Exploring the Epoch of Reionization with Low-Frequency Radio Telescopes

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Abstract

The Epoch of Reonization (EoR) represents a major frontier of cosmic evolution yet to be explored. Redshifted emission from the 21cm hyperfine transition of neutral hydrogen provides a unique tracer of the primordial intergalactic medium. But with foregrounds that exceed the expected EoR signal by more than five orders of magnitude, the level of calibration needed for detecting this signal is unprecedented in the 100-200MHz band expected to encompass EoR. We will discuss the various instrumental approaches underway for achieving the necessary sensitivity and calibration, and discuss plans for second-generation antenna arrays that might explore EoR tomographically.

1 Description

The Epoch of Reionization (EoR) was a key period of cosmic structure formation and represents a major frontier of cosmic evolution yet to be explored. Redshifted emission from the 21cm hyperfine transition of neutral hydrogen provides a unique tracer of the primordial intergalactic medium. The scientific payoff for measuring the 21cm EoR signal includes identifying the primary sources of ionization in the early universe, improving upon current constraints on cosmological parameters obtained from the cosmic microwave background, and informing our understanding of how the first, most massive stars might have cooled enough to undergo gravitational collapse.

With foregrounds that exceed the expected 21cm EoR signal by more than five orders of magnitude, the level of calibration needed for detecting this signal is unprecedented in the 100-200MHz band expected to encompass reionization. With such a premium placed on system and foreground modeling, radio telescopes aiming to detect the 21cm EoR signal must carefully consider how design choices influence calibration. Small, single-dipole antenna elements have many desirable properties from a calibration standpoint; their smooth evolution in response versus angle and frequency require fewer degrees of freedom to model and are less likely to impose spectral structure on foregrounds whose distinguishability from an EoR signal will likely rely on spectral smoothness.

In addition to addressing calibration and foreground-modeling challenges, low-frequency radio telescopes targeting EoR will have to address the substantial sensitivity requirements for detecting a signal. In this aspect, smaller collecting elements place a large burden on the digital signal processing systems employed to cross-correlate each pair of antennas. The drive to obtain the requisite collecting areas and integration times for detecting the 10mK peak fluctuations of EoR relative to 500K sky-dominated noise temperatures has led several groups to favor designs that beam-form many smaller dipoles into station beams before correlation. This solution represents an effective solution for cheaply increasing collecting area and reducing the cost of correlation while also facilitating longer integration times with tracking beams. On the other hand, the sidelobes inherent to the response of a beam-formed station may exacerbate the aforementioned calibration challenges.

A final consideration in the design of these antenna arrays concerns antenna placement within an array. Traditional array configurations aim to sample as many independent spatial Fourier modes as possible. This approach provides the most information for imaging and reduces sidelobes associated with synthesis imaging. On the other hand, for arrays aiming to statistically detect reionization by measuring the three-dimensional power spectrum of temperature fluctuations at cosmological distances, sensitivity can be dramatically improved by redundantly sampling a few Fourier modes with as many antenna-pairs as possible. Hence, the drive to accurately image and characterize foregrounds with a minimum-redundancy configuration is in direct conflict with the need to improve sensitivity with maximum-redundancy configurations.

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Parameter space for designing low-frequency telescopes targeting reionization is fraught with conflicting influences. The optimal balance between smaller antenna elements and beam-formed stations as correlation elements, and between minimum- and maximum-redundancy array configurations must ultimately be informed by real-world experience with the technical challenges of construction, correlation, and calibration. First-generation efforts to explore these challenges include the Giant Metre-wave Radio Telescope (GMRT; Pen et al 2009), the LOw Frequency ARray (LOFAR; Rottgering et al. 2006), the Murchison Widefield Array (MWA; Lonsdale et al. 2009), and the Precision Array for Probing the Epoch of Reionization (PAPER; Parsons et al. 2010). Second-generation efforts on the horizon that will be informed by the successes and failures of these first-generation efforts include the Hydrogen Epoch of Reionization Array (HERA) and the low-frequency component of the Square Kilometer Array (SKA-low). While near-term efforts will be focused toward measuring the power-spectrum of reionization fluctuations, these later efforts will likely aim to explore the EoR tomographically.

References

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