Using Neural Networks to Plot Emulations of the Sky-averaged 21-cm Signal to Deepen Understanding of the Cosmic Dawn and Epoch of Reionization

Rain Jha

The British School
New Delhi, India

Abstract- **This research project focuses on the emulation of the 21-cm signal of neutral hydrogen during the epoch of reionization, using a trained neural network to generate different signatures of this signal. The project employs the "globalemu" network (Bevins et al, 2021) which utilizes training of 10,000 signals generated from semi-numerical simulations to emulate the 21-cm signal. The primary objective of this research is to investigate variations in the astrophysical parameters within the neural network and their subsequent impacts on the emulated signal. A specific area of interest is establishing correlations between changes in these parameters and the occurrence of signal minima corresponding to the maximum signal amplitude. This research was conducted under the guidance of Dr. Saurabh Singh, Associate Professor at the Department of Astronomy and Astrophysics, Raman Research Institute, Bengaluru, India, starting from June 2023.**

Index Terms– **Cosmic dawn, epoch of reionization, 21-cm signal, emulations, neural networks in astrophysics**

I.INTRODUCTION & THEORY OF THE 21-CM SIGNAL

There has been much progress in our understanding of the universe from 400,000 years after the Big Bang to the present day, 13.7 billion years on. Yet, the first billion years, during which the first stars and galaxies formed, remains a mystery. The speed of light gives astronomers a tool to look into the past. Telescopes have enabled astronomers to observe galaxies to distances corresponding to a time when the universe was a billion years old.

Moreover, observations at microwave frequencies illustrate the "cooling afterglow" of the Big Bang. This cosmic microwave background (CMB) decoupled from the cosmic gas 400,000 years after the Big Bang (Pritchard and Loeb, 2012), when the universe cooled sufficiently for protons and electrons to combine to form neutral hydrogen. Radiation from this time reaches us directly, providing a snapshot of the primordial universe.

Still, connecting these two periods poses a challenge as the middle phase is largely untested by observations. To improve on this, astronomers are pursuing two key routes. One, deploy larger, more sensitive, telescopes: work is progressing on the Giant Magellan Telescope (GMT) in Atacama Desert, Chile; and the Thirty Meter Telescope (TMT) in Hawaii, US, that can detect an individual galaxy out to redshifts $z > 10$. Launched in 2021, the James Webb Space Telescope (JWST) can potentially image some of the first galaxies at $z \sim 10–15$. (James Webb, NASA)

This project focuses on the second route: the redshifted 21-cm line of neutral hydrogen. This line is produced by splitting caused by the interaction between electron and proton magnetic moments. Hydrogen amounts to almost three-quarters of the gas mass in the intergalactic medium. As such, it provides a convenient tracer of the properties

The cosmic dawn and epoch of reionization are critical chapters in early cosmic history, and are surrounded by mysteries concerning the formation of the first stars and galaxies. Within this context, the 21-cm signal is a very important tool to further understand the characteristics and causes of events in these epochs. This signal, originating from the red-shifted 21-cm line of neutral hydrogen, undergoes a distinctive change that describes the transformation of the universe.

This research project seeks to explore the changes in this signal's characteristics depending on its various parameters using an emulator to visualize the sky-averaged 21-cm signal during these transformative cosmic epochs, shedding light on the universe's formative years.

II.PROBLEM STATEMENT & PARAMETERIZATION

The challenge lies in accurately modeling the complex 21-cm signal, which can depend on multiple parameters. The paper delves into the problem of enhancing the emulation process and refining signal modeling, by modifying the underlying astrophysical parameters to observe changes in the final function of signal brightness against redshift/frequency.

Initially, during the "Dark Ages," before the first stars ignite, the 21-cm signal exhibits absorption features, revealing the cool, inhomogeneous gas that has been decoupled from background radiation.

As the first galaxies take shape, their radiation alters the gas properties, resulting in spatially varying absorption. Subsequently, X-ray emissions heat the gas, transitioning the signal to emission mode. Finally, ultraviolet photons ionize the gas, introducing dark holes in the 21-cm signal brightness within ionized bubbles around galaxy clusters, leaving only isolated pockets of neutral hydrogen.

From this broad sequence of events, the seven parameters that globalemu takes as inputs can be summarized as follows:

1. **$f*$ (Star Formation Efficiency):** This parameter characterizes the amount of gas converted into stars in dark matter halos. Varying $f*$ helps improve understanding of the impact of star formation on the 21-cm signal, particularly its initial local minima.

2. **Vc (Minimal Virial Circular Velocity):** This is related to the minimum threshold mass for star formation. Changing the value of Vc provides an insight into how the minimum mass affects the timing of Lyman-α coupling that determines how well the signal brightness correlates with the gas temperature and the absorption feature in the 21-cm signal.

3. **fX (X-ray Efficiency of Sources):** This parameter controls the total X-ray luminosity of sources. Adjusting fX reveals insights into the timing of X-ray heating, the depth of absorption, and emission features during reionization.

4. **τ (CMB Optical Depth):** This measures the ionizing efficiency of sources. Varying τ investigates the impact of early or late reionization of hydrogen gas on the 21-cm signal.

5. **α (X-ray Spectral Slope):** This parameter defines the slope of the X-ray spectral energy distribution. Changing α helps evaluate the weak dependence of the 21-cm signal on α, especially at low redshifts.

6. **νmin (Low Energy Cut-off of X-ray SED):** It determines the energy distribution of X-rays. Adjusting νmin assesses the influence of a soft or hard X-ray spectrum on the 21-cm signal.

7. **Rmfp (Mean Free Path of Ionizing Photons):** It measures the distance over which ionizing photons travel. Varying Rmfp studies the weak effects of ionization on neutral hydrogen gas, primarily at low redshifts, although its effects are not very prevalent.

By varying these parameters and observing their effects on the 21-cm signal, we can gain valuable insights into the astrophysical processes that shape the Universe's evolution, and relate the measurements to actual observational capabilities.

III.TRAINING AND TEST DATA

The project utilizes data from the 21CMGEM dataset, available at https://doi.org/10.5281/zenodo.4541500.

This dataset plays a pivotal role in training and testing the neural network-based emulator, globalemu. globalemu, which we use to an extent in this research, relies heavily on the dataset to train the neural network model.

IV.PARAMETER VARIATION

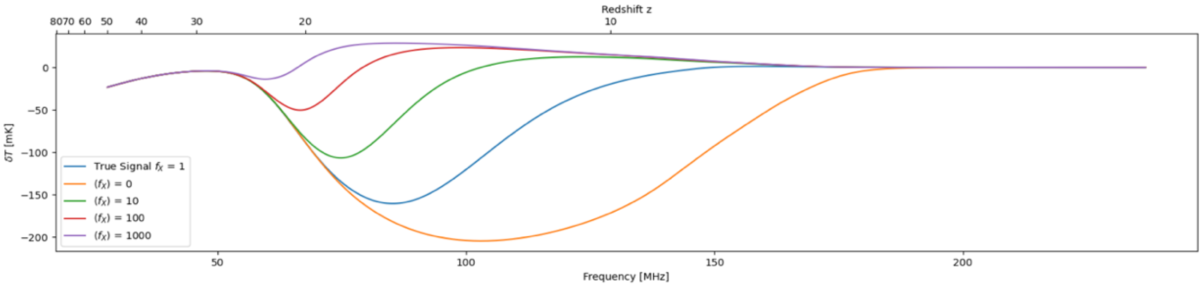
Plot Preparation:

To understand the impact of parameter variations on the emulated 21-cm signal, we delve into an analysis of the variations of the seven parameters outlined in our model. To achieve this, Python code was used to apply the neural network. By systematically modifying these parameters at a time and examining the resulting changes in the signal's characteristics, we can unravel the relationships between the signal brightness and each of the parameters.

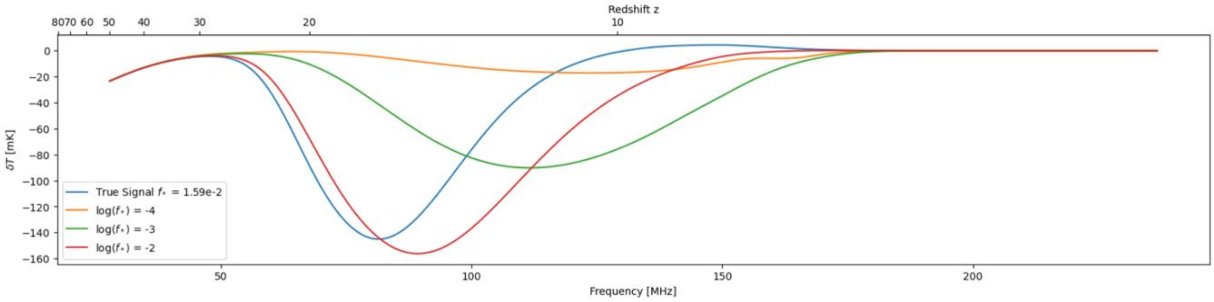
The created graphs involve changing input values and then plotting brightness against both frequency and redshift to provide a visual view of the effects. Given the poor understanding of the early universe, these parameters are vastly unconstrained as reflected in their variations.

The seven plots prepared are:

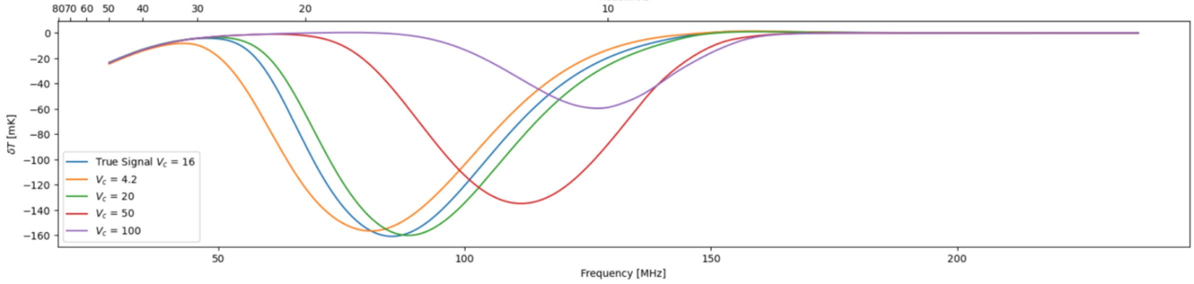
1. X-ray efficiency



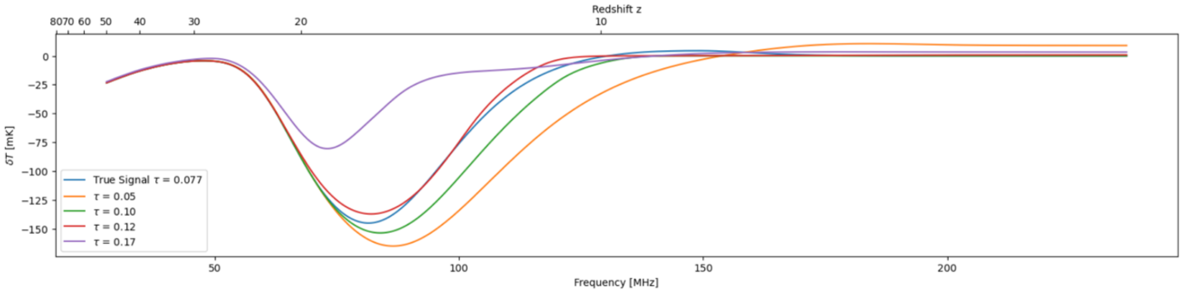
2. Star formation efficiency



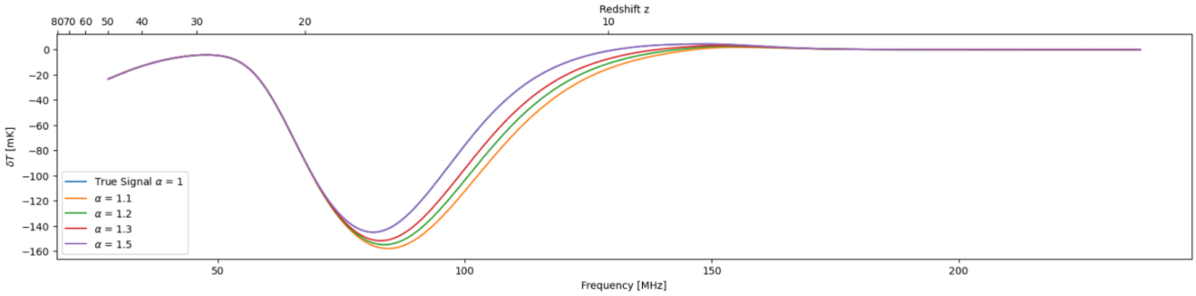
3. Minimal virial circular velocity



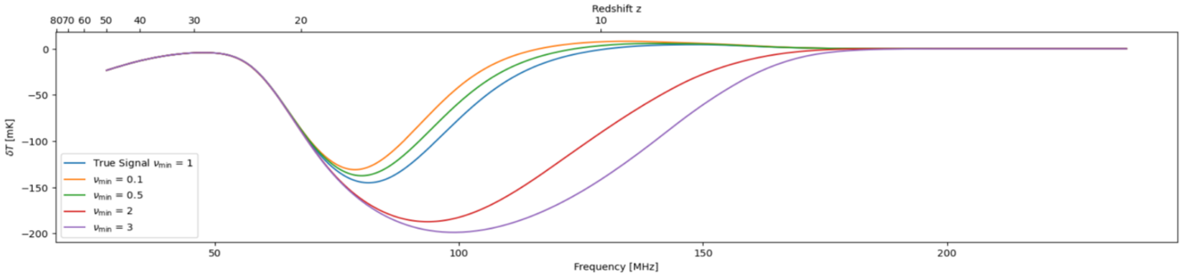
4. CMB optical depth



5. Power of X-ray SED slope

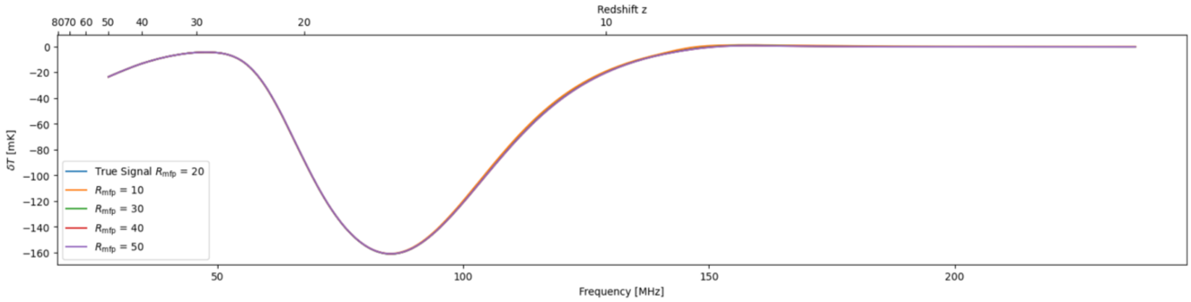


6. Low Energy cutoff of X-ray SED



7. Rmfp, the Mean Free Path of Ionizing Photons

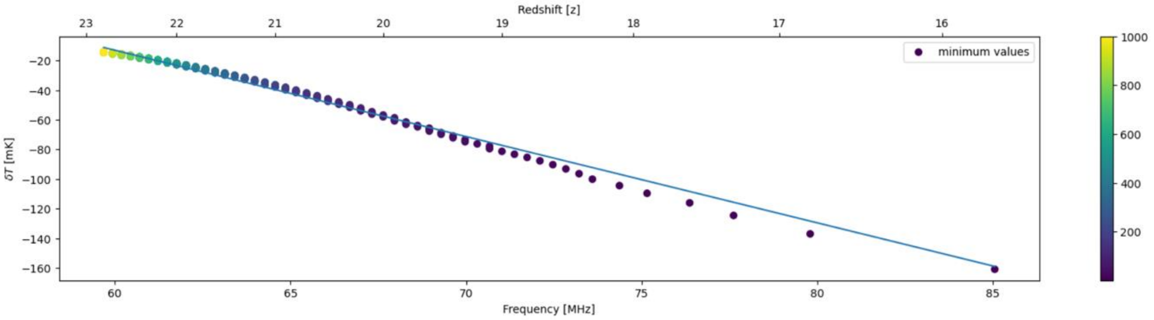
This parameter measures the distance over which ionizing photons travel. While its effects are relatively subtle, we explore the impact of varying Rmfp on neutral hydrogen gas, primarily at low redshifts.

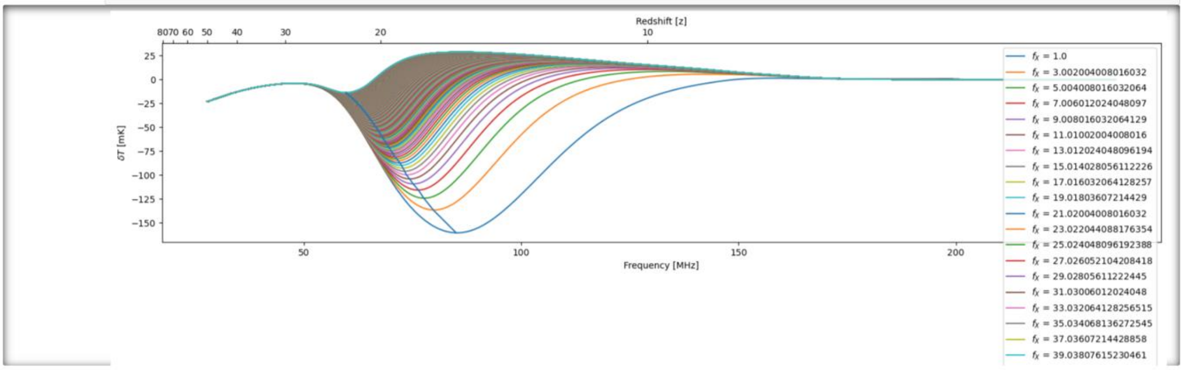


Local Minima Analysis:

One of the parameters, star formation efficiency, is subjected to varying levels. Through analysis, it is revealed that the variation in this parameter showcases a scalar relationship with the minimum points or maximum amplitude of the signal.

We can see that due to the high star formation efficiency, Lyman-α coupling takes place earlier, and therefore the gas temperature is lower and the overall brightness temperature minima is lower as well.





V.CONCLUSION

This research project sheds light on the utility of neural networks in emulating the intricate 21-cm signal. By using the globalemu framework and conducting thorough parameter analysis, the project enhances our understanding of the cosmic dawn and epoch of reionization. The scalar relationships discovered between parameter variations and signal minima offer valuable insights into the underlying physics of these phases.

VI.ACKNOWLEDGMENT

The successful execution of this project is attributed to several key sources, including the Globalemu framework and the 21CMGEM dataset. The guidance of Dr Saurabh Singh from the Raman Research Institute, Bengaluru, played a vital role in shaping the project's direction and outcomes.

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