A New Limit on CMB Circular Polarization from SPIDER

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Stokes Parameters

Plane wave traveling in the z direction

\[ E = \left( E_x e^{i\phi_x} \hat{x} + E_y e^{i\phi_y} \hat{y} \right) e^{i\omega t} \]

\[ I = \langle E_x^2 \rangle + \langle E_y^2 \rangle \quad U = \langle 2E_x E_y \cos (\phi_x - \phi_y) \rangle \]
\[ Q = \langle E_x^2 \rangle - \langle E_y^2 \rangle \quad V = \langle 2E_x E_y \sin (\phi_x - \phi_y) \rangle \]
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Polarization

<table>
<thead>
<tr>
<th>+Q</th>
<th>+U</th>
<th>+V</th>
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<tbody>
<tr>
<td><img src="image" alt="Diagram" /></td>
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<td><img src="image" alt="Diagram" /></td>
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</tbody>
</table>
| Q > 0; U = 0; V = 0  
(a) | Q = 0; U > 0; V = 0  
(c) | Q = 0; U = 0; V > 0  
(e) |
| Q < 0; U = 0; V = 0  
(b) | Q = 0, U < 0, V = 0  
(d) | Q = 0; U = 0; V < 0  
(f) |
Stokes Parameters

Plane wave traveling in the z direction

\[ E = (E_x e^{i\phi_x \hat{x}} + E_y e^{i\phi_y \hat{y}}) e^{i\omega t} \]

\[
\begin{align*}
I &= \langle E_x^2 \rangle + \langle E_y^2 \rangle & U &= \langle 2E_x E_y \cos(\phi_x - \phi_y) \rangle \\
Q &= \langle E_x^2 \rangle - \langle E_y^2 \rangle & V &= \langle 2E_x E_y \sin(\phi_x - \phi_y) \rangle
\end{align*}
\]
Methods of Generating Circular Polarization

1. Magnetic Fields
   - Primordial magnetic fields
   - Galaxy clusters
   - Pop III supernova remnants

2. Interactions with Known Particles
   - Scattering from neutral H
   - Cosmic neutrino background

3. Extensions to QED
   - Quantum vacuum corrections
   - Lorentz invariance violating operators
   - Axion fields

More complete list and references in King and Lubin 2016 (1606.04112)
Predicted V Signals are Small

Signal predictions rely on many assumptions
(some poorly constrained)
Predicted V Signals are Small

V predictions are much smaller than linear polarization measurements

King and Lubin 2016
1606.04112

CMB-S4 Science Book
1610.02743
CMB Circular Polarization Measurements

Lubin et al 1983
MIPOL: Mainini et al 2013 1307.6090
VLA: Partidge et al 1988
SPIDER Overview

- 16 day flight in Jan 2015
- 95 and 150 GHz
- ~0.5 degree beams
- 2nd flight with 285 GHz receivers planned for Dec 2018

Fraisse et al 2013, 1106.3087
Rahlin et al 2014, 1407.2906
HWP Polarization Modulators

Flight Operation
- Step in integer multiples of 22.5° every half day
- Use complementary angles for good Q/U coverage at each frequency
- 8 distinct HWP positions

- Modulate instrument polarization sensitivity
- Birefringent single-crystal sapphires
- 4 K operation
- Rotated in discrete steps
HWPs and Circular Polarization

A non-ideal HWP partially transforms circular polarization to linear

Power detected

\[ d_V \sim s_\gamma \sin(2\theta_{\text{HWP}} - 2\xi_{\text{det}}) \]
Calculating SPIDER’s V-Coupling

Theoretical procedure can be found in Bryan et al 2010 and Savini et al 2006

Calculate \( s \) for each HWP based on

1. Measured physical HWP properties
2. Measured observing bands (for each receiver)
3. Source spectrum (CMB blackbody)

**HWP Properties**

- Refractive index and thickness of
- sapphire
- both AR coats
- bonding layers

for each HWP

Rahlin et al 2014, 1407.2906
Calculating SPIDER’s V-Coupling

Circular Polarization Coupling for the SPIDER HWPs

95 GHz Receivers

Receiver Name: X2
Mean: -0.003
Std: 0.040

Receiver Name: X4
Mean: 0.014
Std: 0.039

150 GHz Receivers

Receiver Name: X1
Mean: -0.088
Std: 0.042

Receiver Name: X3
Mean: -0.154
Std: 0.042

Receiver Name: X6
Mean: -0.039
Std: 0.040

Receiver Name: X5
Mean: -0.096
Std: 0.042

3 independent measurements at each frequency improves V sensitivity
Making V Spectra

Compute cross-spectra for pairs of $s=1$ maps at each frequency

Use Monte Carlo sims to combine with $s$ distributions

No detection of circular polarization

Error in $s$ is highly correlated between bins
SPIDER’s CMB V Limit

Convert spectra to 2σ upper limits and compare to other measurements

**VV Limit Comparison (95% C.L.)**

- MIPOL Limit: 33 GHz
- SPIDER Limit: 95 GHz
- SPIDER Limit: 150 GHz
SPIDER’s CMB V Limit
Can be extended to a limit on foregrounds and other source spectra

E-modes $\sim 10^0 \mu K^2$
Conclusions

- SPIDER is primarily a linear polarization experiment, but can measure V through HWP non-idealities.

- New upper limit on CMB V V spectrum of 141 to 255 μK² from 33 < ℓ < 307 at 150 GHz.

- No proposed generation mechanisms predict signals at this level, but this is a free sanity check on the universe.

- Other CMB experiments may be able to apply this technique to their data to improve this limit (including SPIDER2).

Nagy et al, 1704.00215
Bonus Slides
Making V Maps

Deglitch and filter the raw data

Split data into 4 independent maps for each receiver
Circularly Polarized Foregrounds

- Galactic foregrounds are the primary concern
- Dominated by synchrotron at the low frequencies of interest
- Can extend SPIDER’s limit to foregrounds, but expected signals are small (though typically larger than expected cosmological signals)

Predicted Foreground Signals

King and Lubin 2016
1606.04112
HWP Non-Idealities

- Arise due to wide band and imperfect AR coating
- See evidence from them in our angle calibration
- Create changes in linear polarization modulation

**SPIDER Calibration Data**

X6 Detector Angle vs. HWP Angle for one A/B pair

- Detector Angle (degrees)
- HWP Angle (degrees)
HWP Non-Idealities

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SPIDER Calibration Data