Physics of CMB Polarization and Its Measurement

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Outline

Physics of CMB and its Polarization
- What does WMAP shed light on?
- Unsolved Problems: Beyond SM
- CMB Polarization as a Probe for Inflation

Measurement of CMB Polarization
- Detection Techniques
- Experimental Status and Prospects
  - Current Measurements (1st generation)
  - 2nd Generation Experiments, and beyond
Physics of CMB and Its Polarization
Cosmology After WMAP

WMAP (+ Others)

- **Flat $\Lambda$CDM**
  - $\Omega_{\text{all}} \sim 1$
  - $\Omega_{\Lambda} = 0.74 \pm 0.06$
  - $\Omega_m h^2 = 0.13 \pm 0.01$
    ($\Omega_m \sim 0.26$)
  - $\Omega_b h^2 = 0.022 \pm 0.001$

- **Implications**
  - Dark Energy $\sim \Lambda$
  - Consistent w/ Inflation
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

- **Inflation**
  - Is it true?
  - 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: \( w = \frac{p}{\rho} \)
  - Dark Energy = Cosmological Constant? (i.e., \( w = -1 \)?)
Digression: Can we go further with CMB?

- **Cosmic Variance**
  - We want to measure the “PDF” of CMB.
  - We only have one realization (our sky), i.e., one event.
  - TT at small $l$ (incl. first peak) is now cosmic variance limited.

- **To go further:**
  - TT at large $l$
  - Polarization

**TT (Temperature) Correlation**

Black: WMAP Three-Year
Green: WMAP First-Year
Gray Band: Cosmic Variance Expectation
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

voie sourced by gravitational wave from Inflation
- Unique signal of Inflation
- Intensity of B-mode $\propto$ Tensor/Scalar $\propto V$
- $V$: Inflation potential, GUT scale?

Gravitational lensing converts E-mode $\rightarrow$ B-mode at large $l$.

TT is around here ($\sim 10^3 \mu K$)

$r = (T/S)^2$

T/S~0.1 if V~GUT scale
More on CMB Polarization

- **Lensing B-mode**
  - Not only contamination for primordial B-mode
  - Can be a probe for mass distribution → information for Dark Energy $w$

- **E-mode and TE-correlation**
  - Improvement in cosmological parameters
  - Consistency check (robustness w.r.t. assumptions such as adiabaticity)

- **TB- and EB-correlation**
  - Zero (otherwise, there is parity violation)
Measurement of CMB Polarization
Primary Target: B-mode

Two possible targets

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

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

NOTE: atmosphere is not polarized
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)

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

$$U = 2E_xE_y$$

$$V = 0$$
Two technologies: Bolometer vs. HEMT
Feasibility
Array
Choice of band
  > Which region of 20G Hz~500G Hz
  > “Foreground” contribution
HEMT (+ diode detector)

“Usual” way of radio wave detection: amp. $\rightarrow$ rectification

Established technology
  - WMAP, DASI, CAPMAP, ...

Limited by quantum noise: $T_{\text{det}} \propto h \nu / k$
  - Good in low $\nu$ ($\nu < 100$ GHz)
HEMT (+ diode detector)

Pseudo-correlation polarimeter
(from CMB task force)

- (Pseudo-)Correlation polarimeter
  - Gain diff. cancellation

- Recent technology breakthrough
  (MMIC + packaging) for arraying

CAPMAP polarimeter

QUIET polarimeter (90GHz)

~30cm ~3cm
Bolometer

- Direct detection of total “power” of radio wave
- No quantum noise limit
- Technically challenging
- Low $\nu$ $\rightarrow$ large heat load
  - Difficulty in low $\nu$
    - Overcome by antenna coupled bolometer
- Promising detector type in future
Bolometer

- Good at making large array
- Antenna coupled bolometer has polarization sensitivity (PSB) $|Ex|^2$, $|Ey|^2$ measurement
“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)

Spectra of CMB and foreground sources

PLANCK “Blue Book”
Choice of Technology

- HEMT
  - Quantum noise limit: $T_{\text{det}} \sim h\nu/k_B$
  - Good at $\nu < 100\text{GHz}$
  - Relatively established
  - MMIC + packaging technology for array
  - (Pseudo-)correlation polarimeter

- Bolometer
  - No quantum noise limit
  - Good at $\nu > 100\text{GHz}$
  - Also good at $\nu < 100\text{GHz}$ with antenna coupling
  - Challenging
  - Suitable for array
  - “Brute force” polarimeter
  - (Correlator type is also possible)
Multi-pole analysis

- **TT correlation (scalar field)**
  - Spherical harmonics expansion

- **Polarization (tensor field)**
  - Tensor spherical harmonics expansion
  - Simple FT of div. and rot. field (for small patch of the sky)

- **Practical difficulty**
  - Irregular sampling
  - Border of patch

Three-Year WMAP, Hinshaw et al.
Current Status

- Significantly non-zero EE correlation is found
  - WMAP, DASI, CBI, BOOMERanG, CAPMAP
- WMAP TE correlation
  - Improvement of limits on cosmological parameters
- No significant BB measurement, yet

EE Correlation

Three-Year WMAP, Page et al.
Coming Experiments

- **Targets**
  - Primordial B from inflation
  - Lensing B for mass profile measurement (experiments w/ high resolution)
  - E to improve limits on cosmological parameters

- **Detector improvement**
  - Large array → Better statistics
  - Better detector sensitivity
Coming Experiments

- Bolometer
  - (AMiBA), BICEP, BRAIN/ClOVER, EBEX, MBI-B, MAXIPOL, PAPPA, PolarBear, Polatron(?), QUaD, (SPT), Spider

- HEMT
  - BaR-SPOrt(?)/SPOrt(?), QUIET

- Bolometer + HEMT (depending on freq.)
  - PLANCK

Balloon
Taking data
(Main target=SZE)

See the following site for compilation
http://lambda.gsfc.nasa.gov/links/experimental_sites.cfm
QUIET

- Q/U Imaging Experiment
- Detector: HEMT
  - Two bands: W-band (90GHz) and Q-band (40GHz)
  - HEMT array (91 elements for W, 19 elements for Q)
  - The only next generation HEMT experiment
  - The only next generation (B competitive) program straddling across 60GHz
    - NOTE: 60GHz = WMAP implies lowest foreground
- Site: Chile, Atacama
- Collaboration
  - ~10 US institutes (incl. CAPMAP&CBI) + Oxford, MPI Bonn
  - ~20 staff + students
- Cost: ~a few M USD
QUIET

CBI site at Chile

Sensitivity

Deployment: 2007 Fall, First Science Result: 2008 Summer

All the figures from QUIET web site
http://quiet.uchicago.edu/
Next Next Generation

- Ultimate CMB experiment
  - Satellite
  - Target: B-mode at low $l$
  - Bolometer
- (Ground Based)
- Japanese community may take part
  - Tohoku
  - KEK
  - ...

Beyond Einstein Program
http://universe.nasa.gov/program.html
Summary

- Unsolved Problems of Cosmology
  - Inflation and Dark Energy
- B-mode Polarization of CMB
  - Sensitive to Inflation
- Detector Technology
  - Bolometer vs. HEMT
- Current Measurement: E-mode found
- Experiments Dedicated to B-mode: coming soon...