Observations Of The Universe's First (Radio) Light With HERA

1. Research category: **Science**
2. Academic level: **Doctoral**
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5. Abstract: The Hydrogen Epoch of Reionization Array (HERA) is low-frequency radio interferometer located at the Karoo site, whose goal is the observation of the birth of the first stars and galaxies through the (still undetected) 21 cm line from the intergalactic neutral Hydrogen. The candidate will become part of the HERA collaboration, with the goal of mitigating systematic effects that are limiting current power spectrum measurements. In particular, the candidate will focus on the application of fringe rate filters in order to reduce mutual coupling effects that are limiting the power spectrum sensitivity at small *k* modes in recent analysis (i.e., the HERA collaboration, 2026). Our group has recently demonstrated the potential that fringe rate filters have to suppress systematic effects in HERA simulated observations (Charles et al, 2023; 2024). The candidate will re-analyse a sub-set of the HERA sixth data release using fringe rate filters: in case of a significant improvement, they will extend the analysis to the whole observing season providing, hopefully, a significant improvement on the 21 cm upper limits.

Details of Research Project

1. Scientific merit: One of the outstanding questions in modern cosmology is to understand how the first luminous structures (stars, galaxies) formed (likely at $z \sim 30$) and how they subsequently evolved and completely ionized the intergalactic medium ($z \sim 6$). These two epochs are generally known as Cosmic Dawn and Epoch of Reionization. One of their best observational probes is the redshifted 21 cm line emitted by neutral Hydrogen, observable in the 50-200 MHz radio window. The Hydrogen Epoch of Reionization Array (HERA, deBoer et al. 2017) is a radio interferometer located at the Karoo site, and its goal is to measure the evolution of the 21 cm emission from the Cosmic Dawn to the Epoch of Reionization. The HERA collaboration has recently published the most stringent upper limits on the 21 cm signal in the $6 < z < 10$ range, indicating that the intergalactic medium must have been heated by a population of early sources, likely X-ray binaries in early galaxies, although with different properties than what observed in the nearby Universe (HERA collaboration, 2022; 2023). In the most recent observing season, observations were extended down to ~55 MHz ($z \sim 24.4$), thanks to the new, wideband feeds (HERA collaboration, 2026). These results, however, show a more prominent foreground contamination at $k < 0.55$ h Mpc^{-1} compared to earlier results. This contamination is likely caused by mutual coupling effects, due to the compact array configuration (HERA collaboration, 2026).
Our team at Rhodes University recently explored the use of a specific interferometric technique, called fringe rate filters (Parsons et al., 2016), in order to mitigate systematic effects in HERA observations. Using realistic simulations of HERA observations, we found out that fringe rate filters are an effective signal processing method to suppress the calibration bias introduced by unmodeled Galactic diffuse emission that cannot be completely ignored in HERA observations due to very compact array configuration (Charles et al., 2023). We also generated more realistic simulations of HERA observations by including mutual coupling effects caused, again, by the very compact array configuration, and found that fringe rate filters are effective in mitigating mutual coupling effects, suppressing unwanted foreground leakage up to $k \sim 0.5$ h Mpc^{-1} (Charles et al., 2024).

In this thesis project, the candidate will apply fringe rate filters to actual HERA observations, with the goal to confirm results seen in our simulations. The candidate will use data from the HERA sixth data release and the final (ambitious) goal would be to mitigate systematic effects at small *k* modes,

therefore improving the power spectrum upper limits upon the latest publication (HERA collaboration, 2026). If the application of fringe rate filters will lead to only marginal power spectrum improvements, the candidate will also explore alternative mitigation strategies, taking advantage of the combination of foreground modeling and fringe rate filters.
A contingency plan to mitigate systematic effects may include the use of closure quantities, an approach that was extensively explored by our group. The candidate will take the next step in the analysis of HERA data using closure quantities and verify if/how mutual coupling effects limit the power spectrum obtained from closure quantities.
This is a science project that uses HERA data (focus area 4.1).

2. Feasibility: Observations of the redshifted 21 cm line are difficult: its pursuit started twenty years ago and a solid detection is still awaiting. 21 cm observations are one of the most challenging goals of radio cosmology: the signal is faint and buried under foreground emission which is a few orders of magnitude brighter. Observations therefore require an exquisite interferometric calibration, often exploring novel techniques and approaches, and a careful control (and modeling) of systematic effects. Moreover, 21 cm cosmology requires knowledge of interferometry, cosmology, statistical and numerical methods. It is worth notice that HERA observations led, thus far, the most stringent upper limits on the 21 cm signal
Rhodes University hosts a small (but competitive) EoR group that works on the analysis of HERA data, coordinated by Prof. Smirnov and (visiting) Prof. Bernardi, and collaborating with Dr. Charles (SARAO), Dr. Bester (SARAO) and Prof. Santos (University of Western Cape). The Rhodes EoR group has been part of the HERA project since its beginning, in 2015. Over the last few years the group led the research on the use of HERA closure phase quantities to detect the 21 cm signal (Charles et al., 2022) and the mitigation of systematic effects in HERA observations (Charles et al., 2023; 2024). HERA observations were the focus of two recent MSc theses ("Analysis of HERA observations using closure phase quantities", Mrs. Nomzamo Mokoena, submitted in February 2026; "Simulations of the 21 cm closure phase power spectrum as observed by HERA", Mr. Pierse Mulunda, submitted in February 2026) and one PhD thesis ("Systematic effects and mitigation strategies in observations of cosmic re-ionisation with the Hydrogen Epoch of Reionization Array", 2024, Ntsikelelo Charles).

In this thesis project, the candidate will become part of the group and their specific project will be to apply fringe rate filters to HERA observations in order to mitigate systematic errors. Our group has already developed the fringe rate techniques on simulations and the candidate will simply apply them to HERA data and estimate the power spectrum using the standard HERA pipeline.
In terms of closure phase analysis, the candidate will apply the existing pipeline (e.g., Keller et al., 2023; Charles et al., 2022) to the latest HERA data release to produce multi-redshift upper limits. The candidate will compare results against the fringe rate filter case and assess if/how mutual coupling affects the power spectrum obtained from closure quantities.
We expect that the candidate's work will result in, at least, one first author paper throughout the thesis period. They will have full access to HERA data and computing and storage resources at the RATT cluster at Rhodes University, which have been used so far by the Rhodes EoR group.

3. Skills development: Describe the skills the student will develop from the research project.

The candidate will learn radio interferometric theory and techniques, in particular about drift scan observations at low frequencies (i.e. the HERA case) and advanced interferometric techniques like fringe rate filters. They will learn how to simulate HERA-like observations and how to reduce actual HERA observations, with a particular focus on calibration and power spectrum estimates.
They will also learn the fundamentals of redshifted 21 cm observations, including foreground properties, 21 cm physics and foreground separation techniques.

4. Provide details (and confirmation) on the availability of required data / access to required equipment / availability of research facilities and other resources required.

As in the case of previous MSc and PhD projects carried out at Rhodes University that involved HERA data reduction or simulations, the RATT centre provides adequate computing facilities and storage to process HERA data locally. Access to HERA data is provided through the supervisor and co-supervisor – both HERA members – according to the HERA collaboration agreement.

5. Include expected milestones and associated time-frames towards attaining the overall objectives of the project.

The student is expected to familiarize with the relevant literature, interferometric techniques and specific software (the closure phase pipeline, the fringe rate filters pipeline, the power spectrum estimation pipeline) in the first six to eight months. In the following twelve months the student is expected to apply fringe rate filters to HERA data in order to mitigate systematic effects due to mutual coupling. If promising, the analysis will be extended to longer integrations, leading to a proof-of-concept publication. Eventually (and this effort will already span the second year), the candidate will process the whole observing season, hopefully leading to improved power spectrum upper limits. This case will also lead to a (high impact) publication.
In the last year the candidate is expected to wrap up their work and dedicate the last six months to write up the thesis: according to the aforementioned timeline the various activities will lead to (at least) two published papers, aiding the thesis write up.

6. Qualifications, academic abilities, skills and/or experience that a student should have in order to successfully deliver on the objectives of the research proposed.

Familiarity with interferometry and 21 cm cosmology would be advantageous but not required. The candidate should be ready to undertake a cutting edge project.

Supervisor

Oleg Smirnov 24 February 2026