Polarization with the CMB

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CMB Summer Instrumentation School
Outline

- What is polarization?
- Why do we want to measure CMB polarization?
- How do we measure polarization?
  - Polarization Systematics
  - Polarization Modulation
Electromagnetic Waves

\[ \vec{E}(\vec{r}, t) = \vec{E}_0 \exp \left( i(\omega t - \vec{k} \cdot \vec{r}) \right) \]

Amplitude and **polarization** of the wave.

Direction the wave is traveling

Complex Vector.
Polarization States

\[ \vec{E}_0 = E_x e^{i\delta_x} \cdot \hat{x} + E_y e^{i\delta_y} \cdot \hat{y} \]

- **Horizontal**
  - \( E_y = 0 \)
  - \( E_x = E_y, \delta_x = \delta_y \)
- **±45°**
  - \( E_x = E_y, \delta_x = \delta_y \pm \frac{\pi}{2} \)
- **Circular**
  - \( E_x \neq E_y, \delta_x \neq \delta_y \)
- **Elliptical**
  - \( E_y \neq 0 \)
Polarization Vectors

\[ \vec{E}_0 = \begin{bmatrix} E_x e^{i\delta_x} \\ E_y e^{i\delta_y} \end{bmatrix} \]

**Jones Vectors**
- Often more intuitive
- Complex Numbers
- Single Frequency
- Fully polarized light only

**Stokes Vectors**
- Real Numbers
- Can be integrated over frequency
- Can represent partially polarized light

\[ S = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} |E_x|^2 + |E_y|^2 \\ |E_x|^2 - |E_y|^2 \\ 2 \text{Re} \left( E_x E_y e^{i(\delta_x - \delta_y)} \right) \\ -2 \text{Im} \left( E_x E_y e^{i(\delta_x - \delta_y)} \right) \end{bmatrix} \]
Stokes Vectors

\[ S = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} |E_x|^2 + |E_y|^2 \\ |E_x|^2 - |E_y|^2 \\ 2\text{Re} \left( E_x E_y e^{i(\delta_x - \delta_y)} \right) \\ -2\text{Im} \left( E_x E_y e^{i(\delta_x - \delta_y)} \right) \end{bmatrix} \]

- Horizontal: \( I = +Q \), \( U = V = 0 \)
- \( \pm 45^\circ \): \( I = +U \), \( Q = V = 0 \)
- Circular: \( I = +V \), \( Q = U = 0 \)
- Elliptical: \( I = \sqrt{Q^2 + U^2 + V^2} \), \( Q \neq U \neq V \)
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Cosmic Microwave Background

Inflation seeds initial scale-invariant quantum fluctuations in the early universe.

Density perturbations $\rightarrow$ Temperature Anisotropies

Gif by Wayne Hu

Planck CMB Temperature Map
CMB Polarization

Polarization from the early universe comes from Thomson scattering.

gifs by Wayne Hu
CMB Polarization

Polarization from the early universe comes from Thomson scattering.

All Quadrupole Anisotropies lead to net linear polarization.
Types of Quadrupole Moments

Scalar

Vector

Tensor

Scalors (Compression)

Vectors (Vorticity)

Tensors (Gravity Waves)

(Adapted from Hu, W. and White, M., 9706147)
Types of Quadrupole Moments

Scalar

Vector

Tensor

Early universe plasma physics damps out vector quadrupole moments

(Adapted from Hu, W. and White, M., 9706147)
Cosmic Microwave Background Polarization

Thomson Scattering during periods of changing ionization states.

Take 3D universe and convert to what we see on the sky.
CMB Power Spectrum
Observational Challenge

- Polarized CMB Fluctuations ~ nK - uK
- Unpolarized CMB Fluctuations ~100s uK
- Galactic Emission ~100s uK
- CMB Monopole 2.7 K
- Atmosphere, Wind, Clouds ~15 K
- Polarized Galactic Emission ~10 uK
- Ground, 300 K
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Both TES and KID detectors are *power* detectors

→ Need polarization selection before detectors

![Antenna-Coupled detectors](Image)

\[
d_1 = \frac{1}{2} (I + Q)
\]

\[
d_2 = \frac{1}{2} (I - Q)
\]

Two Orthogonal Detectors can be differenced to get one of the linear polarization states.

In a perfect world:

\[
I = d_1 + d_2
\]

\[
Q = d_1 - d_2
\]
Getting Complete Polarization Angle Coverage

\[
\begin{align*}
    d_1 &= \frac{1}{2} (I + Q) \\
    d_2 &= \frac{1}{2} (I - Q) \\
    d_3 &= \frac{1}{2} (I + U) \\
    d_4 &= \frac{1}{2} (I - U)
\end{align*}
\]

Simons Observatory Detector Wafer
Getting Complete Polarization Angle Coverage

Detector wafer designed to simultaneously measure 12 different linear polarization angles

\[ d_\alpha = \frac{1}{2} (I + Q \cos(2\alpha) + U \sin(2\alpha)) \]
Getting Complete Polarization Angle Coverage

Boresight Rotation: Rotate Telescope Around the Optical Axis:
- Rotates detector polarization angles w.r.t the sky
- Per detector properties remain the same.

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Differential Efficiencies

Each Detector has slightly different efficiencies due to:
- Detector Efficiency
- Optical Efficiency
- Placement in Focal Plane
- ...

\[
\begin{align*}
  d_1 &= \frac{1}{2}(I + Q) \\
  d_2 &= \frac{1}{2}(I - Q)
\end{align*}
\]

\[
\begin{align*}
  d_1 - d_2 &= \left(\frac{\eta_1 - \eta_2}{2}\right) I + \left(\frac{\eta_1 + \eta_2}{2}\right) Q
\end{align*}
\]

In the real world

Relative detector efficiencies mean pair differencing requires careful calibration.
Instrument Polarization

Unpolarized Light In → Partially Polarized Light Out

Reflections off angled surfaces are polarization dependent.

Mitigations:
- Anti-reflection coatings
- Use one reflection to counteract another, ex: Crossed-dragone Telescopes

Figures from Pozar, Microwave Engineering, 4th Edition
Instrument Polarization

Unpolarized Light In → Partially Polarized Light Out

@40 GHz 

@90 GHz and 20 deg incidence, $\sim 10^{-4}$ effect for an Aluminum flat mirror

- Small effects add up while looking for tiny signals.
- Polarization signal proportional to input unpolarized signal.
  - One source of T→ P Leakage

Figures from Harrington, 2018
Cross-Polarization

Detecting some polarization orthogonal to the intended polarization.

ie. detecting some $E_y$ when aligned along $E_x$

All antennas / horns / optical coupling devices have some cross-pol

Figure from Essinger-Hileman et. al., 2014

Feedhorn cross-pol from CLASS 40 GHz and 90 GHz telescopes.
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Polarization Modulation

- Using a polarization selective devices to change or modify the incoming polarization in known ways.
  - Half waveplates (HWPs)
    - Stepped
    - Continuously Rotating
  - Variable-delay polarization modulators (VPMs)

HWPs are birefringent materials with a fast and slow axis. Slow axis delayed by $\pi$ phase compared to fast axis.

If $x$ is fast axis, HWP takes $+Q \rightarrow -Q$

Rotating a HWP mixes $Q$ and $U$.

VPMs have wire grid + moveable mirror
Change mirror position → Mix $Q$ and $V$
Polarization Modulation

Telescope without modulation

Power vs. Frequency
- Polarized: CMB, Foregrounds Etc
- Unpolarized: Atmosphere, Noise

Power vs. Frequency
- Unmodulated Signal

Polarization Modulation

Telescope with modulation

Polarized
CMB, Foregrounds Etc

Modulated Signal

Signal

Power vs Frequency

Unpolarized
Atmosphere

Noise

Power vs Frequency

Polarization at Detectors

Noise

Modulated Signal

Power vs Frequency

Slides from Toby Marriage
Polarization Modulation

- Modulate Polarization at the front of the telescope optics.
  - Before the effects of instrument polarization.
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Thanks!
Modeling Polarization Selective Devices

Jones Calculus Uses Jones Vectors

- 2x2 Matrices
- Complex Numbers
- Single Frequency
- Fully polarized light only

\[ \vec{E}_{out} = J \cdot \vec{E}_{in} \]

\[ \vec{E}_{out} = \begin{bmatrix} E_{xx} & E_{yx} \\ E_{xy} & E_{yy} \end{bmatrix} \begin{bmatrix} E_{in} \\ \end{bmatrix} \]

\[ \vec{E}_0 = \begin{bmatrix} E_x e^{i\delta_x} \\ E_y e^{i\delta_y} \end{bmatrix} \]

\[ \vec{E}_{out} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} E_{in} \\ \end{bmatrix} \]
Modeling Polarization Selective Devices

Mueller Calculus Uses Stokes Vectors
- 4x4 Matrices
- Real Numbers
- Can be integrated over frequency
- Can represent partially polarized light

There is a standard conversion for going from Jones Matrices to Mueller Matrices

\[ \vec{S}_{out} = M \cdot \vec{S}_{in} \]

\[ \vec{S}_{out} = \frac{1}{2} \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \vec{S}_{in} \]