The QUIET experiment

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The Q/U Imaging ExperimenT (QUIET) is a ground-based radiometer array designed to measure the polarization of the cosmic microwave background (CMB). In Phase I, it measures the CMB polarization at angular scales of $25 \lesssim \ell \lesssim 1000$ in the frequencies 95 GHz and 44 GHz. QUIET employs a unique radiometer technology, 'radiometer on chip,' which integrates monolithic microwave integrated circuits (MMIC) of high electron mobility transistor (HEMT) amplifiers into a receiver module. This technology enables us to assemble the world's largest polarimeter array using the HEMT amplifier devices. In these proceedings, we review the QUIET instrument and report on the status of Phase I, observing since October 2008. We also mention prospects for QUIET Phase II.

1 Introduction

The anisotropy of the CMB polarization has yet to be fully explored. It can be decomposed into a curl-free component, or E-modes, and divergence-free component, or B-modes. The E-modes, since their first detection[1], have been measured and characterized by various experiments and are consistent with the predictions of the standard ΛCDM model. The B-modes, on the other hand, remain entirely elusive. While the E-modes are sensitive to the scalar density fluctuations in the early Universe, the B-modes would be evidence primordial gravitational waves, which are sourced only by the inflation. The detection of B-modes in CMB polarization is not only the smoking gun of inflation, but also a unique opportunity to measure the energy scale of the inflationary potential[2,3].

QUIET Phase I and Phase II are among current and next generation experiments aiming for the detection of the inflationary B-modes. Deployed on the Chajnantor plateau in Chile, QUIET Phase-I started its observation with its 44 GHz receiver in October 2008. After nine months of successful observation, we deployed the 95 GHz receiver replacing the 44 GHz one and the observation resumed in August 2009. Among numerous CMB experiments, QUIET stands out with its unique receiver technology. Here we describe the instrumentation, the site, and observation strategy, as well as the current status of the analysis of 44 GHz receiver data.

2 Instrument

We measure the CMB polarization power spectra using receiver arrays at multiple frequencies. In Phase I, the instrument consists of two arrays at 95 GHz and 44 GHz with 90 and 19 receiver elements, respectively. The array is coupled to the optics comprising platelet-array feedhorns[6] and a 1.4 m Mizuguchi-Dragone reflective telescope[7,8]. The optics achieves the beam size of 12 arcmin (27 arcmin) in full-width-half-maximum at 95 GHz (44 GHz), defining the sensitive

Table 1: QUIET Phase-I experiment summary.

Frequencies (GHz)	95 / 44
Angular resolutions (arcmin)	12 / 27 in full-width-half-maximum
Number of receiver elements	90 / 19
Array sensitivity (μK$\sqrt{\text{s}}$)	57 / 64
Detector type	HEMT
Polarization modulation	Phaseswitch (4 kHz and 50 Hz), sky and boresight rotations
Telescope optics	Mizuguchi-Dragone
Field centers (J2000 RA,DEC)	(181°,−39°), (78°,−39°), (12°,−48°), (341°,−36°)
Field size	$15° \times 15°$ each
Observation	August 2009∼ / October 2008∼June 2009

angular scale of $\ell \lesssim 1000$ ($\ell \lesssim 400$). Table 1 summarizes the Phase-I instrument and observing.

Large focal-plane arrays are achieved by a breakthrough in millimeter-wave circuit technology and packaging at JPL[4], which miniaturizes the correlation polarimeter and enables mass production. Each array element is based on a QUIET module: a pseudo-correlation receiver comprising HEMT low-noise amplifiers, phase shifters, detector diodes, and passive components (Fig. 1). The 95 GHz (44 GHz) module dimensions are 3.2 cm × 2.9 cm (5.1 cm × 5.1 cm). The polarization properties of the CMB can be expressed by two linear polarization (Q and U) Stokes parameters. Each module measures both of the linear polarization parameters simultaneously when its inputs are coupled through the septum polarizer[a], which splits the incoming radiation into left- and right-circular polarizations[5]. Pseudo-correlation technique provides not only sensitivity to Q and U polarizations but also makes the polarimeter immune to gain fluctuations and unpolarized signals. Phase modulation occurs at 4 kHz, which is faster than the $1/f$ knee frequency of the atmosphere, amplifiers, and diode detectors. In addition to the 4 kHz phase modulation occurring in one of the amplifier chains, the phase switch in the second chain is also modulated at lower frequency of 50 Hz. This 'double demodulation' cancels out spurious instrumental polarization that can arise if there are transmission differences between the two phase states in either of two phase shifters.

The performances of the QUIET modules are fully calibrated, characterized and verified in the field through observations in Phase I. The mean sensitivity of a module is 0.5 mK$\sqrt{\text{s}}$ (0.25 mK$\sqrt{\text{s}}$) for 95 GHz (44 GHz), making up the combined array sensitivity of 57 μK$\sqrt{\text{s}}$ (64 μK$\sqrt{\text{s}}$). The achieved $1/f$ knee frequencies are typically well below the telescope scan frequency of 0.05–0.1 Hz, thus minimizing the sensitivity degradation due to the $1/f$ noise.

3 Site and Observation

QUIET is located at 5080-m altitude on the Chajnantor plateau in Chile using the platform of CBI[9]. Chajnantor offers exceptional conditions for radio astronomy because of its high altitude and low water vapor[10]. Under median conditions, the zenith sky brightness at 95 GHz (44 GHz) is 5–6 K (9 K).

We started Phase-I observations in October 2008 with the 44-GHz receiver array. The observing season finished in June 2009 after collecting over 3500 hours of data. After the deployment of the 95-GHz receiver array replacing the 44-GHz one, observing resumed in August 2009 and continues. We have already collected more than 3000 hours of 95-GHz data by the end of March 2010 and expect to collect an additional 4500 hours by the end of 2010.

[a] In Phase I, six (two) out of 90 (19) modules of the 95-GHz (44-GHz) array are coupled to assemblies of orthomode transducers and magic tees, instead of to the septum polarizers, providing sensitivity to the temperature anisotropy of the CMB.

Figure 1: A 95-GHz module with the radiometric components integrated (left) and the 90-element 95-GHz array under assembly (right).

QUIET observes the four CMB patches listed in Table 1. Each scan is performed with a half amplitude of 7.5° and repointed when the sky has drifted by 15°, making up deep coverages of $\simeq 15° \times 15°$ on each patch. The observing scan is a periodical scan in azimuth with the speed of $\simeq 6°$/s, with a fixed elevation and rotation angle about the optical axis. We use two means to achieve parallactic-angle coverage: sky rotation from diurnal sky motion and weekly rotation about the optical axis (boresight rotation).

About 10% of our observing time is dedicated to calibrations. Calibrations of polarization angle, spurious polarization due to leakage from I (intensity) to Q/U, and the responsivity are of importance. We calibrate these by combining daily and/or weekly observations of astronomical sources such as the Moon, Jupiter, and Taurus A; and the 'skydip' (scanning the telescope up and down in elevation), which is performed once per 90 minutes. Supplemented by measurements using a broad-band polarized noise source and a rotating wire-grid, we achieve the required calibration precision for Phase I. We also spend $\sim 10\%$ of observation time scanning galactic plane for the purposes of calibration and galactic science.

4 Analysis

Our two independent analysis pipelines employ different and complementary techniques: one uses pseudo-C_ℓ estimators[11,12] and the other is based on maximum-likelihood map-making and power-spectrum estimation[13,14]. It is critical to cut data contaminated by fluctuations of environmental or instrumental origin. Such selection criteria are under development using results obtained from the null-test suite described below.

Our policy is to not look at polarization power spectra until the criteria are defined and the data pass a variety of predefined null tests, each designed to validate our understanding of a particular possible systematic effect. In each test, the data are split into two subsets; CMB maps ($\mathbf{m_1}$ and $\mathbf{m_2}$) are made from each half, and we compute the power spectrum of the difference map ($\mathbf{m_{diff}} \equiv [\mathbf{m_1} - \mathbf{m_2}]/2$), to check consistency with zero signal.

One example is to split the data into those obtained from Q-sensitive channels and U-sensitive ones. Excess power should arise in this null spectrum if there were instrumental systematic effects that show up differently in those channels. A preliminary result for this null test using 44 GHz data is shown in the left panel of Fig. 2, where the power spectra are consistent with zero signal as expected. Each division has 16 bins, 8 bins in E-mode and B-mode power. A test suite of 32 divisions makes a total of 512 points that should be consistent with zero. The right panel of Fig. 2 shows the distribution of the χ^2 values of those points for one of our CMB patches. The data distribution is consistent with that from Monte Carlo simulations, validating our selection criteria and noise model.

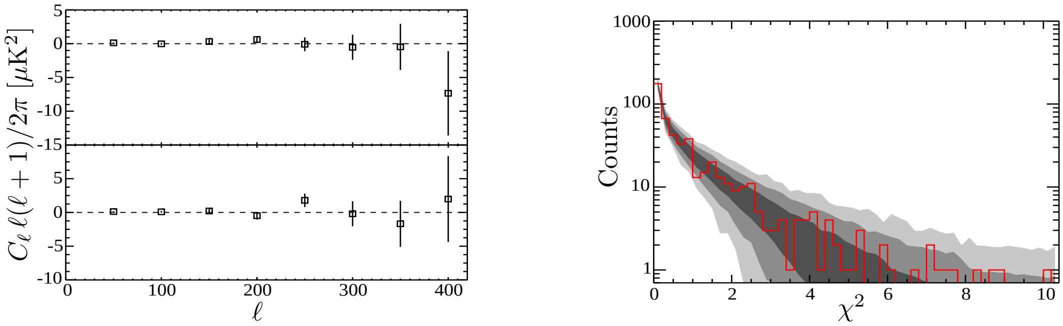

Figure 2: The left panel shows a preliminary null power spectrum obtained by differencing data sets from Q-sensitive and U-sensitive diodes. The right panel is the χ^2 distribution of the null power spectra of 32 divisions, where the red histogram and the shaded region correspond respectively to the data and expectation from Monte Carlo simulation. Both are only for one of the four CMB patches we observe and from the 44 GHz receiver data.

5 Future Prospects: Phase-II

Phase II will consist of three separate telescopes with four cryostats: three will house identical 95-GHz arrays of 499 elements and one houses an array consisting of 61 elements of 44 GHz and 18 elements of 30 GHz polarimeters for control against foreground contamination due to synchrotron radiation from our galaxy. The sensitivity of Phase II allows us to possibly detect B-modes from primordial gravitational waves, or to put a stringent limit on the tensor-to-scalar ratio r of $\simeq 0.01$.

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