The Polarization of the Cosmic Microwave Background

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IAS

DASI
Map of the infant Universe
Overview

• Physical origin of polarization

• The information encoded by polarization

• Summary
The Anisotropies are polarized

DASI

Kovac et al.
astro-ph/0209478

Map is 5 degrees square
The polarization and temperature patterns are correlated.
How is polarization generated?

Thomson Scattering

\[ I_1 \propto \sigma_{\text{Th}} \cos^2 \theta \]

\[ I_2 \propto \sigma_{\text{Th}} \]
THOMSON SCATTERING
Recombination

\[ T = 0.3 \text{ eV} \ll m_e c^2 \]

Thomson Scattering

Hydrogen is ionized

Hydrogen is neutral

Thomson Scattering
Scatterings

\[ \rightarrow \]

Density Pert.

Gravity Waves

Anisotropies

\[ \rightarrow \]

POLARIZATION
The quadrupole created by density perturbations

Doppler shift

\[ \hat{\mathbf{n}} \cdot [v(x_0 + \lambda_T \hat{\mathbf{n}}) - v(x_0)] \sim \lambda_T \hat{\mathbf{n}}_i \hat{\mathbf{n}}_j v_{i,j} \]

\[ \text{Pol} \sim k \lambda_T v \sim k \lambda_T c_s \delta_\gamma \]
Peaks are out of phase

Polarization peaks at smaller scales

\[ \dot{\delta}_\gamma = -\frac{4}{3} k v_\gamma + 4 \phi \]
The quadrupole created by GW

\[
\frac{1}{\nu} \frac{d\nu}{d\tau} \propto \frac{1}{2} (1 - \cos^2 \theta) e^{\pm i 2\phi} \dot{h}_t(\tau)
\]

\[
P \propto \delta \tau_D \dot{h}_t(\tau_D) \sim k \delta \tau_D \ h_t(\tau_D)
\]
Anisotropies created by GW

\[ h_t(k \tau) \propto \frac{3j_1(k \tau)}{k \tau} \]

ISW like effect, produced after recombination

Polarization is produced at recombination
What can we learn?

• **B Modes**: pattern of “vectors”
• **After recombination**: Reionization “Bump”, lensing
• **At recombination**: Acoustic peaks
Information in polarization

- Improvement in parameter constraints + consistency checks
- Test super-horizon nature of perturbations
- Features in the primordial power spectrum
- Isocurvature components
- Test of time evolution of physical constants

- Constrain how and when the universe reionized
- Measure mass distribution along the line of sight (lensing)

- Detect gravity waves from inflation
The Information in the pattern
E-B Decomposition

Map is 5 degrees square
\[ Q = I_\theta - I_\phi \]
\[ U = I_{\theta + \pi/4} - I_{\phi + \pi/4} \]
Density pert. & Gravity Waves

\[ Q > 0 \quad U = 0 \]

\[ Q < 0 \quad U = 0 \]

\[ E < 0 \]

\[ E > 0 \]

\[ Q = 0 \quad U < 0 \]

\[ Q = 0 \quad U > 0 \]

\[ B < 0 \]

\[ B > 0 \]
Power spectra of E & B

- Temperature
- Density modes
- Polarization
- Gravity waves
- B lensing
Gravity waves from Inflation

Each polarization of the GW fluctuates during inflation by

$$\frac{1}{M_{Pl}} \frac{H}{2\pi}$$

$$P_g = \frac{2}{M_{pl}^2} \left(\frac{H}{2\pi}\right)^2$$

$$\frac{l(l + 1)C_l^T}{2\pi} \approx 6 \times 10^{-3} \left(\frac{H}{M_{pl}}\right)^2$$

Directly measure the expansion rate during Inflation

If $$r \sim 10^{-4}$$ (limit imposed by lensing)

$$\frac{H}{M_{pl}} \sim 1.3 \times 10^{-6}$$

$$V^{1/4} \sim 3 \times 10^{15} \text{GeV}$$

$$M_{unification} \sim 3 \times 10^{16} \text{GeV}$$
Super-horizon perturbations

Observer

2°

Decoupling

Initial conditions

Spergel & MZ
TESTING INFLATION
The sign of the TE cross correlation

Causal seed model

Fig. 1. — Temperature-Polarization angular power spectrum. The large-angle TE power spectrum predicted in primordial adiabatic models (solid), primordial isocurvature models (dashed), and in causal scaling seed models (dotted). The WMAP TE data (Kogut et al. 2003) is shown for comparison, in bins of $\Delta l = 10$. 
After Recombination

Tight Coupling

Free Streaming

Observer Today
Gravitational Lensing

Lensing induced $B$ modes

- $Q > 0$, $U = 0$
- $E < 0$
- $Q = 0$, $U < 0$
- $B < 0$
- $Q = 0$, $U > 0$
- $B > 0$

Graph showing
- Temperature
- Density modes
- Polarization
- Gravity Waves

$[\delta(l+1)c^2/2\pi]^2$ [μK] vs. $l$
1. The height of the bump is given by the optical depth
2. The quadrupole is produced by the free streaming of the monopole at recombination, \( k \sim 2/(\tau_{\text{reio}} - \tau_{\text{rec}}) \) produces the biggest quadrupole
3. Angular scale \( l \sim (\tau_{\text{o}} - \tau_{\text{reio}})/(\tau_{\text{reio}} - \tau_{\text{rec}}) \)
Kovac et al.
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Map is 5 degrees square
Power spectra of E & B
The future of GW constraints: Polarization

Density pert. & Gravity Waves

- \( Q > 0 \) \( \Rightarrow U = 0 \)
- \( Q < 0 \) \( \Rightarrow U = 0 \)
- \( E < 0 \)
- \( B < 0 \)

Gravity Waves

- \( Q = 0 \) \( \Rightarrow U < 0 \)
- \( Q = 0 \) \( \Rightarrow U > 0 \)
- \( E > 0 \)
- \( B > 0 \)

Seljak & MZ
Kamionkowski Kosowsy & Stebbins
FIG. 2.— Maps of the $T$ (top panels), $Q$ (middle panels) and $U$ (lower panels) Stokes parameters over the full QUaD sky area at 100 GHz (left) and 150 GHz (right). For display purposes only, the maps have been smoothed with a 5 arcmin Gaussian kernel. Note the difference in the color stretch used to display the temperature and polarization maps.
Constraints on $r$

BICEP \quad r < 0.73 \quad (95\% \text{ conf}) \quad \text{B modes}

WMAP \quad r < 0.4 \quad (95\% \text{ conf}) \quad \text{Shape PS}
Summary

• The CMB is slightly polarized
• Polarization is generated by Thomson scattering of radiation that had a quadrupole anisotropy
• For density modes, polarization is roughly proportional to the velocity gradient across the mean free path
• A stochastic background of gravitational waves leave a characteristic signature
• GW produced in inflation are observable if $E \approx 10^{16}$ GeV
• Reionization leaves an signature on large scales
• Secondary effects such a lensing can create B even if there are no GW