An Absorption Feature in the All-Sky Radio Spectrum

Raul Monsalve

McGill University

Credit: NASA / WMAP Team
**CMB**

**DARK AGE**

**COSMIC DAWN**

**REIONIZATION**

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**Time**

- 380,000 years
- 100 million years
- 300 million years
- 1 Gyr
- 13.8 Gyr

**Redshift**

- 1100
- 30
- 14
- 6

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Neutral Hydrogen in the Intergalactic Medium (IGM)

Targeted by EDGES

Fraction of Neutral Hydrogen < 6%

[McGreer et al. 2015]
Standard Prediction for Global 21-cm Signal

- Dark Ages
- Cosmic Dawn
- Reionization

Brightness Temperature [mK]

Frequency [MHz]

Pritchard & Loeb 2011
EDGES

Experiment to Detect the Global EoR Signature

Prof. Judd Bowman (PI)
Dr. Alan Rogers
Dr. Raul Monsalve
Dr. Thomas Mozdzen
Ms. Nivedita Mahesh
Western Australia

Murchison Radio-astronomy Observatory (MRO)
Radio-Quiet Site
EDGES Instrument Block Diagram

- Total-power Spectral Radiometer
- Drift-scan Instrument
- Single, Wideband, Dipole Antenna

FWHM ≈ 70° × 110°

Zenith-pointing Beam

Antenna

Receiver

Low-noise Amplification + Calibration Electronics

Back-End Stage

Amplification + Digitization + FFT

100-m Cable
EDGES Low-Band

Antenna size:
2m long / 1m high

TWO Low-Band Instruments
Main Challenges

1) **Hard instrument calibration** problem.

2) **Strong diffuse foregrounds (Galactic and Extragalactic)** compared to cosmological 21-cm signal.
Instrumental Calibration

1) Instrument gain and noise offset.

2) Impedance mismatch between receiver and the antenna.

3) Antenna and ground losses.

4) Frequency-dependence of the antenna beam.
Diffuse Foregrounds

45-MHz Map
Guzmán et al. (2011)

1) From hundreds to thousands of Kelvins.
2) Include Galactic and Extragalactic.
3) Mostly Galactic synchrotron radiation.
4) Smooth spectral dependence expected.

408-MHz Map
Haslam et al. (1982)
Beam Projected onto the Sky
Constraining Standard Models with the EDGES High-Band Spectrum
Monsalve, Rogers, Bowman, & Mozdzen (2017b)

No detection claimed in this frequency range

Integration
- 40 days
- 6 hrs of low foreground regions
- Noise of 6 mK at 140 MHz.
Physical 21cm Models from Fialkov et al.

### Early star formation

\( V_c \): minimum virial circular velocity of halos

\( f_* \): star formation efficiency

### IGM X-ray heating

\( f_X \): X-ray heating efficiency

\( \nu_{\text{min}} \): minimum energy of X-rays

### Reionization

\( R_{\text{mfp}} \): mean-free path of ionizing photons

\( \tau_e \): CMB optical depth

Foreground parameters are marginalized

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**Monsalve, Fialkov, Bowman, Rogers, Mozdzen, Cohen, Barkana, & Mahesh 2019**
High-z Quasars and Galaxies

Planck

Monsalve, Fialkov, Bowman, Rogers, Mozdzen, Cohen, Barkana, & Mahesh 2019
Planck + High-z Quasars + Galaxies

$V_c$ [km s$^{-1}$]

Normalized probability density

Monalve, Fialkov, Bowman, Rogers, Mozdzen, Cohen, Barkana, & Mahesh 2019

$V_c$ [km s$^{-1}$] $f_*$ $f_X$ $\nu_{\text{min}}$ [keV] $\tau_e$
Planck + High-z Quasars + Galaxies + EDGES High-Band

Constraints independent from Low-Band data

Monsalve, Fialkov, Bowman, Rogers, Mozdzen, Cohen, Barkana, & Mahesh 2019
EDGES Low-Band Detection of an Absorption Feature
An absorption profile centred at 78 megahertz in the sky-averaged spectrum

Judd D. Bowman¹, Alan E. E. Rogers², Raul A. Monsalve¹,³,⁴, Thomas J. Mozdzen¹ & Nivedita Mahesh¹
Summary of Detection

- Integrated spectrum
- \( \sim 430 \) hours
- Low foreground regions

Absorption deeper than expected by factor > 2

Two Instruments / Several Configurations

Bowman, Rogers, Monsalve, Mozdzen, Mahesh 2018, Nature, 555, 67
Sensitivity to Possible Calibration Errors

<table>
<thead>
<tr>
<th>Error source</th>
<th>Estimated uncertainty</th>
<th>Modelled error level</th>
<th>Recovered amplitude (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNA S11 magnitude</td>
<td>0.1 dB</td>
<td>1.0 dB</td>
<td>0.51</td>
</tr>
<tr>
<td>LNA S11 phase (delay)</td>
<td>20 ps</td>
<td>100 ps</td>
<td>0.48</td>
</tr>
<tr>
<td>Antenna S11 magnitude</td>
<td>0.02 dB</td>
<td>0.2 dB</td>
<td>0.50</td>
</tr>
<tr>
<td>Antenna S11 phase (delay)</td>
<td>20 ps</td>
<td>100 ps</td>
<td>0.48</td>
</tr>
<tr>
<td>No loss correction</td>
<td>N/A</td>
<td>N/A</td>
<td>0.51</td>
</tr>
<tr>
<td>No beam correction</td>
<td>N/A</td>
<td>N/A</td>
<td>0.48</td>
</tr>
</tbody>
</table>

### Absorption Amplitude for Various GHA

<table>
<thead>
<tr>
<th>Galactic Hour Angle (GHA)</th>
<th>SNR</th>
<th>Amplitude (K)</th>
<th>Sky Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>6-hour bins</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>8</td>
<td>0.48</td>
<td>3999</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
<td>0.57</td>
<td>2035</td>
</tr>
<tr>
<td>12</td>
<td>23</td>
<td>0.50</td>
<td>1521</td>
</tr>
<tr>
<td>18</td>
<td>15</td>
<td>0.60</td>
<td>2340</td>
</tr>
<tr>
<td><strong>4-hour bins</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>5</td>
<td>0.45</td>
<td>4108</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>0.46</td>
<td>2775</td>
</tr>
<tr>
<td>8</td>
<td>13</td>
<td>0.44</td>
<td>1480</td>
</tr>
<tr>
<td>12</td>
<td>21</td>
<td>0.57</td>
<td>1497</td>
</tr>
<tr>
<td>16</td>
<td>11</td>
<td>0.59</td>
<td>1803</td>
</tr>
<tr>
<td>20</td>
<td>9</td>
<td>0.66</td>
<td>3052</td>
</tr>
</tbody>
</table>

Total temperature varies by a factor of up to 3.

Parameter Estimates

From All Cases Processed

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best Fit</th>
<th>Uncertainty (3(\sigma))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>0.5 K</td>
<td>+0.5/-0.2 K</td>
</tr>
<tr>
<td>Center</td>
<td>78 MHz</td>
<td>+/-1 MHz</td>
</tr>
<tr>
<td>Width</td>
<td>19 MHz</td>
<td>+4/-2 MHz</td>
</tr>
<tr>
<td>Flatness</td>
<td>7</td>
<td>+5/-3</td>
</tr>
</tbody>
</table>

Amplitude is in tension with standard models by \(\geq 3.5\sigma\)
How to Explain Deep Absorption?

\[ T_{21}(z) \propto \left( 1 - \frac{T_{\text{CMB}} + T_{\text{EXCESS}}}{T_S} \right) \]

- Radio emission from early black holes [Ewall-Wice et al. 2018]
- Decay of unstable particles [Pospelov et al. 2018] [Aristizabal Sierra & Sheng Fong 2018]

Lower than expected

\[ T_{\text{IGM}} \text{ Lower than expected} \]

Suggested source:
- Interactions between Baryons and Dark Matter particles [Muñoz and Loeb 2018]
Ancient hydrogen reveals clues to dark matter’s identity
To Judd Bowman, Raul Monsalve, Thomas Mozdzen and Nivedita Mahesh of Arizona State University Arizona State University and Alan Rogers of the Massachusetts Institute of Technology for using the EDGES radio telescope to observe colder-than-expected hydrogen gas that existed just 180 million years after the Big Bang; and Rennan Barkana, of Tel Aviv University for calculating that this could be the first direct observation of a non-gravitational interaction between dark matter and conventional matter. While further observations are needed to back-up this hypothesis, the research could help resolve one of the most important unsolved mysteries of physics: what is the nature of dark matter?
Concerns about modelling of the EDGES data

ARISING FROM J. D. Bowman, A. E. E. Rogers, R. A. Monsalve, T. J. Mozdzen & N. Mahesh Nature 555, 67–70 (2018); https://doi.org/10.1038/nature25792

A Ground Plane Artifact that Induces an Absorption Profile in Averaged Spectra from Global 21-cm Measurements - with Possible Application to EDGES

Richard F. Bradley, Keith Tauscher, David Rapetti, and Jack O. Burns
Addressing Concerns: Recent Tests in the Field

**Null Tests** *(feature should not be found)*
1) Measuring noise sources that produce a flat spectrum.
2) Measuring noise sources that produce a spectrum resembling the diffuse foregrounds.

**Tests Addressing Antenna Beam Effects** *(feature should be found)*
1) Using smaller Mid-Band antenna covering 60-160 MHz.
2) Using Low-Band antenna over a smaller 9m x 9m ground plane. We call this Low-Band 3.

These tests have been passed successfully. This supports a spectral feature from the sky.
Verification with EDGES Mid-Band

Low-Band

Mid-Band (~25% smaller)

Same Ground Plane as Low-Band
Preliminary Mid-Band Results

1) Data from May - August 2018.
2) Low foregrounds.
3) Best-fit absorption consistent with Bowman et al. (2018).
4) Some alternative models suggested can be disfavored.

Monsalve, Mahesh, Rogers, Bowman, Mozdzen, & Johnson (in preparation)
Worldwide Effort

+ a few Space-Based Efforts
- Continue favoring a spectral feature in the sky spectrum

- Constraining models and parameters of the early Universe

- Expecting results soon from other experiments

Credit: NASA / WMAP Team
We are Witnessing the Dawn of 21-cm Cosmology
Thank you
Extra Slides
Global Interaction

Background Radiation Temperature

Ly-\(\alpha\) Coupling (WF Effect)

IGM Temperature

Coupling due to atomic collisions

IGM X-ray Heating

Adapted from Greenhill 2018, Nature, 555, 38
$T_b(z) \approx 28 \text{ mK} \cdot \sqrt{\frac{1+z}{10}} \cdot \bar{x}_{\text{HI}} \cdot \left( \frac{T_S - T_R}{T_S} \right)$
High redshift -> Low frequency

\[ \nu_{\text{rest frame}} = 1420 \text{ MHz} \]

Due to Cosmological Expansion

\[ \nu_{\text{obs}} = \frac{\nu_{\text{rest frame}}}{(1 + z)} \]

<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>13</td>
<td>100 MHz</td>
</tr>
<tr>
<td>140</td>
<td>10 MHz</td>
</tr>
</tbody>
</table>

First Billion Years
Field Relative Calibration

3-position switching removes time variability.

In each 3-position switching cycle we measure power spectral density from:
1) Antenna
2) Ambient Load
3) Ambient Load + Noise Source
Receiver parameters are obtained measuring **calibration standards in the lab**.

We measure with high precision and accuracy the **spectrum, reflection, and temperature of the standards**.
Antenna Reflection Coefficients

78 MHz
Beam Chromaticity

Antenna-to-Sky 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

\[
C(\nu, \text{LST}) = \frac{\int T_{\text{sky}}(\nu_{\text{ref}}, \text{LST}, \Omega) \cdot B(\nu, \text{LST}, \Omega) \, d\Omega}{\int T_{\text{sky}}(\nu_{\text{ref}}, \text{LST}, \Omega) \cdot B(\nu_{\text{ref}}, \text{LST}, \Omega) \, d\Omega}
\]
Extended Ground Plane:
Central Square: 20m x 20m
16 Triangles: 5m-long
Foreground Spectral Index

Low-Band

High-Band
Bayesian Approach

\[ P(\theta|D) \propto P(D|\theta) \cdot P(\theta) \]

\[ \propto P(D_1|\theta) \cdot P(D_2|\theta) \cdot P(D_3|\theta) \cdot P(\theta) \]
Constraints from EDGES High-Band

Monsalve, Fialkov, Bowman, Rogers, Mozdzen, Cohen, Barkana, & Mahesh 2019
Low-Band Ground Plane: 2015-2016

Metal wire mesh

Solid metal sheet

2m

10m
Same Ground Plane as **Low-Band**

- Metal wire mesh
- Solid metal sheet

Diagram with dimensions:
- 2m
- 30m

Note: The diagram shows a ground plane configuration with specific dimensions and layers for low-band operations.
Low-Band Ground Plane: 2018-2019

We call this configuration “Low-Band 3”
Monsalve, Mahesh, Rogers, Bowman, Mozdzen, & Johnson (in preparation)

1) Data from **August - October 2018**.
2) **Low foregrounds**.
3) Best-fit absorption parameters consistent with Bowman et al. (2018).
Model of the Spectrum

\[ m(\nu) = m_{21}(\nu) + m_{fg}(\nu) \]
Phenomenological 21-cm Model
“Flattened Gaussian”

\[ m_{21}(\nu, \theta_{21}) = -A \left( \frac{1 - e^{-\tau}e^B}{1 - e^{-\tau}} \right) \]

\[ B = \frac{4(\nu - \nu_0)^2}{w^2} \ln \left[ -\left( \frac{1}{\tau} \right) \ln \left( \frac{1 + e^{-\tau}}{2} \right) \right] \]

\( A \): absorption amplitude
\( \nu_0 \): center frequency
\( w \): width
\( \tau \): flattening parameter
“Foreground” Models

Linearized Version of Physically-Motivated Foreground Model

\[ m_{fg}(\nu, a_i) = \nu^{-2.5} \left\{ a_0 + a_1 \log \nu + a_2 [\log \nu]^2 + a_3 \nu^{-2.0} + a_4 \nu^{0.5} \right\} \]

Alternative Polynomial Model

\[ m_{fg}(\nu, a_i) = \nu^{-2.5} \sum_{i=0}^{N_{fg}-1} a_i \nu^i \]

Smooth sets of basis functions that model well, with few terms, the spectrum over wide frequency ranges.

Linear fit coefficients not intended to be assigned physical interpretation.
MCMC Parameter Estimation

Foreground

21-cm
Parameter Estimates

Estimates from Nominal Spectrum
1) Enough IGM cooling achieved if small fraction (<1%) of DM particles possess electric mini-charge ($\sim 10^{-6}$ the charge of an electron).

2) Mass of these DM particles constrained to $\sim 1$-60 MeV.
Global 21-cm Experiments

PRI\textsuperscript{Z}M
(McGill, Sievers et al.)

SARAS 2
(RRI, Subrahmanyan et al.)

LEDA
(Harvard, Greenhill et al.)

CTP
(NRAO, Bradley et al.)
Epoch of Reionization Constraints (Hot IGM)

- TANH model for the evolution of the average neutral hydrogen fraction ($\bar{x}_{HI}$).

- Parameters are EoR center ($z_r$) and duration ($\Delta z$).

Monsalve, Rogers, Bowman, & Mozdzen (2017b)
Epoch of Reionization Constraints (Hot IGM)

Monsalve, Rogers, Bowman, & Mozdzen (2017b)
NO IGM Heating prior to Reionization

1) Perfect Lyman-\(\alpha\) coupling at early times (\(T_S = T_{IGM}\)).
2) No X-ray heating. IGM cools adiabatically.
3) Only reionization.
4) TANH model for \(\bar{x}_{HI}\).

\(\bar{x}_{HI} < 1\%\) at \(z = 6\)

We rule out at \(\geq 2\sigma\) all models with:
- \(\bar{x}_{HI} \leq 1\%\) at \(z = 6\)
- \(0.086 \geq \tau_e \geq 0.038\)

*Monsalve, Rogers, Bowman, & Mozdzen (2017b)*
Verification Using \(~300\)K Passive Noise Sources

Residuals After Removing a Constant

\[
\text{temperature \ [mK]} \\
\text{temperature \ [mK]}
\]

\[
78 \text{ MHz} \\
\text{78 MHz}
\]

\[
\text{Low-Band 1} \\
\text{Low-Band 2}
\]

\[
\text{RMS: 26 mK} \\
\text{RMS: 25 mK}
\]

\[
\text{frequency \ [MHz]} \\
\text{frequency \ [MHz]}
\]
EDGES-3 Recently Proposed to NSF-ATI

1) Observe from Oregon, USA.
2) Improved hardware.
3) More portable design.
4) Electronics within antenna.
New Global 21-cm Experiment

**MIST**: Mapper of the IGM Spin Temperature

PI: Ricardo Bustos  
**Chilean Andes**  
Site elevation: 4,500 m