Observing cosmic reionization with PAPER: polarized foreground simulations and all sky images

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Challenges of 21 cm experiments

Bright foregrounds
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Bright foregrounds

Strength

- Distinct spectral behaviors between foregrounds and EoR signal
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Bright foregrounds

Methodologies

- Foreground subtraction

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- Distinct spectral behaviors between foregrounds and EoR signal
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- Foreground subtraction
- Foreground avoidance

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- Distinct spectral behaviors between foregrounds and EoR signal

Dillon et al., 2015
Challenges of 21 cm experiments

Bright foregrounds

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Dillon et al., 2015

Pober et al., 2013
Challenges of 21 cm experiments

**Bright foregrounds**

- Extragalactic foregrounds (\(\approx 0.8\)K)
- Galactic foregrounds (\(\approx 2\)K)
- Cosmological 21 cm signal
- Radio galaxies and clusters
- Free-free emission
- Synchrotron emission

**Methodologies**

- Foreground subtraction
- Foreground avoidance

**Polarized foregrounds**

- Unsmooth spectral behaviour

**Strength**

- Distinct spectral behaviors between foregrounds and EoR signal

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Dillon et al., 2015

Jelic et al., 2010
Simulation of leakage of polarized foregrounds to the EoR power spectrum

Polarized foregrounds leak into the EoR signal

- Generate visibilities

\[ v(b, \nu) = S^{-1} v_c(b, \nu) \]
\[ = \int_{\Omega} A(\hat{r}, \nu) s(\hat{r}, \nu) e^{-2\pi i \nu \frac{b \cdot \hat{r}}{c}} d\Omega \]
\[ = S^{-1} \int_{\Omega} [J(\hat{r}, \nu) \otimes J^*(\hat{r}, \nu)] S s(\hat{r}, \nu) e^{-2\pi i \nu \frac{b \cdot \hat{r}}{c}} d\Omega \]
Polarized foregrounds leak into the EoR signal

- Generate visibilities

\[
\mathbf{v}(\mathbf{b}, \nu) = S^{-1} \mathbf{v}_c(\mathbf{b}, \nu) = \int_{\Omega} A(\mathbf{\hat{r}}, \nu) s(\mathbf{\hat{r}}, \nu) e^{-2\pi i \nu \mathbf{b} \cdot \mathbf{\hat{r}} / c} d\Omega = S^{-1} \int_{\Omega} \left[ J(\mathbf{\hat{r}}, \nu) \otimes J^*(\mathbf{\hat{r}}, \nu) \right] S s(\mathbf{\hat{r}}, \nu) e^{-2\pi i \nu \mathbf{b} \cdot \mathbf{\hat{r}} / c} d\Omega
\]

Mueller matrix at 150 MHz
Polarized foregrounds leak into the EoR signal

- Generate visibilities

\[ \mathbf{v}(b, \nu) = S^{-1} \mathbf{v}_c(b, \nu) = \int_\Omega \mathbf{A}(\hat{r}, \nu) s(\hat{r}, \nu) e^{-2\pi i \nu \frac{b \cdot \hat{r}}{c}} d\Omega \]

\[ = S^{-1} \int_\Omega [\mathbf{J}(\hat{r}, \nu) \otimes \mathbf{J}^*(\hat{r}, \nu)] \mathbf{S}(\hat{r}, \nu) e^{-2\pi i \nu \frac{b \cdot \hat{r}}{c}} d\Omega \]

- Delay Transform visibilities

\[ \tilde{\mathbf{v}}(b, \tau) = \int_B w(\nu) \mathbf{v}(b, \nu) e^{-2\pi i \nu \tau} d\nu \]

\[
\begin{pmatrix}
I' \leftrightarrow I & I' \leftrightarrow Q & I' \leftrightarrow U & I' \leftrightarrow V \\
Q' \leftrightarrow I & Q' \leftrightarrow Q & Q' \leftrightarrow U & Q' \leftrightarrow V \\
U' \leftrightarrow I & U' \leftrightarrow Q & U' \leftrightarrow U & U' \leftrightarrow V \\
V' \leftrightarrow I & V' \leftrightarrow Q & V' \leftrightarrow U & V' \leftrightarrow V
\end{pmatrix}
\]

Mueller matrix at 150 MHz
Polarized foregrounds leak into the EoR signal

- Generate visibilities

\[
v(b, \nu) = S^{-1} v_c(b, \nu) = \int_{\Omega} A(\hat{r}, \nu) s(\hat{r}, \nu) e^{-2\pi i \nu \frac{b \cdot \hat{r}}{c}} d\Omega
\]

\[
= S^{-1} \int_{\Omega} [J(\hat{r}, \nu) \otimes J^*(\hat{r}, \nu)] S s(\hat{r}, \nu) e^{-2\pi i \nu \frac{b \cdot \hat{r}}{c}} d\Omega
\]

- Delay Transform visibilities

\[
\tilde{v}(b, \tau) = \int_{B} w(\nu) v(b, \nu) e^{-2\pi i \nu \tau} d\nu
\]

- Generate power spectrum

\[
p(k) = \left(\frac{\lambda^2}{2k_B}\right)^2 D^2 \Delta D B^{-1} \{\tilde{v}(|b|, \tau) \circ \tilde{v}(|b|, \tau)^*\}
\]
Simulation Pipeline
Simulation Pipeline

Foreground modelling
Simulation Pipeline

Foreground modelling

Point Source

Diffuse Emission

Bernardi et al., 2013
Simulation Pipeline

Foreground modelling

Point Source

Instrument modelling

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- Foreground modelling
- Instrument modelling
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Foreground modelling

Instrument modelling

Generate visibilities

Power Spectrum Estimates

Point Source

Diffuse Emission

Bernardi et al., 2013
Power Spectrum Results

2D polarized power spectra generated from point source simulation
Leakage Estimation

Polarized power spectra generated assuming no total intensity.
PAPER-128 Data Analysis
PAPER-128 Observation setup
PAPER-128 Observation setup

uv-coverage of PAPER-128 for 10 minutes observations across a single frequency channel
Calibration & Imaging Pipeline

PAPER Data

Data Compression → Flagging → Absolute Calibration → Form Stokes visibilities

Phase rotate visibilities → Map making → RM Synthesis

Science Results
Stokes I map between 120-175 MHz averaged over 40 days of observations
Stokes Q map between 120-175 MHz averaged over 40 days of observations
Estimate of Instrumental Polarization

Polarization fraction estimated from the source extracted from the averaged maps as a function of radial distance from the phase center.
Conclusions

- The challenge in EoR observations is the separation of the 21 cm signal from the bright foregrounds.
- We presented a formalism to describe the leakage in the 2D power spectra due to instrumental widefield effects.
- We found that the leakage due to a population of point sources is expected to be higher than the galactic diffuse emission -- whose power spectra is
  \[ \Delta^2(k) < 10 \text{ (mK)}^2; \ k > 0.2 \text{ hMpc}^{-1} \]
- We also presented all-sky polarized maps obtained from the last observing season from PAPER-128.
- We attempted to constrain the polarization fraction at low frequency using observations from PAPER-128.
- We shall be using these observations to characterize polarized foregrounds through RM synthesis.
THANK YOU