Hydrogen Epoch of Reionization Arrays (HERA): Beyond Detection

This proposal targets the Mid-Scale Science Projects category of the Mid-Scale Innovations Program solicitation. The Hydrogen Epoch of Reionization Arrays (HERA) is a program for using the unique capabilities of the 21cm hyperfine line to trace neutral hydrogen through the cosmic dawn of our Universe. The HERA roadmap that was submitted to the *New Worlds, New Horizons of Astronomy and Astrophysics* 2010 decadal survey, (hereafter NWNH) was given "top priority in this [Radio, Millimeter, and Sub-millimeter] category of recommended new facilities for mid-scale funding." The HERA roadmap proceeded in three stages: HERA-IB called for \$25M to complete the PAPER and MWA experiments; HERA-II budgeted \$62M for an array with 0.1 km^2 of collecting area capable of characterizing the power spectrum of cosmic reionization in detail; HERA-III targeted 1 km^2 of collecting area to image reionization structures in detail.

The PAPER and MWA experiments are now fully constructed, and nearing the completion of their groundbreaking science program over the coming two years. Although significantly less than \$25M was invested in HERA-IA/B, these 'spearhead projects' are leading the global effort to tap the transformative potential of the 21cm line as a probe of cosmic history. The most difficult challenge involves balancing stringent sensitivity requirements against the need to suppress foregrounds that are five orders of magnitude brighter than the signal. In this area, there has been a major breakthrough. Based on a new understanding of how instrumental characteristics can be leveraged to isolate foreground emission from the cosmological signal on the basis of spectral smoothness, foreground emission has been suppressed by four orders of magnitude in PAPER observations, down to the current limits of PAPER's sensitivity. HERA-IA/B instruments are now sensitivity-limited, and making the first statistical detection of 21cm reionization remains viable at the limits of the sensitivity of current projects.

Given this new conclusive answer to the question of how to optimize 21cm reionization experiments for foreground removal, the time is ripe to launch the next phase of HERA. We propose a staged approach to building the next-generation experiment that incorporates these new breakthroughs, targets reionization science beyond the first detection, and is timed to begin producing transformative science just as current HERA-I instruments are finishing. As described below, recent technical breakthroughs favor larger, close-packed antenna elements, and this has substantially altered the HERA plan. The next step for HERA targeted in this proposal delivers the 0.1 km^2 collecting area and associated science of HERA-II, but with less than 600 antennas, the budget (\$16.3M), project complexity, and project team are of a modest HERA-IB scope.

1. Scientific Justification

The period beginning with the birth of the first luminous objects in the universe, and culminating with the ionization of the intergalactic medium (IGM) ∼500 Myrs later, is one of the last unexplored phases of cosmic evolution. Exploring this epoch of reionization was highlighted as one of the three "priority science objectives chosen by the [NWNH] survey committee for the decade 2012-2021" (Comm. for a Decadal Survey of A&A; NRC 2010). Observations of Gunn-Peterson absorption by the IGM toward the most distant quasars (Fan et al. 2006), kinetic Sunyaev-Zel'dovich features in the CMB (Zahn et al. 2012), and CMB anisotropy and polarization (Page et al. 2007; Planck Collaboration et al. 2013) indicate that reionization was a complex process, starting perhaps as early as $z \approx 14$, with the last vestiges of the the neutral IGM being etched away by $z \approx 6$. Unfortunately, these ground-breaking results are limited in diagnostic capabilities: the Gunn-Peterson effect saturates for even low neutral fractions, and the CMB only provides an integral measure of the Thompson optical depth back to recombination.

Redshifted emission from the 21cm hyperfine transition of neutral hydrogen has gained considerable attention as a unique (albeit weak) tracer of the primordial IGM. The direct observation of the neutral IGM via this signal would be an achievement comparable with the discovery of the CMB. As emphasized in NWNH (Comm. for a Decadal Survey of A&A; NRC 2010): "The panel concluded that to explore the discovery area of the epoch of reionization, it is most important to develop new capabilities to observe redshifted 21-cm HI emission, building on the legacy of current projects and increasing sensitivity and spatial resolution to characterize the topology of the gas at reionization."

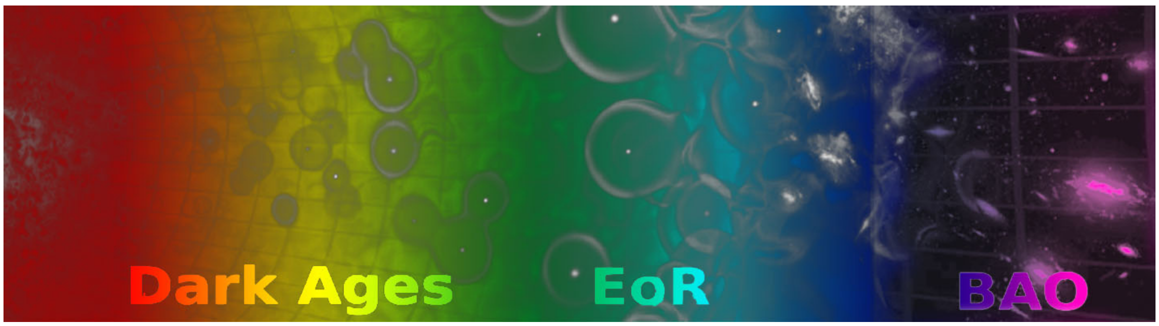

Fig. 1.— The 21cm hyperfine line of neutral hydrogen represents the next frontier in precision cosmology. Following recombination (left edge), the spin temperature of 21cm emission is sensitive to the density and temperature of the intergalactic medium (IGM) through the Dark Ages, evolves with the heating and ionization of the IGM during the Epoch of Reionization (EoR), and traces the distribution of galaxies as the universe expands, leading up the the present day (right edge). Color indicates redshift, which stretches the 21cm line to frequencies ranging from 50 MHz (red) to 1.4 GHz (violet).

The challenges associated with 21cm cosmology experiments are daunting. Such experiments require unprecedented levels of sensitivity, instrumental calibration, and foreground characterization. The spectral response of these instruments is of paramount importance; it is used both for constructing the line-of-sight direction of 3D space, and also for differentiating smooth-spectrum foreground emission from spatial fluctuations in the cosmological signal. The brightness temperatures of foregrounds, in the form of galactic synchrotron emission, continuum point-sources, and polarized galactic/extra-galactic emission, exceed the fluctuations of the 21cm signal by more than 5 orders of magnitude (Santos et al. 2005; Pritchard and Loeb 2012; Pober et al. 2013).

As is being discovered, these foregrounds are proving very difficult to attack head-on. To achieve the necessary sensitivity, experiments are driven toward using interferometers, but the frequency dependence of the angular wavemode sampled by an interferometer causes smooth-spectrum foregrounds to appear unsmooth, degrading the separation that can be achieved between foregrounds and k-modes of the 21cm power spectrum $\Delta^2_{21}(k)$. Experimental approaches adopted by LOFAR and the MWA aim to achieve sufficient accuracy in foreground characterization and instrument calibration to model and remove such chromatic effects. However, this is proving to be an extremely challenging and costly task, and it remains uncertain whether this approach is practically viable given realistic limitations on calibration accuracy.

PAPER has made significant progress following a different approach. Based on a "delay-

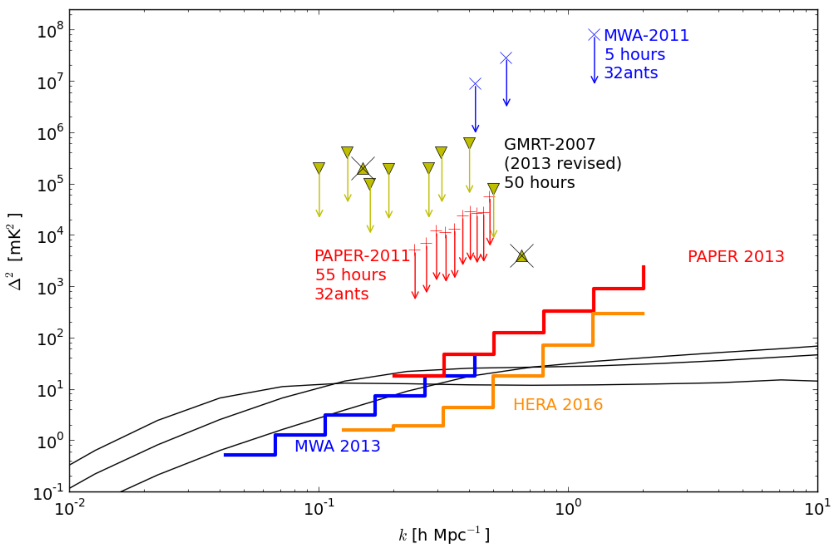

Fig. 2.— Current best upper limits on the power spectrum of 21cm emission from reionzation at $z = 7.7$, made with a 32-antenna deployment of the PAPER experiment (Parsons et al. 2013). Black indicates the final measurements with 2σ confidence intervals. The yellow triangles indicate the previous best 2σ upper limits at $z = 8.6$ (Paciga et al. 2013). Magenta illustrates a fiducial 50% ionization model (Lidz et al. 2008). The 8 orders of magnitude (in mK^2) of foreground suppression outside of the dashed lines (left panel) are a testament to the crucial role that instrument design plays in mitigating foreground systematics.

spectrum" understanding of the mechanism for how instrumental responses modulate foregrounds on spectral scales of cosmological interest (Parsons et al. 2012), PAPER has optimized its instrument to focus on regions in Fourier space that have weak coupling to foregrounds. XXX describe optimization to foreshadow changes in HERA. These regions are determined both by chromatic instrumental responses and by the inherent frequency evolution of the foregrounds. As shown in Figure 2, observations based on this new approach are demonstrating that the extremely stringent level of foreground removal needed to access the 21cm signal is largely in hand, with upper limits that are beginning to rule out cold reionization scenarios.

2. Project Description

This HERA proposal targets a 568-element array that incorporates these proven foreground avoidance techniques while addressing the sensitivity limitations of current experiments. With a better understanding of how antenna size and separation affect the interaction of sensitivity and foreground isolation, it has become clear that larger, close-packed antenna elements can yield up to 30 times the sensitivity of current elements without substantially degrading foreground isolation. Where PAPERs elements lack collecting area and are smaller than strictly required for foreground isolation, and the majority of MWA and LOFAR elements are spaced too widely to avoid foregrounds, HERA employs an extremely compact array of large — but not *too* large — antenna elements, building on PAPER's design. As illustrated in Figure 3, these elements consist of PAPER-style dipole feeds suspended over 14m parabolic dishes. The short (∼5m) focal height of these dishes is central to limiting the path length of reflections whose time-delay gives rise to chromatic instrumental systematics.

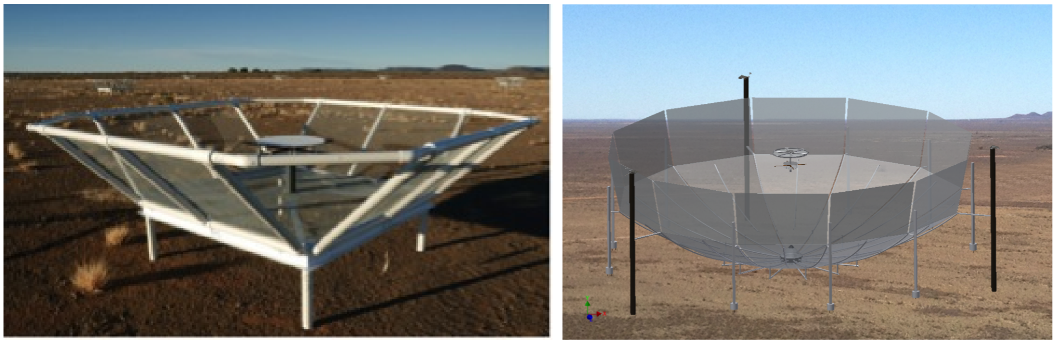

Fig. 3.— The PAPER element (left) provides a clean instrumental response as a function of frequency (Parsons et al. 2010, 2012), which is crucial to the foreground isolation shown in Figure 2. A 14m dish designed around the same feed (right) dramatically improves sensitivity while constraining the path length and amplitude of reflections to ensure that foreground isolation is not substantially degraded.

The size of the new HERA dish optimizes cost for a fixed sensitivity and level of foreground isolation. The associated reduction in the number of antenna elements, combined with the fact that these dishes have no moving parts, are built from inexpensive materials, and follow a simple construction that can be delegated to local contractors, makes the cost of building HERA's Phase-II experiment several times cheaper than was anticipated in the HERA roadmap submitted to NWNH.

HERA follows a staged build-out plan similar to that championed by PAPER. In each deployment stage, improvements are incorporated into the system, and new science capabilities are unlocked. This approach has the advantage of providing early access to science, permitting longer development times for certain system components, and reducing the project risk by testing systems early and changing them incrementally. As shown in Figure 2, each stage of HERA brings an associated improvement in sensitivity that allow key aspects of 21cm reionization science to be addressed. The timeline of HERA development, along with the associated science producets, is outlined below.

Year 1 (FY 2015). In the first year, development of infrastructure (ground leveling, power, basic network connectivity) begins immediately on a new 'K3' site approximately 10 km from the current PAPER site at the Karoo Radio Observatory in South Africa. As final PAPER-128 observations complete in Apr. 2015, the existing PAPER-128 antennas, correlator, and EMC container are migrated to the K3 site, where they are combined with 37 prototype HERA dishes that use existing PAPER feeds and electronics, and are arranged in a compact hexagonal configuration. Physical construction is handled by students, engineers, and local interns. Activities for developing and improving HERA baluns, receivers, and feeds from PAPER designs begin, as do the in-situ antenna calibration subsystems and the longer-term development activities for node electronics, the (exploratory) spatial FFT correlator, and the various software analysis pipelines.

Year 2 (FY 2016). Commissioning observations begin with HERA-37, correlated along with 91 PAPER elements using the PAPER correlator on site. This first observations test the performance of the HERA dishes, verifying beam patterns against known PAPER beam responses, and checking for any problematic spectral structure arising from signal reflections. Science observations begin in Oct. 2015 and run until Apr. 2016. Because HERA-37 has ~10 times the sensitivity of

PAPER-128, thes observations have a high probability of detecting the peak levels of the 21cm EoR power spectrum. Development of site infrastructure (high-bandwidth optical network, surveying, trenching) finishes. Development activities begun in Year 1 continue, culminating in the finalization and fabrication of improved HERA feeds and receivers in Jan. 2016. As observations with HERA-37 complete, deployment of the next stage of HERA begins: a larger, 127-element array of HERA dishes in a hexagonal configuration, featuring new feeds and (if necessary) a refined dish design. If possible, the 37 existing elements are retrofitted, but if necessary, HERA-127 budgets for replacement. Physical construction (trenching, pole installation, assembly) is handled by local contractors.

Year 3 (FY 2017). Construction of HERA-127 completes, and science observations begin in Oct. 2016, again using the PAPER correlator. Science papers from HERA-37 are published. Node and correlator designs are finalized and fabrication begins. Science observations with HERA-127 complete in Apr. 2017; analysis begins on a dataset capable of constraining the timing and duration of reionization. Deployment of HERA-331 begins. Contractors lead physical construction, expanding from the existing 127 elements. Node electronics are installed for all 331 elements, and a new, 331-element GPU-based correlator is installed in the Karoo Array Processing Building (KAPB), operating on digital data that are transmitted from the nodes through optical links. Additional data storage infrastructure is installed in the KAPB. The UPenn data analysis cluster is upgraded.

Year 4 (FY 2018). Construction of HERA-331 completes, and science observations begin in Oct. 2017. HERA-127 results are published. Fabrication of nodes and antenna parts continues. Science observations with HERA-331 complete in Apr. 2018, and analysis begins on a dataset capable of characterizing the slope of the power spectrum, distinguishing between various sources of ionizing photons. Deployment of HERA-568 begins, following the same pattern as in Year 3. If the design of the spatial FFT correlator is mature and successfully tested in commissioning observations, the FX correlator hardware will be repurposed as a spatial FFT correlator, with spare hardware used to compute the real-time calibration parameters that are necessary to the functioning of the spatial FFT correlator.

Year 5 (FY 2019). In the final year, construction of HERA-568 completes, and science observations begin in Oct. 2018. Papers from HERA-331 are published. With build-out complete, all attention is now directed toward preparing and testing final imaging and power-spectrum software pipelines, such that processing proceeds on HERA-568 as data are available. Science papers resulting from these observations are published, including extensions of analysis to lower frequency bands and imaging of bright reionization structures.

References

Comm. for a Decadal Survey of A&A; NRC, 2010: *New Worlds, New Horizons in Astronomy and Astrophysics*. Natl. Academies Press.

Fan, X., C. L. Carilli, and B. Keating, 2006: Observational Constraints on Cosmic Reionization. *ARA&A*, **44**, 415–462, arXiv:astro-ph/0602375.

Lidz, A., O. Zahn, M. McQuinn, M. Zaldarriaga, and L. Hernquist, 2008: Detecting the Rise and Fall of 21 cm Fluctuations with the Murchison Widefield Array. *ApJ*, **680**, 962–974, arXiv:0711.4373.

Paciga, G., J. G. Albert, K. Bandura, T.-C. Chang, Y. Gupta, C. Hirata, J. Odegova, U.-L. Pen, J. B. Peterson, J. Roy, J. R. Shaw, K. Sigurdson, and T. Voytek, 2013: A simulation-calibrated limit on the H I power spectrum from the GMRT Epoch of Reionization experiment. *MNRAS*, 1301.5906.

Page, L., G. Hinshaw, E. Komatsu, M. R. Nolta, D. N. Spergel, C. L. Bennett, C. Barnes, R. Bean, O. Doré, J. Dunkley, M. Halpern, R. S. Hill, N. Jarosik, A. Kogut, M. Limon, S. S. Meyer, N. Odegard, H. V. Peiris, G. S. Tucker, L. Verde, J. L. Weiland, E. Wollack, and E. L. Wright, 2007: Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Polarization Analysis. *ApJS*, **170**, 335–376, arXiv:astro-ph/0603450.

Parsons, A. R., D. C. Backer, G. S. Foster, M. C. H. Wright, R. F. Bradley, N. E. Gugliucci, C. R. Parashare, E. E. Benoit, J. E. Aguirre, D. C. Jacobs, C. L. Carilli, D. Herne, M. J. Lynch, J. R. Manley, and D. J. Werthimer, 2010: The Precision Array for Probing the Epoch of Re-ionization: Eight Station Results. *AJ*, **139**, 1468–1480, 0904.2334.

Parsons, A. R., A. Liu, J. E. Aguirre, Z. S. Ali, R. F. Bradley, C. L. Carilli, D. R. DeBoer, M. R. Dexter, N. E. Gugliucci, D. C. Jacobs, P. Klima, D. H. E. MacMahon, J. R. Manley, D. F. Moore, J. C. Pober, I. I. Stefan, and W. P. Walbrugh, 2013: New Limits on 21cm EoR From PAPER-32 Consistent with an X-Ray Heated IGM at z=7.7. *ArXiv e-prints*, 1304.4991.

Parsons, A. R., J. C. Pober, J. E. Aguirre, C. L. Carilli, D. C. Jacobs, and D. F. Moore, 2012: A Per-baseline, Delay-spectrum Technique for Accessing the 21 cm Cosmic Reionization Signature. *ApJ*, **756**, 165, 1204.4749.

Planck Collaboration, P. A. R. Ade, N. Aghanim, C. Armitage-Caplan, M. Arnaud, M. Ashdown, F. Atrio-Barandela, J. Aumont, C. Baccigalupi, A. J. Banday, and et al., 2013: Planck 2013 results. XVI. Cosmological parameters. *ArXiv e-prints*, 1303.5076.

Pober, J. C., A. R. Parsons, J. E. Aguirre, Z. Ali, R. F. Bradley, C. L. Carilli, D. DeBoer, M. Dexter, N. E. Gugliucci, D. C. Jacobs, P. J. Klima, D. MacMahon, J. Manley, D. F. Moore, I. I. Stefan, and W. P. Walbrugh, 2013: Opening the 21 cm Epoch of Reionization Window: Measurements of Foreground Isolation with PAPER. *ApJ*, **768**, L36, 1301.7099.

Pritchard, J. R. and A. Loeb, 2012: 21 cm cosmology in the 21st century. *Reports on Progress in Physics*, **75(8)**, 086901, 1109.6012.

Santos, M. G., A. Cooray, and L. Knox, 2005: Multifrequency Analysis of 21 Centimeter Fluctuations from the Era of Reionization. *ApJ*, **625**, 575–587, arXiv:astro-ph/0408515.

Zahn, O., C. L. Reichardt, L. Shaw, A. Lidz, K. A. Aird, B. A. Benson, L. E. Bleem, J. E. Carlstrom, C. L. Chang, H. M. Cho, T. M. Crawford, A. T. Crites, T. de Haan, M. A. Dobbs, O. Doré, J. Dudley, E. M. George, N. W. Halverson, G. P. Holder, W. L. Holzapfel, S. Hoover, Z. Hou, J. D. Hrubes, M. Joy, R. Keisler, L. Knox, A. T. Lee, E. M. Leitch, M. Lueker, D. Luong-Van,

J. J. McMahon, J. Mehl, S. S. Meyer, M. Millea, J. J. Mohr, T. E. Montroy, T. Natoli, S. Padin, T. Plagge, C. Pryke, J. E. Ruhl, K. K. Schaffer, E. Shirokoff, H. G. Spieler, Z. Staniszewski, A. A. Stark, K. Story, A. van Engelen, K. Vanderlinde, J. D. Vieira, and R. Williamson, 2012: Cosmic Microwave Background Constraints on the Duration and Timing of Reionization from the South Pole Telescope. *ApJ*, **756**, 65, 1111.6386.