Rencontres du Vietnam, Windows on the Universe Quy Nhon, Vietnam

An Absorption Signal in the Sky-Averaged Radio Spectrum

Raul Monsalve¹, Judd Bowman², Alan Rogers³, Thomas Mozdzen², Nivedita Mahesh²

¹McGill University ²Arizona State University ³MIT Haystack Observatory



Summary

- 1) The **EDGES experiment** has **detected an absorption feature** in the sky-averaged spectrum centered at 78 MHz.
- 2) This is consistent with stars forming by 180 Myrs after the Big Bang.
- 3) Feature is **deeper and sharper** than expected.
- 4) We **remain agnostic** regarding the **interpretation**.
- 5) We are working to verify the measurement.
- 6) Also, **constraining high-z astrophysical parameters**, including properties of X-rays that heat the IGM.





Bowman, Rogers, Monsalve, Mozdzen, Mahesh 2018, Nature, 555, 67

Global (sky-average) 21-cm Signal



Global 21-cm Measurement

- 1) One of few current alternatives to access Cosmic Dawn (z > 14) period.
- 2) Probes the (sky-averaged) interaction of :
 - IGM Neutral Hydrogen Fraction
 - IGM Kinetic and 21-cm Spin Temperature
 - Background Radiation Temperature
- 4) Provides constraints on:
 - Timing and strength of UV coupling and X-ray heating
 - Type of early sources (PopII vs PopIII, Black Holes, X-Ray Binaries, etc.)
 - Star formation cooling and feedback mechanisms
 - Redshift and Duration of epoch of Epoch of Reionization

Challenges

- 1) Hard instrument calibration problem.
- 2) Strong diffuse foregrounds compared to 21-cm signal.

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

Radio-Quiet Site Murchison Radio-astronomy Observatory (MRO)





MWA



SKA-Low



EDGES Instruments



EDGES Block Diagram



Instrumental Calibration

- 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.

EDGES Low-Band



Low-Band Ground Plane



Observations

EDGES Low-Band



Daily Low-Band Residuals

21/	1 AMO I MAD	169 mK
514	- Co Man was more way	151 mK
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318	- Markanna mana	162 mK_
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320	- Manna Manna	144 mK
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323	- Mrs Marson Marson Marson	166 mK_
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227		175 mK
527	- W. W. A . W. W. W. W. W. W. W.	165 mK
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329	- Manumum	218 mK_
332	- My many many	160 mK _
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338	- Jar Mary	174 mK_
339	- Mm mmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmmm	194 mK_
340	- Munimumum	261 mK_
341	- 1 Marthalanna - Marthalanna	169 mK_
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242	Man March Caro March and March	204 mK
343	- Mar Amanda Amanda Maria	204 mk
348	- Managel - Mana	100 mK -
350	- M.	172 mK_
351	- 1MM Mm mmmmmmm	168 mK_
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354		196 mK
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357	- My Manumenter	10/ MK_
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361	- Mary Mary - Ma	174 mK_
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262	W Manual Andrew and the second and	296 mK
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365	- Mummum	192 mK_
366	- Jumphamman	167 mK_
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Summary of the Detection



Bowman, Rogers, Monsalve, Mozdzen, Mahesh 2018, Nature, 555, 67

Phenomenological 21-cm Model "Flattened Gaussian"

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

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

- **A** : absorption amplitude
- v_0 : center frequency
- w: width
- *t*: flattening parameter

"Foreground" Models

Linearized version of Physically-Motivated foreground model

$$m_{\rm fg}(\boldsymbol{a_i}) = \boldsymbol{a_0} \left(\frac{\nu}{\nu_n}\right)^{-2.5} + \boldsymbol{a_1} \left(\frac{\nu}{\nu_n}\right)^{-2.5} \left[\log\left(\frac{\nu}{\nu_n}\right)\right] + \boldsymbol{a_2} \left(\frac{\nu}{\nu_n}\right)^{-2.5} \left[\log\left(\frac{\nu}{\nu_n}\right)\right]^2 + \boldsymbol{a_3} \left(\frac{\nu}{\nu_n}\right)^{-4.5} + \boldsymbol{a_4} \left(\frac{\nu}{\nu_n}\right)^{-2}$$

Alternative Polynomial Model

$$m_{\rm fg}(\boldsymbol{a_i}) = \left(\frac{\nu}{\nu_n}\right)^{-2.5} \quad \sum_{i=0}^{N_{\rm fg}-1} \boldsymbol{a_i} \left(\frac{\nu}{\nu_n}\right)^i$$

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.

Parameter Estimates

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Estimates from Nominal Spectrum



Reported Estimates Including All Cases

Parameter	Best Fit	Uncertainty (3 σ)
A	0.5 K	+0.5/-0.2 K
ν_0	78 MHz	+/-1 MHz
W	19 MHz	+4/-2 MHz
τ	7	+5/-3

Sensitivity to Possible Calibration Errors

Estimated uncertainty	Modelled error level	Recovered amplitude (K)
0.1 dB	1.0 dB	0.51
20 ps	100 ps	0.48
0.02 dB	0.2 dB	0.50
20 ps	100 ps	0.48
N/A	N/A	0.51
N/A	N/A	0.48
	Estimated uncertainty 0.1 dB 20 ps 0.02 dB 20 ps N/A N/A	Estimated uncertaintyModelled error level0.1 dB1.0 dB20 ps100 ps0.02 dB0.2 dB20 ps100 psN/AN/AN/AN/A

Hardware and Processing Cases

Configuration	Sky Time (hours)	SNR	Centre Frequency (MHz)	Width (MHz)	Amplitude (K)
Hardware configurations (all P6)			\frown	\wedge	\frown
H1 – low-1 10x10 ground plane	528	30	78.1	20.4	0.48
H2 – low-1 30x30 ground plane	428	52	78.1	18.8	0.54
H3 – low-1 30x30 ground plane and recalibrated receiver	64	13	77.4	19.3	0.43
H4 – low-2 NS	228	33	78.5	18.0	0.52
H5 – Iow-2 EW	68	19	77.4	17.0	0.57
H6 – low-2 EW and no balun shield	27	15	78.1	21.9	0.50
Processing configurations (all H2 except P17)				1	
P3 – No beam correction		19	78.5	20.8	0.37
No beam correction (65-95 MHz)		25	78.5	18.6	0.47
HFSS beam model		34	78.5	20.8	0.67
FEKO beam model		48	78.1	18.8	0.50
P4 – No loss corrections		25	77.4	18.6	0.44
P7 – 5-term foreground polynomial (60-99 MHz)		21	78.1	19.2	0.47
P8 – Physical foreground model (51-99 MHz)		37	78.1	18.7	0.53
P14 – Moon above horizon		44	78.1	18.8	0.52
Moon below horizon		40	78.5	18.7	0.47
P17 – 15°C calibration (61-99 MHz, 5-term)		25	78.5	22.8	0.64
35°C calibration (61-99 MHz, 5-term)		16	78.9	22.7	0.48

Bowman, Rogers, Monsalve, Mozdzen, Mahesh 2018, Nature, 555, 67

Different Instruments/Hardware Cases



Bowman, Rogers, Monsalve, Mozdzen, Mahesh 2018, Nature, 555, 67

Absorption Amplitude for Various GHA

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

Bowman, Rogers, Monsalve, Mozdzen, Mahesh 2018, Nature, 555, 67

How to Explain Deep Absorption?



Producing a Deep Absorption



Greenhill 2018, Nature, 555, 38

With EDGES we remain agnostic about the cosmological/astrophysical explanations, and focused on the verification of our measurement.

Other experiments trying to verify the measurement include PRI^ZM, LEDA, and SARAS 2

EDGES Instruments



Preliminary Mid-Band Results with Imperfect Data



- 1) Data from November 2017-February 2018.
- 2) **Imperfect calibration** (noise source level too low).
- 3) Frequency range **65-120 MHz**.
- 4) **5-term linear "physical" foreground model.**



- **A**: 0.61 K
- ν ν₀: 78.9 MHz
- *w*: 18.2 MHz
- **t**: 7

Recent EDGES High-Band Analyses



Epoch of Reionization Constraints (Hot IGM)



Monsalve, Rogers, Bowman, Mozdzen³¹(2017)

Constraining High-z Astrophysical Parameters

- 1) We test **traditional models** that assume **standard temperatures** for the **IGM and radiation background** in the Early Universe.
- Do NOT assume that absorption feature of Bowman et al. (2018) is the cosmological signal.
- 3) 10,000 models from semi-numerical simulations with the **21cmFAST** code.

High-z Astrophysical Parameters:

- 3: Ionizing efficiency of halos that host galaxies
- $T_{\rm vir}^{\rm min}$: Minimum virial temperature of halos that host star-forming galaxies
- L_X /SFR: X-ray luminosity per star-formation rate from galaxies (up to 2 keV)
 - E_0 : Minimum energy of X-rays

Sample of Models from 21cmFAST





Summary

- 1) The **EDGES experiment** has **detected an absorption feature** in the sky-averaged spectrum centered at 78 MHz.
- 2) This is consistent with stars forming by 180 Myrs after the Big Bang.
- 3) Feature is **deeper and sharper** than expected.
- 4) We **remain agnostic** regarding the **interpretation**.
- 5) We are working to verify the measurement.
- 6) Also, **constraining high-z astrophysical parameters**, including properties of X-rays that heat up the IGM.

Thank You

Bayesian Analysis

$$m(\boldsymbol{\theta}) = m_{21}(\boldsymbol{\theta}_{21}) + m_{\mathrm{fg}}(\boldsymbol{\theta}_{\mathrm{fg}})$$

$$\mathcal{L}(d|\boldsymbol{\theta}) = \frac{1}{\sqrt{(2\pi)^{N_{\nu}}|\boldsymbol{\Sigma}|}} \times e^{\left\{-\frac{1}{2}[d-m(\boldsymbol{\theta})]^{T}\boldsymbol{\Sigma}^{-1}[d-m(\boldsymbol{\theta})]\right\}}$$

- d: data
- *m*: model
- Σ : covariance matrix of data (Noise + Systematic Uncertainty)
- N_{ν} : number of spectral channels

We Marginalize Uncertainty in the Foreground Model Parameters

and Obtain:

Likelihood of each 21-cm Model:
$$\mathcal{L}(d|\theta_{21})$$

Likelihood for Original Models



Interpolation of Likelihood onto Regular Grid



This Enables Rigorous Marginalization Over Parameters.

New Model Set

Interpolation of Standard Semi-Numerical Models from Cohen+ (2017)

Description of Interpolation Code in Cohen+ (2018)



Direct Evaluation of Likelihood at High Resolution Grid Points

- 5 Parameters
- 3.2 Million Signals





Expecting to Conduct Similar Analyses Using Low- and Mid-Band Data once Large Physical Model Sets are Available.

Diffuse Foregrounds



6) Large **spatial gradients**.

Verification Using ~300K Antenna Simulators

Residuals After Removing a Constant



Global 21-cm Experiments

PRI^ZM (Kwazulu-Natal, Sievers et al.)



SARAS 2 (RRI, Subrahmanyan et al.)



LEDA (Harvard, Greenhill et al.)



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



HYPERION (Berkeley, Parsons et al.)



CTP (NRAO, Bradley et al.)



Interactions of Baryons with Dark Matter?

A small amount of mini-charged dark matter could cool the baryons in the early Universe

Julian B. Muñoz¹* & Abraham Loeb²

LETTER

NATURE, 557, 31 MAY 2018

https://doi.org/10.1038/s41586-018-0151-x

- 1) Enough IGM cooling achieved if small fraction (<1%) of DM particles posses electric mini-charge (~ 10^{-6} the charge of an electron).
- 2) Mass of these DM particles constrained to \sim 1-60 MeV.

EDGES Mid-Band

Low-Band



High-Band



Mid-Band



Antenna Reflection Coefficients



Preliminarily