QUIET Science Results and Instrument Performance: Towards Measurements of Inflation with the Polarized Cosmic Microwave Background

Laura Newburgh
for the QUIET Collaboration
Moriond 2012
• QUIET Experiment Overview
  – Instrument
  – Science goals
• Observation & Analysis
  – Observation and calibration summary
  – CMB Q-band power spectrum results
  – Implications for Foregrounds
  – Preliminary W-band maps and systematics
QUIET Experiment Overview

- CMB polarization experiment
- Coherent detector technology
- Ground-based in the Atacama Desert
  - Observing at the former CBI site @ 5080m altitude (~16500 ft)
- Two frequency bands, two separate receivers:
  - Q-band:
    - 19 detectors @ 43 GHz, 64 µK sqrt{s} array sensitivity
    - $\ell < 500$
  - W-band:
    - 90 detectors @ 95 GHz, ~77 µK sqrt{s} array sensitivity
    - *Observed*: June 2009 - Dec 2010
    - $\ell < 1000$
Science Goals

- Place competitive constraints on B-mode amplitude

- Measure first three peaks of CMB E-mode polarization spectrum

- Measure amplitude of polarized foreground emission to inform future instruments

- Understand instrument systematics for development of larger arrays
QUIET: The Instrument

Telescope Structure
- Telescope mount
- Deck
  (3 independent rotation axes)

OMTs and hybrid Ts

Electronics crate
- Detector bias boards
- Data acquisition cards

Crossed Dragone design with two 1.4m mirrors
- Reduces cross-polarization
- Reduces side-lobe pickup
- 27.3/~13 arcmin resolution Q/W

Receiver
- Cryostat
- Optical components
- QUIET modules

QUIET Modules
W-band (full array)
QUIET Principles

- Optical design is simple
  - Limits systematics from optics

- The QUIET coherent polarimeters:
  - Q and U Stokes parameters are the QUIET module “natural units”
    - Q & U measured directly @ detector diodes
  - LNAs: InP HEMT low-noise amplifiers
  - Integrated circuitry with strip-line coupling allows miniaturization suitable for polarimeter arrays
  - Switch the signal at 4kHz, 50 Hz and difference : limits instrumental systematics

\[ L = E_x - iE_y \quad R = E_x + iE_y \]
Polarized Foregrounds

- Synchrotron are dominant foreground at low frequencies
- Patch selection can be a useful tool to minimize contamination from foreground emission
- Understanding foregrounds is critical
- Combination of Q and W band frequencies will map synchrotron emission in selected CMB and galaxy patches
Scan Strategy

- Four CMB patches in ‘low foreground’ regions
- Two galactic plane patches
- Each patch is ~250 square degrees
- QUIET employs azimuth scanning at a fixed elevation, and change elevation after the patch has drifted 15°

![Graph showing hours of CMB data collected in Q-band and W-band over days.]

- Q-band: 3458 hours of CMB data collected
- W-band: ~7600 hours CMB data collected

Sensitivity per square-degree pixel (Q-band):

- CMB-1: 1.1 µK
- CMB-2: 1.4 µK
- CMB-3: 1.4 µK
- CMB-4: 2.3 µK
• **Pointing**
  - Q-band
    • Moon, Jupiter -- 3.5 arcmin RMS
  - W-band
    • Jupiter, RCW38, galactic center

• **Responsivity**
  - Q-band
    • Moon, Tau A, sky dips, Jupiter (TT) -- 4-6% error
  - W-band
    • Tau A, large sky dips, Jupiter (TT)

• **Detector Angles**
  - Q-band
    • Moon, Tau A, wiregrid -- 2° error
  - W-band
    • Tau A, wiregrid

• **Beams**
  - Q-band:
    • Polarized: Tau A -- 4% error
    • TT: Jupiter (edge polarimeters)
  - W-band:
    • Polarized + TT: Jupiter + Tau A

• **Temp-to-polarization leakage**
  - Q-band: Tau A: 1%/0.2% (Q/U)
  - W-band: Tau A: 0.3%
• Systematic errors allow a measurement of \( r < 0.1 \)
• Dominant systematic for primordial peak is instrumental polarization
• Polarization angles dominate the gravitational lensing region
• Low level of systematics a result of polarization-optimized optics, excellent cross-linking via sky rotation and deck rotation, and fast modulation and signal differencing
Analysis Pipelines

- We implement two separate pipelines
  - Pseudo-$\mathcal{C}$
  - Maximum Likelihood
- Data cutting for both includes:
  - Has cuts for glitches, weather, non-working detector diodes, poor noise fits, etc
  - Each pipeline filters scan-synchronous pickup, sidelobe pickup, $1/f$, and atmospheric fluctuations
- Both pipelines followed a "blind analysis" philosophy while developing data cuts
- We kept ~70% of the data
Data Verification

- Data verification via a suite of 40+/20+ null tests (PCL/ML)
- In Pseudo-Cl, categorize all scan-maps by azimuth and deck, and use only the cross-correlation power spectra
Data Verification

• Data verification via a suite of $40+/20+$ null tests (PCL/ML)
• In Pseudo-Cl, categorize all scan-maps by azimuth and deck, and use only the cross-correlation power spectra
  • Evaluate ‘null-ity’ via $\chi$ and $\chi^2$:
    – $\chi$ mean: $0.19/0.21$ (Maximum Likelihood, Pseudo $C\ell$ prior to cross-correlation via pointing divisions)
    – $\chi$ mean: $0.02 +/− 0.02$ (Pseudo $C\ell$, after cross-correlation divisions)
    – PTEs derived from $\chi^2$ consistent with a uniform distribution
Q-band Polarized Power Spectrum Results

- Consistent with $\Lambda$CDM
- Pseudo-CL pipeline: $r=0.35$ (+1.06, -0.87) $\rightarrow$ no detection of BB power
- Maximum likelihood pipeline: $r=0.52$ (+0.97, -0.81) $\rightarrow$ no detection of BB power
- Power spectra from each pipeline are consistent with each other
QUIET Foregrounds

- Excess power in $25<\ell<75$ of patch CMB-1 (closest to the galaxy), $3\sigma$ from $\Lambda$CDM
- Process WMAP7 K-band map through Pseudo-Cl pipeline: K-band power spectrum, K-Q cross power spectrum, and Q-band power spectrum.
- Extrapolate $25<\ell<75$ bin from K-band to Q-band with spectral index $\beta=-3.1$, and find it is consistent with the QUIET results
QUIET W-band sky map

- Patch CMB-1 polarization map
- Still working out final responsivity and beam solid angle
- Squint and see the orthogonal polarization?
QUIET Q-band sky map
W-band Systematics

- Systematic errors allow a measurement of $r<0.01$
- Still unclear where responsivity systematics will land
Summary

• QUIET Q-band and W-band observations complete

• Q-band analysis yielded polarization spectra consistent with $\Lambda$CDM and no BB power

• Excess power in the lowest spectrum bin for patch CMB-1 consistent with synchrotron foreground emission

• Q-band data paper:
  – arXiv:1012.3191
  – More information can be found at: http://quiet.uchicago.edu/results/index.html

• W-band analysis is underway

• Expect papers on the instrument, galaxy, and W-band to round out the QUIET release
## Patch Cuts

### TABLE 3
**Total Hours Observed and Data-Selection Efficiencies**

<table>
<thead>
<tr>
<th>Patch</th>
<th>Total Hours</th>
<th>A %</th>
<th>B %</th>
<th>Common %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMB-1</td>
<td>905</td>
<td>81.7</td>
<td>84.3</td>
<td>76.7</td>
</tr>
<tr>
<td>CMB-2</td>
<td>703</td>
<td>67.3</td>
<td>70.0</td>
<td>61.2</td>
</tr>
<tr>
<td>CMB-3</td>
<td>837</td>
<td>56.0</td>
<td>61.4</td>
<td>51.4</td>
</tr>
<tr>
<td>CMB-4</td>
<td>223</td>
<td>70.6</td>
<td>74.2</td>
<td>65.9</td>
</tr>
<tr>
<td>All Patches</td>
<td>2668</td>
<td>69.4</td>
<td>72.9</td>
<td>64.2</td>
</tr>
</tbody>
</table>

**Note.** — Selection efficiencies for each pipeline. “Common” gives the efficiencies if both sets of cuts were applied.
Systematics

• Studied with simulations in the Pseudo-Cl pipeline:
  
  – Pointing:
    • Estimated from the difference between two models
  
  – Beam window function:
    • Estimated from the difference between central- and edge-horn beams
  
  – Polarization Angle:
    • Estimated from the difference between calibrators (Moon, TauA): +/- 2 degrees
  
  – Responsivity Model:
    • Estimated from the difference between two responsivity models
    • Responsivity magnitude error is 6% (12% in power spectrum)
  
  – I → Q/U leakage:
    • 1%/0.2% (Q/U), estimate from running a ‘leakage’ map through the pipeline
  
  – Sun contamination:
    • Inject excess power into simulated full season maps where we have known sidelobes
Data Selection

- Each pipeline has cuts for:
  - Glitches, weather, non-working detector diodes, poor noise fits, etc
- Each pipeline filters scan-synchronous pickup, sidelobe pickup, 1/f, and atmospheric fluctuations:
  - Maximum likelihood: keeps only $[2.5 f_{\text{scan}}, 4.5 \text{Hz}]$, removes a time-independent ‘pickup’ map
  - Pseudo-Cl: remove fourier modes around $f_{\text{scan}}, >4.6$ Hz, azimuth filter