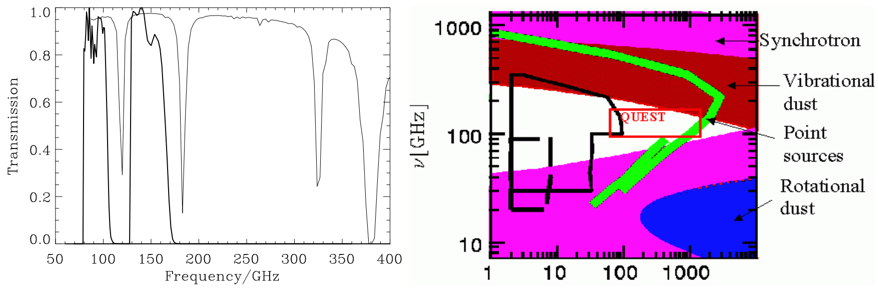


Fig. 1.2. Left: Superposition of the QUEST observing bands over a predicted spectrum of atmospheric transmission from Chajnantor for a typical 1mm PWV. Right: Polarized foregrounds to the E-mode polarization, from Tegmark et al., 2000. The colored regions predict a foreground level higher than the CMB signal. The black box regions show where the MAP and PLANCK detector noise lie under the CMB signal.

tant points of note are the large field of view, the large number of pixels, the instantaneous sensitivity and fine angular resolution which will permit fast mapping of large areas of sky to high sensitivity and detail.

Just as important as raw sensitivity however are the details of the design to minimize systematics which can easily dominate at such signal levels. QUEST also incorporates, and will be operated, with many layers of differencing to further reduce such contamination including; simultaneous observation at two frequencies for spectral discrimination; rotating optics to characterize the instrumental polarization; modulation of the incoming radiation by a continuously rotating waveplate; differential detection by orthogonal polarization-sensitive bolometers within the same feedhorn; AC biasing of the bolometers to remove $1/f$ noise, and an heavily cross-linked scan strategy.

1.2.1 Observing Frequency and Site

QUEST will simultaneously observe in two bands centered close to 100 and 150 GHz that span atmospheric windows and the expected minimum in the foreground contribution (fig. 1.2). The telescope will be sited at 5000-m on the Chajnantor plateau in Chile. This is one of the premier millimeter observing sites in the world (Peterson et al., 2002) and is home to the Cosmic Background Imager (Padin et al., 2002) and the future ALMA array. Besides its excellent opacity Chile also offers good sky coverage, variable parallactic angle, and access to calibrators such as the planets. The latter is vital for the beam calibration necessary for the accurate recovery of high-l structure. The QUEST telescope was chosen to have a rotatable, axisymmetric Cassegrain design for its low polarization systematics and to enable its polarization properties to be quantified. Cassegrain designs have been used before in CMB polarization experiments (COMPASS, Piccirillo et al., 2001); their optimization for low sidelobes/spillover is also well understood and can be dealt with by such features as under-illumination, baffling, a Lyot stop, and a small aperture in the center of the primary (which will also be used to inject a calibration signal directly into the optical system for regular gain calibration). The QUEST secondary will be supported by a foam cone rather than discrete supports which would break the axial symmetry.

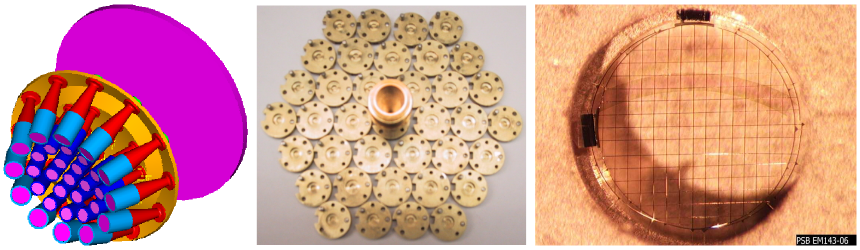


Fig. 1.3. Left: The QUEST focal plane layout concept. The 19x150 GHz channels are the in the center surrounded by the 12x100 GHz feeds. Center: The PSB casings after manufacture. Right: A PSB pair.

1.2.2 Waveplate

A key part of QUEST is a rotating cryogenic half-waveplate. The primary function of this waveplate is to rotate the beams of the detectors on the sky and enable the measurement of both Q and U. As a secondary function however it also allows slow drifting signals, such as $1/f$ noise in the detectors, to be filtered from the time ordered data early in the analysis process. Critically, by symmetry, the polarization modulation occurs at four times the rotation of the actual waveplate material, allowing the removal of synchronous noise, a problem common to scanned or chopped experiments (e.g. the striping in the BOOMERANG maps reported in Netterfield et al., 2002).

The waveplate itself will be constructed from three layers of sapphire to achieve the required broad-band spectral transmission; the entire assembly, including anti-reflection coating will be just 15-mm thick. The waveplate will be embedded in a direct drive motor to eliminate belts or cogged-drive mechanism that could lead to reduced reliability and microphonics in the detectors. The motor itself is a zero-cogging, linearly-commutated brushless motor capable of high velocity stability.

1.2.3 QUEST Receiver

The QUEST receiver consists of 31 corrugated profiled feeds and 31 pairs of polarization sensitive bolometers, currently being manufactured in JPL/Caltech. The 3.25λ feeds have been designed to provide low sidelobes and cross polarization. Each bolometer consists of a NTD Ge thermistor mounted on a grid substrate, which detects only a single direction of linear polarization. Two orthogonally-orientated bolometers can thus be mounted at the back of each feedhorn, allowing a differential sky measurement to be made within the same beam (Jones et al., 2000). This avoids systematics that could arise by trying to measure polarization with separate feed optics. Differencing also produces a output directly proportional to either StokeŠs Q or U, depending on co-ordinate system and position of the waveplate. The readout electronics are AC-biased/cold JFET buffered/lock-in chain similar to BOLOCAM.

1.3 Observational Strategy and Predicted Results

QUEST is one of the most sensitive CMB polarization experiments due to come online in the next few years and will produce high signal-to-noise measurements of the peak region of E power spectrum. The high angular resolution of QUEST means that it will

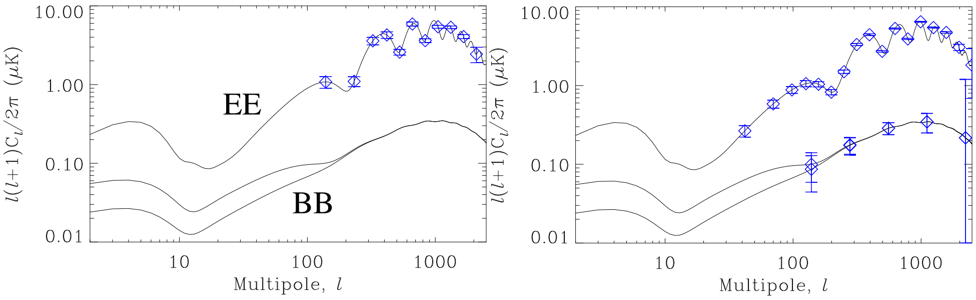


Fig. 1.4. Expected results from QUEST. The *BB* power spectrum in both panels is the combination of the lensing and gravitational-wave components. The two *BB* spectra at $\ell < 200$ represent different inflaton potentials. The power spectra were calculated using CMBFAST (Seljak & Zaldarriaga 1996). Left: QUEST 500 sq. deg. survey after 6 months. Right: QUEST after two years shallow integration on 500 sq. deg. and deep integration on 30 sq. deg.

also measure the *B* signal due to lensing, which is essential before any measurement of the gravitational-wave signal can be made. *E* and *B*-mode measurements however both demand very different survey sizes due to their unequal brightness, so QUEST will observe in two modes optimized for the sky coverage from Chile and appropriately weighted in integration time. The fields will be quickly scanned in constant elevation to avoid changes in air mass, and will be distributed so as to leverage the rotation of the sky apparent from Chile to achieve an interlinked and redundant scan pattern. The expected power spectrum recovery for a total of two years of such observation is shown in fig. 1.4.

1.4 Acknowledgements

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