Section A: Overview of the Research Project Proposal

1. Title of the research project: **How to mitigate errors in the observations of the closure phase power spectrum with HERA using fringe rate filters**
2. Broad area of research: **Science**
3. Academic level of research project: **Masters**
4. Abstract: The Hydrogen Epoch of Reionization Array (HERA) is currently in an advanced stage of construction at the Karoo site, with the goal of observing the birth of the first stars and galaxies through the (still undetected) 21 cm line from the intergalactic neutral Hydrogen. A recent technique to detect the 21 cm signal uses the interferometric closure phase, as they are more robust to calibration errors. The analysis of HERA observations only partially confirms this hypothesis, with some limitations due to systematic effects (Thyagarajan et al., 2020; Keller et al., 2023). The candidate will explore the use of fringe rate filters to mitigate systematic effects in HERA simulated observations of the closure phase power spectrum and, if successful, will apply them to actual HERA data.
5. Primary supervisor: **Prof. Oleg Smirnov,** o.smirnov@ru.ac.za, Rhodes University
6. Research supervisor: **Dr. Gianni Bernardi,** INAF-IRA (Italy) & Rhodes University

Section B: 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 ~ 30) and how they subsequently evolved and completely ionized the intergalactic medium (z ~ 6). These two epochs are generally known as Cosmic Dawn and Epoch of Reionization (EoR). One of their best observational probes is the redshifted 21 cm line emitted from neutral Hydrogen, observable in the 50-200 MHz radio window. The Hydrogen Epoch of Reionization Array (HERA, deBoer et al. 2017) is in an advanced stage of construction 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 next season, HERA observations will reach a deeper sensitivity and will likely be able to place tighter constraints on the expected 21 cm signal. The main threat to the detection of the 21 cm signal remains, however, the contamination from foreground emission due to calibration errors. Some of these errors are already limiting the sensitivity in observations taken with other telescopes like LOFAR and MWA.

Thyagarajan, Carilli and Nikolic (2018) recently proposed the use of closure phase quantities to detect the 21 cm signal, as they are more robust to calibration errors. The analysis of HERA observations through the closure phase power spectrum led to the first upper limits to the 21 cm signal, mostly limited by the instrumental noise (Thyagarajan et al, 2020; Keller et al., 2023). The closure phase power spectrum at small k-values is, however, also affected by systematic effects that may limit the sensitivity of further, deeper observations and, ultimately, prevent the detection of the 21 cm signal.

In this thesis project, the candidate will explore the use of a specific interferometric technique, called fringe rate filters (Parsons et al. 2016), with the specific goal to mitigate the impact of systematic effects that may still impact closure quantities, like, for example, mutual coupling effects (Charles et al., 2022). The candidate will simulate observations of HERA closure quantities and apply various types of different fringe rate filters to assess their benefit in suppressing systematic effects (Charles et al., 2023). In case of a successful demonstration, the candidate will also apply them to real HERA observations in order to demonstrate its effectiveness towards the detection of the 21 cm signal.

2. Feasibility: Observations of the redshifted 21 cm line are difficult: its pursuit started fifteen 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) 21 cm group that works on the analysis of HERA data, coordinated by Prof. Smirnov and (visiting) Prof. Bernardi, Mr. Ntsikelelo Charles (North West University Potchefstroom Campus) and collaborating with Prof. Santos (University of Western Cape) and Dr. Landman Bester (SARAO). 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 optimization of redundant calibration for HERA (Grobler et al., 2017), on the application of Gaussian Progress Regression to model and subtract foregrounds from HERA data (Ghosh et al., 2020), 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). HERA observations were the focus of one MSc thesis ("Observations of cosmic re-ionisation with the Hydrogen Epoch of Reionization Array: simulations of closure phase spectra", 2020, Mr. Ntsikelelo Charles), one PhD thesis ("Systematic effects and mitigation strategies in observations of cosmic re-ionisation with the Hydrogen Epoch of Reionization Array", 2023, Ntsikelelo Charles) and are the focus of two current MSc theses ("Analysis of HERA observations using closure phase quantities", Nomzamo Mokoena and "Simulations of the 21 cm closure phase power spectrum as observed by HERA", Pierse Mulunda).

In this thesis project, the candidate will continue the work on the closure phases activities carried out by the group. Closure phase is the sum of the visibility phase of a triad (i.e. the baselines formed by a group of three antennas) and is largely independent of interferometric calibration. This is the reason why closure phases are thought to be more robust to systematic effects arising by calibration imperfection and, therefore, promising to separate the feeble 21 cm signal from the EoR from bright foreground emission (Thyagarajan et al. 2018, 2021). Our work has shown that this property may still hold even when more realistic simulations of the interferometric array are used, although mutual coupling between closely packed elements of the HERA array may not be a completely negligible effect (Charles et al., 2022).

The candidate will be expected to carry out simulations of HERA closure phase observations and explore how fringe rate filters may mitigate mutual coupling effects - an approach that has shown some promises in the standard 21 cm power spectrum observations (Charles et al., 2023). If promising, the candidate will apply fringe rate filters to actual HERA observations of closure phase and assess their impact.

3. Link to SARAO research priority areas for 2024: This is a science project that uses HERA data (focus area 5.1).

4. **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 26 February 2024