REACH: Radio Experiment for the Analysis of Cosmic Hydrogen

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***Abstract*—The Radio Experiment for the Analysis of Cosmic Hydrogen (REACH) is a new instrument dedicated to the detection of the red-shifted radio signature signal from Hydrogen from the times when the universe transitioned from a vast empty space to a realm of celestial objects. These times are known as the Cosmic Dawn and the Epoch of Re-ionization. REACH will use our best knowledge of the Physics that governed the Universe during these early epochs and of the much brighter foreground signals later added to the faint radio cosmic signal. Furthermore, it will make use of physics rooted models describing the electromagnetic response of the telescope itself, alongside with state of the art Bayesian analysis aiming at opening a new window to the early Universe.**

Keywords—radio astronomy, cosmology, radiometer

I. Introduction

The first stars and galaxies formed some time after the epoch of cosmic recombination (when the Cosmic Microwave Background formed ~378,000 years after the Big Bang at a redshift (z) of ~1100) and before the current 'realm of the galaxies' that we can see today (~1 to 13.7 billion years after the Big Bang). The radiation from these first luminous sources heated and re-ionized the neutral hydrogen that pervaded the primordial Cosmos. Probing these epochs, the 'Dark Ages' before the first galaxies, through cosmic re-ionization and first new light in the Universe, represents the frontier in studies of cosmic structure formation. Neutral hydrogen has a rest wavelength of 21 cm and by observing at low radio frequencies we can study directly its red-shifted radio emission (and absorption) from the gas clouds that were the raw material that formed the first luminous cosmic structures at these early epochs. While the future SKA telescope [1] will aim to do full tomography of the hydrogen emission from the Cosmic Dawn (CD) and the Epoch of Re-ionization (EoR), an in principle simpler way to attempt the detection and study of this signal aims to observe the monopole emission (averaged from all directions in the sky, i.e. global, see Fig. 1) through cosmological time, red-shifted from 21-cm to a few meters due to the expansion of the Universe, with a stand alone radiometer system.

REACH [2] is an experiment to detect this monopole emission. Section II describes the science behind REACH. Section III details the principle of the experiment. Section IV of this paper explains the novel aspects of REACH with respect to other similar global experiments. Section V is dedicated to the description of the REACH project and finally some conclusions are drawn in section VI.

II. Science

During the Dark Ages, the hydrogen gas expands and cools, becoming colder than the microwave background photon gas. At redshifts z~25-30 we expect the first stars to shine in the Universe during the so-called Cosmic Dawn. The resulting ambient radiation (through the so-called Wouthuysen-Field effect) couples the electron spin temperature to the colder hydrogen gas temperature. This latter effect leads to a deep (few tens-hundreds mK) absorption trough at z~20 (see Fig. 1): the depth, width and position of this trough encode the information on the nature of the very first luminous sources as well as the sources responsible for the IGM heating. As the formation of the first sources progresses, X-rays heat the intergalactic medium, causing the absorption trough to disappear and eventually reappear as an emission feature. As heating and star formation progresses further, the UV photons produced in galaxies start to escape in the IGM, originating its widespread ionization which is expected to be concluded at z~6 (end of the Epoch of Re-ionization). Measurement of the 21-cm signal throughout this epoch will not only time the duration of re-ionization but will also tell us about the nature of the first galaxies in the Universe and their interplay with the IGM. The global 21-cm signal (see Fig. 1 and equation (1)) has a key z-dependency on the average ionized fraction (x_i (z)) and the spin temperature T_S (z).

$$T_{21} \approx 27(1-\bar{x}_i)((T_S - T_{CMB})/T_S)((1+z)/10)^{1/2} mK \quad (1)$$

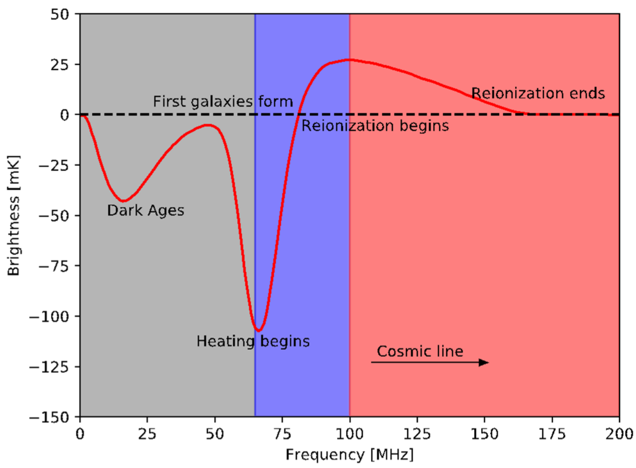

Fig. 1. Model of the redshifterd 21-cm line from [3]. Figure available in [4] (credit: Dr Christos Kolitsidas).

III. The Experiment

A CD/EoR global experiment [5] is fundamentally targeting the detection of power from a monopole sky signal. As such, the most fundamental way to measure this is though the use of a single radiometer antenna capable of observing large enough [5] portions of the sky. Figure 2 shows the sky HASLAM foreground map [6] scaled to 160 MHz and an example of a broad beam antenna located in the Karoo radio reserve (South Africa).

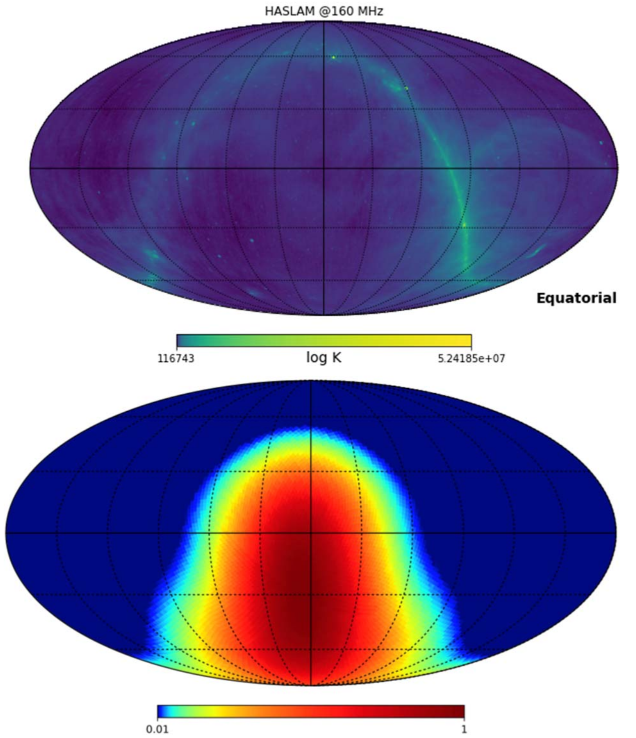

Fig. 2. HASLAM 408 MHz sky map scaled to 160 MHz (top) and example of broad antenna normalized beam pattern if located in the Karoo (bottom).

The power measured by a radiometer in a given integration time τ is T_r, and it is described by equation (2). T_{sky} (equation (3)) accounts for the additive contribution of the global signal and the much brighter (several orders of magnitude) foregrounds (eg. the galactic synchrotron radiation). Equation (2) shows the dependency of the measured power on the directional gain of the antenna, D_A, the radiation efficiency, η, and the power gain of the receiver chain, G_{RX}, as well as the receiver noise, n_{RX}. While G_{RX} and n_{RX} are frequency dependent and direction independent, the gain of the antenna is both frequency and direction dependent and also time dependent at these meter wavelengths due to changes in the environment (eg. humidity of the soil beneath the ground plane). So is the efficiency. Most current global experiments either omit the influence of both D_A and the radiation efficiency, or rely on computer simulations with limited accuracy and heavily affected by the actual in-situ environment of the antenna.

$$\boldsymbol{T_r(\nu)} = \int_0^{\tau}\left(\left(\frac{\oiint_0^{4\pi} T_{sky}(\theta,\varphi,\nu,t)\cdot D_A(\theta,\varphi,\nu,t)\cdot \sin\theta\, d\theta\, d\varphi}{\oiint_0^{4\pi} D_A(\theta,\varphi,\nu,t)\cdot \sin\theta\, d\theta\, d\varphi}\right)\cdot \eta(\nu,t)\cdot G_{RX}(\nu,t) + n_{RX}(\nu,t)\right)\cdot dt \tag{2}$$

$$T_{sky}(\theta,\varphi,\nu,t) = T_f(\theta,\varphi,\nu,t) + T_{21}(\nu) \tag{3}$$

REACH, as other radiometers for global experiments, is made of a low frequency wideband radio antenna, an RF receiver including a switch calibration system and a digital back-end capable of digitizing the signal in channels of approximately 10-20 KHz (in order to perform the required RFI excision) and performing the required integration cycles (see Fig. 3).

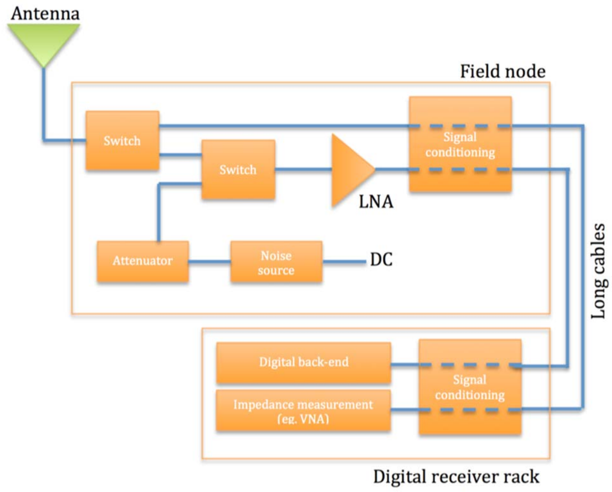

Fig. 3. Example of a figure caption.

The recent results from the EDGES team [7] have caught the attention of the cosmology community with a potential detection of an absorption feature at 78 MHz. The absorption feature is deeper than expected, and if confirmed, would call for new physics. However, different research groups have re-analyzed the EDGES data and questioned the reliability of the signal [8]. These issues call for an urgent, independent confirmation of the signal detection through another experiment, which should include results at higher frequencies at the EoR band.

The aim of REACH is to improve and complete the current observations by tackling some of the challenging issues faced by current instruments. These include: the chromatic effects of the antenna beam across a larger bandwidth, a joint foreground + instrument calibration and the use of advanced Bayesian techniques for the signal analysis.

IV. Novelty

REACH is trying to improve on current global instruments [7, 9-14] by taking a wideband approach, on the basis that spectral differences between the cosmic signal and the foregrounds are the prime tool to separate both signals. Furthermore, REACH aims to apply physics rooted models in a joint cosmic signal-foregrounds-instrument fit.

The main novel points of REACH are:

- Use of wideband spectrally-smooth antenna designs (50-150 and up to 200 MHz), allowing us to obtain more information on the foregrounds and on instrument calibration effects for the data analysis. A key component of the radiometer design will focus on the insensitivity to tolerances and environmental effects. REACH is exploring the use of cavity-backed antennas, which are well known for achieving large operating bandwidths in the presence of a ground mesh by incorporating the radiation and coupling to and from the ground in the main radiation mechanism of the antenna. This design may include the use of a metasurface for the ground mesh aimed at further minimizing direct re-radiation to the antenna.

- The experiment will aim to do a joint fit of 3 tyoes of models:
    - Physics rooted models of the Cosmic signal
    - Physics rooted models of the foregrounds
    - Physics rooted models of the instrument informed by in-field measurements. Aside from the well-known noise injection techniques for the receiver calibration we propose the use of external power injection techniques to constrain physics rooted models for the instrument including the antenna. This will allow us to achieve better and more comprehensive foreground substation compared with current experiments.
- REACH will use advanced Bayesian techniques for the signal analysis and extraction (eg. nested sampling).
- The system will be composed initially of a single antenna covering a wide frequency range but it is envisaged that multiple antennas (scaled and/or different types) will be added to realize a joint confident detection.

A different strategy followed by other groups to do a detection of the same physical phenomenon consists in the use of interferometers [15-17].

V. The Project

REACH is an international collaboration with 33 participants from 12 institutions (see [2] for more information). With primary funding from the Kavli Institute for Cosmology in Cambridge, the University of Cambridge is the main partner of the collaboration together with Stellenbosch University.

A great wealth of knowledge is rapidly building up in this field making these investigations not only scientifically valuable but also very well timed and aligned with the current international activities around the re-ionization era. Knowledge about the duration and depth of the sky averaged 21-cm line from the early Universe is not only a extremely important science case on its own, but it will also provide invaluable information for the upcoming super interferometers such as the SKA. Furthermore, accurate measurements of the diffuse radio background absolute brightness temperature will be possible and will constitute yet another a fundamental input for the interferometry observatories and experiments, both by guiding the observing strategies and data analysis of the future facilities. REACH is therefore expected to open up a range of possibilities for high impact science beyond the aforementioned detection.

REACH has existed as a project since the beginning of 2019 and it is aiming at obtaining significant results in a period of 2 years (see Fig. 4).

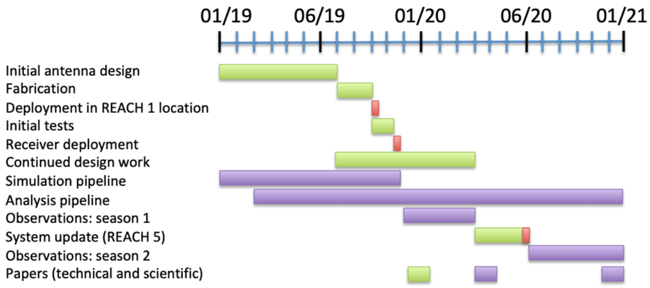

Fig. 4. Project timeline.

The experiment requires an RFI quiet location. Several have been surveyed including the MRO, Australia, where EDGES is currently installed (and it is the location of the future SKA1-LOW and the current MWA telescopes) and the Karoo radio reserve in South Africa, home of the HERA telescope, all operating in the same frequency band as the proposed instrument and with very similar constrains in terms of RFI. The RFI measurements performed recently indicate that the Karoo radio reserve could potentially be a good enough location (see Fig. 5) with the added advantage of synergies with HERA and a fully operational radio astronomy site with easy access to the project members.

Fig. 5. ProjPotential location for REACH in the Karoo radio reserve, South Africa.

VI. Conclusions

The Radio Experiment for the Analysis of Cosmic Hydrogen is a novel experiment for the detection of the 21-cm line from Hydrogen red-shifted to a few hundreds MHz due to the expansion of the Universe. REACH is based on state of the art Bayesian analysis informed by physics-rooted models of the cosmic signal, foregrounds and the instrument itself. REACH is expecting to start data collection by the end of 2019.

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