QUIET Experiment and HEMT receiver array

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Outline

- Introduction
  - Physics of CMB Polarization
  - QUIET Project Overview
- QUIET Instrumentation
  - HEMT Array Receiver
  - Optics and Mount
  - Data Acquisition and electronics
- Summary and Future Plan
Introduction
Cosmology After WMAP

WMAP + Others

- Flat \( \Lambda \text{CDM} \)
  - \( \Omega_{\text{all}} \sim 1 \)
  - \( \Omega_\Lambda = 0.74 \pm 0.06 \)
  - \( \Omega_m h^2 = 0.13 \pm 0.01 \)
Solved and Unsolved Problems

Solved: Time Evolution of the Universe

Unsolved: Physics of the Beginning (Inflation)
Source of the Evolution (Dark Energy, Dark Matter)
Unsolved Problems

Direccion

- Did it happen?
- What’s the correct model?
- Shape of potential: Physics at GUT Scale?
- Signature: Primordial Gravitational-Wave (CGB?)
- Detectable via CMB Polarization

Dark Energy

- Equation of State: $w = p/\rho$
- Dark Energy = Cosmological Constant? (i.e., $w = -1$ ?)

Cluster, Weak Lensing, BAO, SNe Ia, etc…
CMB Polarization

- CMB is from last (Thomson) scattering  
  ➔ Linearly polarized

- Anisotropy  
  ➔ Non-zero overall polarization
E-mode and B-mode

- **Polarization: Tensor-field**
  - Tensor = “Bar” without direction
  - c.f. Vector = “Bar” with direction

- **Decomposable into E-mode and B-mode**
  - Analogous to the vector field decomposition to (rot. free mode) + (div. free mode)
**B-mode Polarization**

- Gravitational wave from Inflation
  - Tensor perturbation of metric
    - Gravitational wave
    - B-mode
  - Unique signal of Inflation
  - Size of B-mode
    - Tensor/Scalar $\propto V$
  - $V$: Inflation potential, GUT scale?

$T/T~0.1$ if $V$~GUT scale

$r = T/S$
Two possible targets

- Large $l$ ($l \sim 100$: $\sim 2^\circ$)
  - Ground based is competitive
  - Could be lensing $B$ dominant (subtract?)

- Small $l$ ($l \sim 5$: $\sim 50^\circ$)
  - Originates from reionization
  - Advantageous to Satellite
  - Free from lensing $B$

NOTE: atmosphere is not polarized
Current Status

- Significantly non-zero $EE$ correlation is found
  - WMAP, DASI, CBI, BOOMERanG, CAPMAP, QuaD, BICEP
- No significant $BB$ measurement, yet

Plot from Chiang et al (2009)
QUIET Experiment

- CMB polarization measurement
- At two frequencies
  - W-band (90GHz)
  - Q-band (44GHz)
  - [At phase-II: Ka-band (30GHz)]
- First large HEMT polarimeter array
  - State-of-the-art packaged MMIC technology
  - Competitive sensitivity
- Targeted $\ell \sim 50-1000$ (1°~0.05°)
- Located at Chajnantor, Chile
The QUIET Observing Site

- Chajnantor Plateau, Chile
  - 17,000’
  - Extremely low moisture
  - ~1 hour drive from San Pedro de Atacama
  - Year-round access
  - Observing throughout the year (day and night)
QUIET collaboration

Chicago (KICP)
Fermilab

Stanford (KIPAC)

Caltech JPL

Columbia Princeton

Miami

Manchester
Oxford

Oslo

MPI-Bonn

KEK

Observational Site
Chajnantor Plateau, Chile

5 countries, 13 institutes, ~35 scientists
QUIET Time Schedule

Development

2008, October
Q-band obs. start

Q-band observing

2009, July
W-band obs. start

W-band observing

Phase-II
Instrumentation
QUIET – a big picture

- Primary Mirror
- 2nd Mirror
- Focal Plane (Receiver)
- Platelet Array
- Electronics Box
- Primary Mirror
- Mount
Receiver
Basics of Polarization

- Stokes parameters ($I, Q, U, V$)
  - A set of parameters fully characterizing intensity and polarization of radio wave.
  - $I$: Intensity ($\rightarrow T$ in CMB)
  - $Q, U$: Two linear polarization ($\rightarrow E, B$ in CMB)
  - $V$: Circular polarization (zero in CMB)

$$Q = E_x^2 - E_y^2$$

$$U = 2E_xE_y - U$$
Choice of Technology

- **HEMT**
  - Good at $\nu < 100\text{GHz}$
  - Established (used in WMAP etc.)
  - MMIC + packaging technology for array
  - (Pseudo-)correlation polarimeter
  - Quantum noise limit:
    $$T_{\text{det}} \sim \frac{h\nu}{k_B}$$
    - Not significant for ground based.

- **Bolometer**
  - Good at $\nu > 100\text{GHz}$
  - Suitable for array
  - "Brute force" polarimeter
  - No quantum noise limit
Choice of $\nu$ and “Foreground”

- Contamination for “Background” measurement: “Foreground”
- Primary, inevitable systematic error
- Two large sources
  - Synchrotron radiation from cosmic ray
  - Dust emission (dust aligned in $B$ field)
- QUIET (W) is around minimum

Spectra of CMB and foreground sources
Key Technology: Polarimeter on Chip

L-R decomposition

OMT (Princeton)

HEMT Module

“Polarimeter On Chip” Key technology for large array (JPL)

c.f. CAPMAP polarimeter

~3cm

~30cm
Radiometer Equation

Performance of radiometer:
- Receiver temperature $T_{\text{rec}}$
- Band width $BW$
- Type-dependent pre-factor (1 per diode at QUIET)

Per-diode noise level

$$\Delta T = \frac{T_{\text{rec}}}{\sqrt{BW}}$$

Noise level per Fourier mode

Integration time

Effective number of Fourier modes / sec

$$BW = \left[ \frac{\int g(f) df}{\int g^2(f) df} \right]^2$$

$g(f)$: gain
Flat & Wide $\rightarrow$ Large $BW$
HEMT MMIC Amplifier

Amplification “with phase info”
- Intrinsic adv.: Q/U simultaneous meas
- Fundamental limit: \( \Delta n \cdot \Delta \phi \geq 1/2 \Rightarrow \Delta T \geq h\nu/k_B \)

Noise level:
- \(~55\text{K}@90\text{GHz}\)
- \(~25\text{K}@45\text{GHz}\)

Well above quantum limit
Further degradation in modules
**Principle of Receiver Element**

\[ L = E_x + iE_y \]
\[ R = E_x - iE_y \]

- **HEMT Amp.**
- **Phaseswitch**
  - 4kHz & 50Hz

\[ |L \pm R|^2 = 2E_x^2 + 2E_y^2 \pm 2(E_x^2 - E_y^2) \]

\[ |L \pm iR|^2 = 2E_x^2 + 2E_y^2 \pm 4E_xE_y \]
\[ = 2E_a^2 + 2E_b^2 \pm 2(E_a^2 - E_b^2) \]
Principle of Receiver Element

- Q-U simultaneous measurement
- Use of L-R (not $E_X - E_Y$)
  - No fake signal from gain difference
- Demodulation
  - $1/f$ noise reduction

\[ L = E_X + iE_Y \quad R = E_X - iE_Y \]

HEMT Amp.
Phaseswitch 4kHz & 50Hz
180° Coupler
Det. Diode
\[ +Q \leftrightarrow |L \pm R|^2 \]
\[ +U \leftrightarrow |L \pm iR|^2 \]
\[ -Q \leftrightarrow |L \pm R|^2 \]
\[ -U \leftrightarrow |L \pm iR|^2 \]
Why demodulation?

\[ L = E_X + iE_Y \]

\[ R = E_X - iE_Y \]

HEMT Amp.

Phaseswitch 4kHz & 50Hz

180° Coupler

Det. Diode

90° Coupler

\[ +Q \]

\[ +Q \]

\[ -Q \]

\[ -Q \]

0.5ms

\[ +1 \]

\[ -1 \]

\[ |L \pm R|^2 \]

\[ |L \pm iR|^2 \]
Time Stream

800kHz timestream

Addition

Switching@4kHz

Subtraction

Tiny tiny signal on top of huge offset

CMB polarization (E-mode) ~ 0.00002 mV

50Hz timestream

rms ~ 0.05 mV
Noise spectrum

Switching frequency 4kHz
Q-band Array

Array sensitivity
~70 $\mu$K·s

Integrated at Columbia
W-band Array

Array sensitivity
\(~60 \, \mu \text{K}\cdot\sqrt{\text{s}}\)

The world largest HEMT array polarimeter

Integrated at Chicago
Lab. Measurements

- Difficulty: everything emits microwave
  - Things around us ~300K
  - Impossible to input zero-signal

- Our signal is Gaussian noise
  - How to distinguish from detector noise?
Lab. Measurements

- Reflection by metal plate
  - Known polarization
- Direct measures of
  - Responsivity
  - Noise level

Detector

Metal plate (reflector)

Cryogenic bucket

RMS ~50 mK (@100 Hz) ~1 K

AI

1095 Steel

Stainless
Lab. Measurements
Lab. Measurements

Demod (mV)

Q1 U1 U2 Q2

50_M05A3

(mV)

(sec)
Optimization Procedure

To exploit best performance, especially BW, bias needs to be optimized

› 10 bias/module (drain & gate)
› Simultaneous optimization of many modules
Telescope and Mount
Optics: Telescope

1.4m Primary mirror
FWHM ~ 28arcmin @ Q-band
FWHM ~ 13arcmin @ W-band

Stanford Caltech/JPL
Optics: Platelet Array

Q-band platelet

W-band platelet

Horn array to couple to modules
Created by diffusion bonding

Miami

~40cm
Digression: bigger telescope?

You may think bigger telescope collects more light and thus reduces noise. NO!

$A$: Area of the primary mirror
You may think bigger telescope collects more light and thus reduces noise. NO!

Amount of light collected \( \propto A \)

\( A \): Area of the primary mirror
Digression: bigger telescope?

You may think bigger telescope collects more light and thus reduces noise. NO!

Amount of light collected \( \propto A \)

Size of the image on the sky (=Area of integration) \( \propto \frac{1}{A} \) (diffraction limit)

\( A \): Area of the primary mirror
You may think bigger telescope collects more light and thus reduces noise. NO!

Amount of light collected \( \propto A \)

Size of the image on the sky (Area of integration) \( \propto \frac{1}{A} \) (diffraction limit)

Cancels out for "surface like" target

\( A \): Area of the primary mirror
Mount
Mount: Importance of Speed

Noise Power

$f (\text{Hz})$

$\Delta T [\mu K]$

$\theta$ /s

2°/s  0.5°/s

Caltech
Mount: Importance of Speed

Noise Power

\[ f \text{ (Hz)} \]

\[ \Delta T \text{ [\mu K]} \]

\[ \text{Multipole moment, } l \]

Caltech
Mount: Importance of Speed

Caltech
Data Acquisition and Electronics
Enclosure (on the mount)

- Cryo. regulation
- Bias Electronics
- ADC boards (x13)
DAQ

- 18-bit, 800kHz ADC (Chicago)
  - Based on the one used at CDF
- Control and down sample (average) by FPGA

250μs (4kHz)  
200 samples/period
Observation at Chile

Full data (BD, snail) ~25GB/day

Important calibration, Digest (Internet) ~2GB/day

KEK, Japan (Mirror)

Oslo, Norway (Mirror)

U Chicago (Primary)

U.S. Institutes

Data Management: Bring it off of the mountain!!
(Near) Future
QUIET Phase-II (x16 scale up!)

Phase-I W-band 91-element array

499-element array (x3)
Expected Sensitivity

E-mode: High S/N measurement up to $\ell \sim 2000$
B-mode: Detection or significant limit on $r$, detection of lensing
Summary

- CMB polarization
  - A unique opportunity to access fundamental physics
  - A field where new technologies are growing

- QUIET experiment
  - HEMT receiver array experiment using state-of-the-art MMIC packaging technique
    - Demodulation, Q/U simultaneous meas.
  - Competitive sensitivity
  - Phase-I observing, proposing phase-II
Phase switch

- Switch between two paths with 180° different phases
- One of the fundamental limitations to BW