Synchrotron Radiation as a Foreground to the Global Redshifted 21-cm Measurement by EDGES

Raul A. Monsalve

University of Colorado Boulder - Arizona State University
**Take Home Message:**

1) EDGES is ruling out an important set of physical models for the Global 21-cm Signal, and has sensitivity that would allow detection.

2) Current focus is on understanding the measurements at the mK level.

3) Accuracy of the diffuse galactic and extragalactic foreground model is of great importance for this purpose.
The Global Redshifted 21-cm Signal
Some Constraints on Reionization:
- Universe ionized by $z \sim 6$ from Gunn-Peterson trough (Fan et al. 2002).
- Planck collaboration et al. (2016) suggest reionization redshift of $z_r = 8.5 \pm 1$. 
Emission at 21-cm from Hydrogen Atom

Parallel spins
Upper ground state

Anti-parallel spins
Lower ground state

Due to Cosmological Expansion

\[ v_{\text{obs}} = \frac{v_{\text{emit}}}{1 + z} \]

<table>
<thead>
<tr>
<th>Redshift</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1420 MHz</td>
</tr>
<tr>
<td>6</td>
<td>200 MHz</td>
</tr>
<tr>
<td>35</td>
<td>40 MHz</td>
</tr>
</tbody>
</table>
21-cm Cosmology

Cosmological Brightness Temperature

\[ T_{21}(\theta, z) \approx 28 \text{ mK} \cdot (1 + \delta) \cdot \sqrt{\frac{1+z}{10}} \cdot x_{\text{HI}} \cdot \left( \frac{T_S - T_{\text{CMB}}}{T_S} \right) \]
Spin Temperature

\[
\frac{n_{\text{upper}}}{n_{\text{lower}}} = 3 \cdot \exp \left( - \frac{h \cdot v_{21\text{cm}}}{k_b \cdot T_S} \right)
\]

\( v_{21\text{cm}} = 1420 \text{ MHz} \)
\( h \): Planck constant
\( k_b \): Boltzmann constant

http://www.cv.nrao.edu/course/astr534/HILine.html

\[
T_{S}^{-1} \approx \frac{T_{\text{CMB}}^{-1} + x_c T_{K}^{-1} + x_\alpha T_{\alpha}^{-1}}{1 + x_c + x_\alpha}
\]

\( T_K \): kinetic temperature of the gas
\( T_\alpha \): color temperature of Ly\( \alpha \) photons
\( x_c \): coupling due to collisions
\( x_\alpha \): coupling due to Wouthuysen-Field effect
Global (sky-average) 21-cm Signal

Model

Pritchard & Loeb 2011
Global Signal for Different Scenarios

Pritchard & Loeb (2011)
Global Signal Examples

**Fialkov et al. (2014)**
- Semi-numerical.
- Hard spectra of X-ray binaries.

**Mirocha et al. (2017)**
- Analytical.
- No Pop III stars.
- $z < 8$ galaxy luminosity function extrapolated to lower luminosities and higher redshifts.
- Inefficient heating induced by XRBs with hard spectra.

**Kaurov & Gnedin (2016)**
- Uncertainty in models is high.
Analogy with the CMB
Arrays Targeting the EoR (> 100 MHz)

<table>
<thead>
<tr>
<th>Array</th>
<th>FoV deg²</th>
<th>Area m²</th>
<th>Type</th>
<th>FWHM$_{150}$ arcmin</th>
<th>PS S/N* FG Avoidance</th>
<th>PS S/N* FG Removal</th>
<th>Start date</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAPER-128</td>
<td>1600</td>
<td>1200</td>
<td>Dipole</td>
<td>23</td>
<td>1.2</td>
<td>4.8</td>
<td>2013</td>
</tr>
<tr>
<td>MWA-128 Im</td>
<td>300</td>
<td>3600</td>
<td>Tile</td>
<td>10</td>
<td>0.6</td>
<td>6.4</td>
<td>2013</td>
</tr>
<tr>
<td>LOFAR Im</td>
<td>25</td>
<td>36000</td>
<td>Tile</td>
<td>5</td>
<td>1.4</td>
<td>17</td>
<td>2013</td>
</tr>
<tr>
<td>HERA-331</td>
<td>64</td>
<td>54000</td>
<td>Dish</td>
<td>20</td>
<td>23</td>
<td>91</td>
<td>2018</td>
</tr>
<tr>
<td>SKA-I Low Im</td>
<td>30</td>
<td>420000</td>
<td>Tile</td>
<td>5</td>
<td>13</td>
<td>140</td>
<td>2021+</td>
</tr>
</tbody>
</table>

LWA New Mexico / OVRO: @ lower frequencies
Power Spectrum of Anisotropies

Credit: M. Eastwood

Redshift Evolution

Scale Dependence

Fialkov et al. 2014
Real Progress in Techniques and Science from Arrays

First astrophysically relevant limits from PAPER:
Early pre-heating of neutral IGM before reionization
Why Global Measurements

1) Direct probe of the average gas temperature (kinetic and spin) and fraction of neutral hydrogen.
2) This provides constraints on:
   • star and galaxy formation history
   • early feedback mechanisms
   • heating of the IGM
   • redshift and duration of epoch of reionization
3) “Simpler” instrumentation than arrays.
4) One of the few current alternatives to probe Cosmic Dawn (z > 14) period.

Challenges

1) Hard instrument calibration problem.
2) Strong diffuse foregrounds compared to signal.
No Cosmological 21-cm Signal Detected Yet

Constraints on the global signal from EDGES, LEDA, SCIHI, SARAS
Diffuse Foregrounds
Dark Ages Radio Explorer (DARE)
Proposed to NASA MIDEX program in Dec 2016
1) Used for calibration and simulation of observations.
2) From hundreds to thousands of Kelvins.
3) Include Galactic and Extragalactic.
4) Mostly synchrotron radiation.
5) Large spatial gradients.
6) Techniques suggested to take advantage of these gradients for signal separation (e.g. Liu et al. 2013, Switzer & Liu 2014).
Global Sky Models

Oliveira-Costa et al. (2008)

Zheng et al. (2017)

1) **Sky models** from MHz to THz.
2) **Interpolation** requires up to 5 terms.
3) **Spectral smoothness** supported by, i.e.:
   - Theoretical models (Bernardi et al. 2015)
   - Measurements from ARCADE-2 (Kogut et al. 2011; Kogut 2012)

Also:
Sathyanarayana Rao et al. (2016)
Polarized Diffuse Foreground

1) Cosmological signal is **NOT polarized**.
2) Diffuse foreground is **polarized** ($\leq 5\%$) (Lenc et al. 2016).
3) **Potential leakage** from Polarized signal to Unpolarized Intensity.
4) **Potential introduction of spectral structure** due to Faraday Rotation.
5) From simulations, **low impact expected** on the Global 21-cm signal due to beam dilution.

Observation with MWA $\sim 150$ MHz
Low-foreground region
Lenc et al. (2016)
Induced Polarization Technique

1) Technique based on the **modulation of foregrounds**.
2) **Foreground** varies spatially but is **spectrally smooth**.
3) **Global 21-cm** signal is spatially uniform but **spectrally complex**.
4) Frequency-dependent modulation amplitude represents the **foreground alone, and is contained in Stokes Q**.
5) **Stokes I contains both**, foreground and 21-cm signal.
6) Tested on the ground, **in preparation for DARE**.

Cosmic Twilight Polarimeter (CTP)

- **Top view:** Y crosses dipole for polarization measurements
- **Center at the North Celestial Pole with revolving foreground**
- **Antenna Primary Beam**
- **Tilted ground screen (Galvanized steel mesh)**
- **Ground**
- **Scale & subtract**
- **Only scaling error**

Nhan et al. (2017)
Global Experiments
BIGHORNS
(Curtin U., Australia, Sokolowsky et al.)

HYPERION
(Berkeley)

SARAS
(RRI, India, Subrahmanjan et al.)

SCI-HI -> PRIZM
(Carnegie Mellon, Peterson et al.)

LEDA
(Harvard, Caltech, Greenhill et al.)
EDGES
Experiment to Detect the Global EoR Signature

Prof. Judd Bowman (PI)
Dr. Alan Rogers
Dr. Raul Monsalve
Mr. Thomas Mozdzen
Ms. Nivedita Mahesh
Murchison Radio-astronomy Observatory (MRO)
Radio-Quiet Site
Two EDGES Instruments

- **EDGES Low Band**
- **EDGES High Band**

![Graph showing the relationship between frequency and brightness for different cosmic periods](image)

- **Dark Ages**
- **Cosmic Dawn**
- **Reionization**

- Key events:
  - Thermal Decoupling
  - First Galaxies Form
  - UV pumping (Wouthuysen-Field effect)
  - (X-ray) Heating

- Frequency range: 0 - 200 MHz
- Brightness range: -150 to 50 mK

- Pritchard & Loeb 2011
EDGES Block Diagram

Wideband Antenna

Receiver
Low-noise Amplification + Calibration Electronics

Back-End Stage
Amplification + Digitization

Details in:
Mozdzen et al. (2016)
Monsalve et al. (2017)

FWHM $\approx 70^\circ \times 110^\circ$
EDGES High-Band 2015-2016

Ground plane:
10m x 10m

Antenna size:
1m long / 0.5m high
OLD Ground plane:
10m x 10m

Antenna size:
2m long / 1m high
NEW Ground Plane:
Central Square: 20m x 20m
16 Triangles: 5m-long

Welding Wiregrid Panels
Example 10-day averages:

OLD
180 mK

NEW
68 mK

Factor ~3 improvement due to NEW Ground Plane
Instrumental Calibration

Calibration involves removing the following effects:

1) Receiver gain and offset.
2) Impedance mismatch between receiver and the antenna.
3) Antenna and ground losses.
4) Frequency-dependence of the antenna beam.
Observations

Beam snapshots

-26.7°
Observations

EDGES Low-Band

EDGES High-Band

antenna temperature [K]

frequency [MHz]

LST = 3.2 hr

LST = 17.8 hr
Beam chromaticity

Antenna-to-Sky Average Temperature

\[ \langle T_{\text{ant}}(\nu, \text{LST}) \rangle_\Omega = \int T_{\text{sky}}(\nu, \text{LST}, \Omega) \cdot B(\nu, \text{LST}, \Omega) \, d\Omega \]

\[ \langle T_{\text{ant}}(\nu, \text{LST}') \rangle_\Omega = C(\nu, \text{LST}') \cdot \langle T_{\text{sky}}(\nu, \text{LST}) \rangle_\Omega \]

Chromaticity Correction

\[ C(\nu, \text{LST}) = \frac{\int T_{\text{sky}}(\vec{\nu}_{\text{ref}}, \text{LST}, \Omega) \cdot B(\vec{\nu}, \text{LST}, \Omega) \, d\Omega}{\int T_{\text{sky}}(\vec{\nu}_{\text{ref}}, \text{LST}, \Omega) \cdot B(\vec{\nu}_{\text{ref}}, \text{LST}, \Omega) \, d\Omega} \]

Simulated Antenna Beam at One Frequency
Chromaticity Correction

Scaled Haslam [%]

Guzman-Haslam Interpolation [%]

Difference [%]
Beam-Weighted Spectral Index of Diffuse Foregrounds at $\text{DEC} = -26.7^\circ$

Fit Model:
Two-parameter Power Law:

$$T_{\text{sky}}(v) = T_{150} \left( \frac{v}{150 \text{ MHz}} \right)^{+\beta} + T_{\text{CMB}}$$

Mozdzen et al. (2017)

Previous result:
Rogers & Bowman (2008) estimated $\beta = -2.5 \pm 0.1$
Space-dependent Spectral Index

Example of discrepancies between the spectral index computed from maps of the GSM-2008, and directly from the low-frequency measurements.
EDGES High-Band
Observations from 2015

1. Residuals to 5-term polynomial
2. 40 days of nighttime
3. 6-hr averages
4. Low foregrounds
5. Typical daily RMS residuals ~ 60 mK
1. Residuals to 5-term polynomial
2. Average of 40 days of nighttime
3. 6-hr average
4. Low foregrounds
Parameter Estimation: Weighted Least Squares

Measurement model
\[ d = T_{21} + T_{\text{fg}} + \text{noise} = a_{21} \text{ Model}_{21} + \left[ \sum_{i=0}^{N_{\text{fg}}^{-1}} a_i u^{-2.5+i} \right] + \text{noise} \]

Linear parameter vector
\[ \lambda = [a_{21}, a_i] \]

Estimates
\[ \hat{\lambda} = (A^T WA)^{-1} A^T W d \quad \Rightarrow \quad \hat{a}_{21} \]
\[ \hat{\Sigma} = (A^T WA)^{-1} \quad \Rightarrow \quad \hat{\sigma}_{21} \]

Number of foreground terms \( N_{\text{fg}} \)

Uncertainty
residuals
covariance

Estimates
\( \hat{\lambda} \)
\( \hat{\Sigma} \)
Rejection of Physical Models: Mirocha et al. (2017)

Galaxy Luminosity Function (LF): number density of galaxies per unit luminosity

Parameters explored:
1) Star formation rate density (SFRD).
2) Intrinsic UV and X-ray photon production of galaxies.
3) Escape of photons from galaxies.

Thousands of models available.
Rejection of Physical Models: Mirocha et al.

Sample of Rejected 21-cm Amplitudes

Monsalve et al., in preparation

From numerical simulations:
Fialkov et al. (2016)
Cohen et al. (2017)

Parameters explored:
1) Star formation efficiency.
2) Minimal mass of star-forming halos.
3) Efficiency and spectral energy distribution of first X-ray sources.
4) History of reionization.

Thousands of models available.

Monsalve et al., in preparation
EDGES **Low-Band 1**: Sample of Observations (4-terms removed over 30-MHz Bandwidth)

**Day of Year**, 2015 [2 K per division]
1) From both Low-Band instruments we have enough data to reduce the noise below $\sim 20$ mK over wide (>40 MHz) frequency ranges.

2) Carefully exploring the consistency of the different data sets, using two independent processing pipelines.

3) Main target is 21-cm signal, but enough data and sensitivity to conduct refined spectral index study. Future Work.
Diffuse Foregrounds Among Calibration Uncertainties

Uncertainties Assigned to Calibration Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1-σ Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Receiver</strong></td>
<td></td>
</tr>
<tr>
<td>Temperature correction</td>
<td>0.1°C</td>
</tr>
<tr>
<td>Absolute calibration</td>
<td>from Monsalve et al. (2017) (*)</td>
</tr>
<tr>
<td><strong>Antenna Reflection Coefficient</strong></td>
<td></td>
</tr>
<tr>
<td>Magnitude</td>
<td>$10^{-4}$ in voltage ratio (*)</td>
</tr>
<tr>
<td>Phase</td>
<td>0.1° (*)</td>
</tr>
<tr>
<td><strong>Antenna Losses</strong></td>
<td></td>
</tr>
<tr>
<td>Balun length</td>
<td>1 mm</td>
</tr>
<tr>
<td>Connector length</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Balun and connector radii</td>
<td>3%</td>
</tr>
<tr>
<td>Balun and connector conductivity</td>
<td>1%</td>
</tr>
<tr>
<td>Connector teflon permittivity</td>
<td>1%</td>
</tr>
<tr>
<td>Panel loss</td>
<td>10% (*)</td>
</tr>
<tr>
<td>Ground loss</td>
<td>10% of nominal +</td>
</tr>
<tr>
<td></td>
<td>30% from FEKO and CST (*)</td>
</tr>
<tr>
<td><strong>Chromaticity Factor</strong></td>
<td></td>
</tr>
<tr>
<td>Foreground model</td>
<td>50% of difference between</td>
</tr>
<tr>
<td></td>
<td>nominal and Zheng et al. (2017) (*)</td>
</tr>
<tr>
<td>Antenna panel height</td>
<td>2 mm</td>
</tr>
<tr>
<td>Antenna panel length</td>
<td>2 mm</td>
</tr>
<tr>
<td>Antenna panel width</td>
<td>2 mm</td>
</tr>
<tr>
<td>Antenna panel separation</td>
<td>1 mm</td>
</tr>
<tr>
<td>Ground plane length</td>
<td>5 cm</td>
</tr>
<tr>
<td>Ground plane width</td>
<td>5 cm</td>
</tr>
<tr>
<td>Antenna orientation angle</td>
<td>0.5°</td>
</tr>
<tr>
<td>Soil conductivity</td>
<td>50%</td>
</tr>
<tr>
<td>Soil relative permittivity</td>
<td>50%</td>
</tr>
</tbody>
</table>

**Note.** — (i) Unless otherwise noted, percentages are given as relative to the nominal value. (ii) The symbol (*) denotes frequency-dependent values.

**Work in Progress**

1) Implementing a rigorous quantification and propagation uncertainties.

2) Using **Singular Value Decomposition (SVD)** to find foreground and instrument orthogonal basis functions.

3) Incorporating all diffuse foreground maps available.

4) **Sampling** physical, instrumental, and foreground parameters using MCMC.
Summary

- **EDGES High-Band noise** < 10 mK.
- Probing thousands of physical models, produced analytically and numerically.
- Ruling out large fractions of those models with high significance.
- Estimated **B-W spectral index of diffuse foregrounds** with 0.01 uncertainty at DEC = −26.7°.
- **Low-Band noise** < 20 mK.
- Two Low-Band instruments, in different configurations, to distinguish the spectral features intrinsic to the sky from those due to calibration systematics.
- Intending to do a refined **Low-Band spectral index study** to complement High-Band results.
Thank you