HERA: Illuminating our Early Universe

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Abstract

The Hydrogen Epoch of Reionization Arrays (HERA) roadmap is a staged plan for using the unique properties of the 21cm line from neutral hydrogen to probe our cosmic dawn, from the birth of the first stars and black holes, through the full reionization of the primordial intergalactic medium (IGM). HERA is a collaboration between the Precision Array Probing the Epoch of Reionization (PAPER), US-Murchison Widefield Array (MWA), and MIT Epoch of Reionization (MITEOR) teams.

1 Introduction

The Hydrogen Epoch of Reionization Arrays (HERA) roadmap is a staged plan for using the unique properties of the 21cm line from neutral hydrogen to probe our cosmic dawn, from the birth of the first stars and black holes, through the full reionization of the primordial intergalactic medium (IGM). During these epochs, roughly 0.3–1 Gyr after the Big Bang, the first stars and black holes heat and reionize the neutral IGM that pervades the Universe following cosmic recombination. Direct observation of the large scale structure of the primordial IGM, and its evolution with time, via the HI 21cm line, will have a profound impact on our understanding of the birth of the first galaxies and black holes, their influence on the surrounding gas, and cosmology.

The first phase of the HERA roadmap entailed the operation of the PAPER and MWA telescopes to explore techniques and designs required to detect the primordial HI signal in the presence of radio continuum foreground emission some four orders of magnitude brighter. Studies with PAPER and the MWA have led to a new understanding of the interplay of foreground and instrumental systematics in the context of a three-dimensional cosmological intensity-mapping experiment. We are now able to remove foregrounds to the limits of our sensitivity with these instruments, culminating in the first phys-

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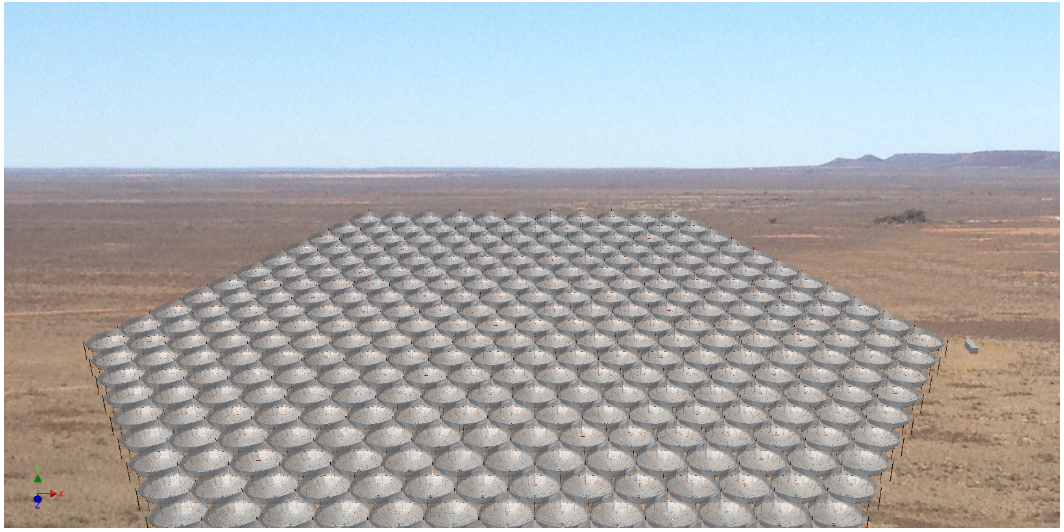

Figure 1: Rendering of the 331 element array.

ically meaningful upper limits on the power spectrum of 21 cm emission from reionization.

Building on this understanding, the next stage of HERA entails a new 14m diameter antenna element that is optimized both for sensitivity and for minimizing foreground systematics. Arranging these elements in a compact hexagonal grid yields an array that facilitates calibration, leverages proven foreground removal techniques, and is scalable to large collecting areas. The HERA phase II will be located in the radio quiet environment of the SKA site in Karoo, South Africa, and have a sensitivity close to two orders of magnitude better than PAPER and the MWA, with broader frequency coverage, HERA can paint an uninterrupted picture through reionization, back to the end of the Dark Ages. HERA will proceed in two stages:

HERA 127, deployed in 2016, will measure the rise and fall of the 21 cm reionization power spectrum, constraining the timing and duration of reionization.

HERA 331, deployed in 2017, will measure fluctuations in the 21 cm signal over a variety of spatial scales to determine the nature and distribution of the first galaxies that dominate cosmic reionization. HERA 331 will also extend precision power-spectrum observations back to the end of the 'Dark Ages' (z 20), when the first stars and black holes warm the primordial IGM.

2 Science

The *cosmic dawn*, the period beginning with the birth of the first stars and culminating with the full reionization of the IGM some 500 Myrs later, represents one of the last unexplored phases in the history of structure formation. During this period, a wealth of astrophysical and cosmological phenomena are

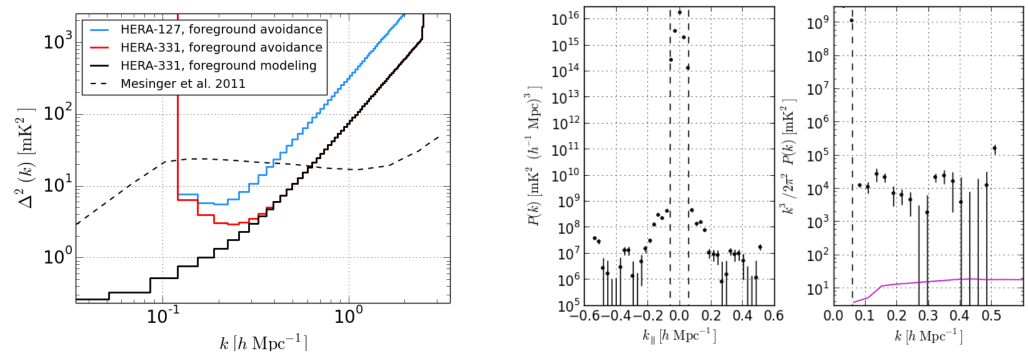

Figure 2: Left: HERA's power-spectrum sensitivity (solid) relative to a fiducial ionization model (dotted line; $x_{\mathrm{HI}} = 0.37$, $z = 9.0$). Sensitivities reflect staged array size and improving analysis software that expands the range of modes free of foreground systematics. Right: The current best upper limit on the 21 cm reionization power spectrum, obtained with a 32-element PAPER deployment (Parsons et al., 2013). These upper limits constrain the brightness temperature of the IGM at $z \sim 8$, showing a departure from adiabatic cooling presumed to be indicative of X-ray heating.

at work. The characteristics of the IGM depend on the cosmic density field, the formation sites of the first luminous sources (e.g., their typical masses and clustering), their constituents (e.g., exotic Population III stars, more normal stars, stellar remnants, or supermassive black holes) their ultraviolet luminosities (which affect the IGM's ionization state), the efficiency and abundance of X-ray sources (which affect the IGM temperature), and even more exotic effects like the relative velocity of baryons and dark matter.

A season of observing with HERA-127 will yield high-significance constraints on the 21 cm power spectrum across a wide range of k modes and redshifts (Pober et al., 2014). In Figure 2 we show the $z = 9$ power spectrum predicted by the publicly available 21cmFAST software (Mesinger et al., 2011), along with 2σ HERA sensitivities. Using the conservative delay-spectrum ("foreground avoidance") approach pioneered by PAPER (Parsons et al. 2014), we find that HERA-127 can achieve a $> 10\sigma$ detection of fiducial power spectra over a broad range of redshifts. The subsequent observing season with HERA-331 can increase this detection significance to over 25σ using the same methods. With detailed foreground modeling, the more sophisticated power spectrum estimator developed for the MWA could increase the size of the "EoR window", the region of Fourier space with minimal foreground contamination. This would allow for an overall detection significance of up to 90σ, along with access to lower k modes and therefore qualitatively different physics. Such a high sensitivity measurement would also allow one to go beyond constraining parameters, testing rather than assuming the underlying theoretical framework and starting to image the large neutral bubbles during reionization.

The ability of HERA to image enables an exciting range of cross-correlation science. HERA HI images reveal the large-scale reionization environment for pointed ALMA and JWST observations, and other deep near-IR surveys (Lidz et al., 2009). Knowing whether an observed galaxy is in a region that was previously reionized (center of large HII bubble), recently reionized (edge of HII bubble), or is forming from pristine neutral gas provides important contextual information on early galaxy formation.

The HI images can be cross-correlated with other diffuse tracers of large scale structure. A number of studies have proposed cross-correlation with large scale intensity mapping of molecular CO Lidz et al. (2011) and atomic CII (Gong et al., 2011) lines. These studies trace the large scale galaxy distribution – the sources of reionization. Prototypes of these experiments may be operating on the HERA timescale. Such probes have the advantage of having different systematics compared to HERA, potentially allowing clean measurements of the underlying signal.

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