Section A: Overview of the Research Project Proposal

1. Title of the research project: **Observations of the Universe first (radio) light with HERA**
2. Broad area of research: **Science**
3. Academic level of research project: **Doctoral**
4. Abstract: The Hydrogen Epoch of Reionization Array (HERA) is currently under 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. The candidate will become part of the HERA collaboration, with the goal of producing the deepest, all-sky, HERA images to date. This goal will require the development of a direction-dependent imaging algorithm for transit arrays - like HERA. The images will be crucial to study the low frequency sky as well as foreground emission - crucial to reveal the faint 21 cm signal.
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/Engineering 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 from neutral Hydrogen, observable in the 50-200 MHz radio window. The Hydrogen Epoch of Reionization Array (HERA, deBoer et al. 2017) is currently under 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 candidate will analyze HERA observations with the goal to make the deepest, all-sky HERA images to date and study the foreground properties in an unprecedented detail. The characterization of foreground emission is crucial to reveal the faint, underlying 21 cm signal. Very little effort has gone into all-sky imaging within the collaboration and this project will push the envelope of the analysis of HERA observations.

2. Feasibility: Observations of the redshifted 21 cm 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.

Rhodes University hosts a tightly-knit 21 cm group that works on the analysis of HERA data, coordinated by Prof Smirnov and (visiting Prof) Bernardi, often collaborating with Prof Santos (University of Western Cape). Over the last few years the group worked 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., submitted), on the use of HERA closure phase quantities to detect the 21 cm signal (Ntiskelelo Charles, MSc thesis). Ntsikelelo Charles is now a PhD student at Rhodes University, extending his MSc thesis into his PhD project.

The candidate will become part of the group and their specific project will be to make full-sky, deep images of HERA observations. HERA is not built to facilitate sky images: its highly redundant configuration is highly optimized for observations of a number of selected power spectrum modes, and the very poor uv-coverage makes the reconstruction of the sky brightness difficult, due to the high side lobes of the point spread function. For this reason, little effort has gone into imaging of HERA observations so far. On the other hand, imaging is the best way to reconstruct the sky brightness distribution and, therefore, characterize foreground properties, in particular deviations from spectral smoothness. It is important to underline that the detection of the 21 cm signal can only happen if foregrounds are accurately isolated.

HERA is now in an advanced deployment stage, with more than 200 dishes built and the new wide-band (50-250 MHz) feeds installed in ~50 dishes. Deep integrations have already been carried out (Kern et al., 2019; Kern et al., 2020) and the first 21 cm are likely to be published by the end of 2021. With upper limits becoming deeper and deeper, the role of imaging as a tool to understand and characterize systematic effects and precise foreground properties becomes more and more compelling.

The candidate will work in adapting an existing direction dependent imaging algorithm (DDFacet, Tasse et al. 2019) to a transit array like HERA, in order to produce all-sky, full-polarization HERA images in the 70-200 MHz frequency range. They will then characterize polarization and total intensity foreground properties in order to predict the level of contamination expected in the 21 cm power spectrum measurements. The images produced will be the deepest to date below 200 MHz.

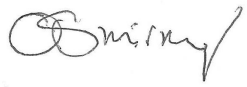
Depending upon their background, the candidate may spend their first year mastering interferometry and 21 cm cosmology. They will then work on adapting the DDFacet algorithm to HERA observations, including the most up to date beam models. Eventually the candidate will generate images from the currently calibrated internal data releases - i.e., the long integration campaigns used for 21 cm power spectrum measurements.

The candidate will publish collaboration papers, but we expect that their 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 of the RATT cluster at Rhodes University, which have been used so far by the local HERA group.

3. Link to SARAO research priority areas for 2021: 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 22 February 2021