HERA: Characterizing Our Cosmic Dawn

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 submitted to the *New Worlds, New Horizons of Astronomy and Astrophysics* 2010 decadal survey, (Comm. for a Decadal Survey of A&A; NRC 2010; 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 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 will complete their ground-breaking science program over the coming two years. Although significantly less than \$25M was invested in HERA-IA/B, these 'spearhead projects' lead the global effort to tap the transformative potential of the 21cm line as a probe of cosmic history. Their greatest challenge is 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 foregrounds from the cosmological signal on the basis of spectral smoothness, foreground emission has been suppressed by four orders of magnitude (in Jy) in PAPER observations, down to the current sensitivity limits. HERA-I instruments are now sensitivity-limited, and have begun ruling out certain reionization scenarios (Parsons et al. 2013). Making the first statistical detection of 21cm reionization remains possible 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 the improved design makes 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) $\sim$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". 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 various CMB probes provide only integral measures of ionization history.

Redshifted emission from the 21cm hyperfine transition of neutral hydrogen has gained considerable attention as a unique tracer of the primordial IGM. Indeed, in the early universe, 21cm emission provides the only direct probe of the complex astrophysical interplay between the first luminous structures and their surroundings. The direct observation of the neutral IGM via this signal would be an achievement with a scientific payoff comparable to that of the CMB. As emphasized in NWNH: "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."

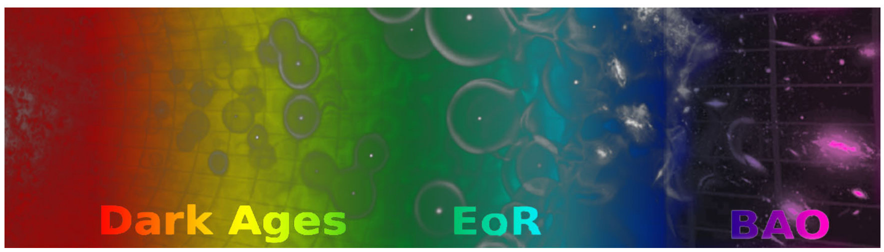

Fig. 1.— Following recombination (left edge), the brightness temperature of 21cm emission is sensitive to the density and temperature of the IGM through the Dark Ages ($z\sim$120–20), evolves with the heating and ionization of the IGM during the Epoch of Reionization (EoR; $z\sim$12–6), and traces the distribution of galaxies as the universe expands ($z<4$), leading up the the present day (right edge). Color indicates the redshifting of the 21cm line between 50 MHz (red) and 1.4 GHz (violet).

As large scale structures in the IGM grow through gravitational instability and are heated and ionized by luminous sources, fluctuations are introduced in 21cm emission (see Figure 1). Imaging of these fluctuations is a long-range goal, but in the short term, statistical measurements (such as the power spectrum shown in Figure 2) may be more powerful. Fluctuations decrease in amplitude as the gas is heated in the first stages of reionization, then increase as large ionized bubbles form around galaxies, and finally fade again as the majority of the gas is ionized. Variations in the ultraviolet and X-ray backgrounds, in addition to the normal density fluctuations in the IGM, induce additional structure in the 21cm background. These fluctuations, from the Dark Ages through reionization, are the primary target of HERA. Measuring them allows us to probe the properties of high$-z$ galaxies and how they affected the Universe around them. Specifically, HERA will help us understand when reionization occurred, how the cosmic web evolved, where the first generation of quasars formed, when the first galaxies formed, and what their properties were.

2. Experimental Approach

The challenges facing 21cm reionization experiments are daunting. Such experiments require unprecedented levels of sensitivity, and 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). These foregrounds are proving very difficult to attack head-on. The need for sensitivity drives experiments toward using interferometers, but the frequency-dependent instrumental response of antenna cross-correlations causes what are otherwise smooth-spectrum foregrounds to appear with spectral structure that mimics the variation expected from 21cm reionization. Approaches adopted by LOFAR and the MWA aim to use extremely accurate models of foreground and instruments to remove such chromatic effects. However, this is proving to be a challenging and costly task, and it remains uncertain whether this approach is practically viable given realistic limitations on calibration accuracy.

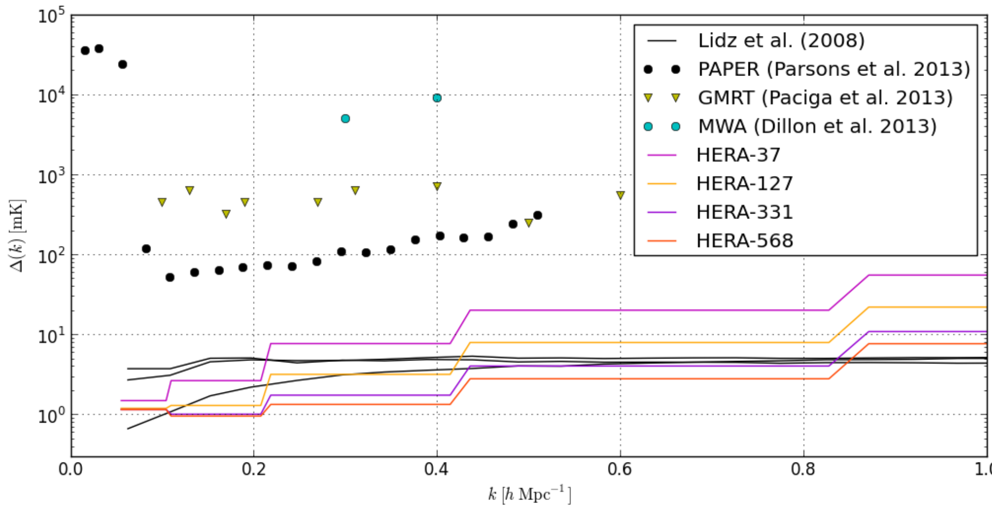

Fig. 2.— 2σ upper limits on the 21cm EoR power spectrum at $z \sim 8$, along with fiducial signal models for several ionization fractions (black; Lidz et al. 2008), and the predicted RMS sensitivies of HERA in various stages, including sample variance and baseline-dependent foreground cutoffs. The foreground isolation in PAPER measurements above $k \approx 0.1h$ Mpc^{-1} are a testament to the crucial role that instrument design plays in mitigating foreground systematics.

PAPER has made significant progress following a different approach. Based on a "delay-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. These regions are determined both by chromatic instrumental responses and by the inherent frequency structure of the foregrounds. In order to access these regions, PAPER employs antenna elements with smooth spectral responses and uses compact antenna configurations to minimize instrumental chromaticity. 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 (as shown in Figure 2), with upper limits that are beginning to rule out cold reionization scenarios.

3. Project Plan and Timeline

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 new understanding of how antenna size and separation affect sensitivity and foreground isolation, it has become evident a revision of the PAPER design can yield up to 30 times the sensitivity per element without substantially degrading foreground isolation. Where PAPER's 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

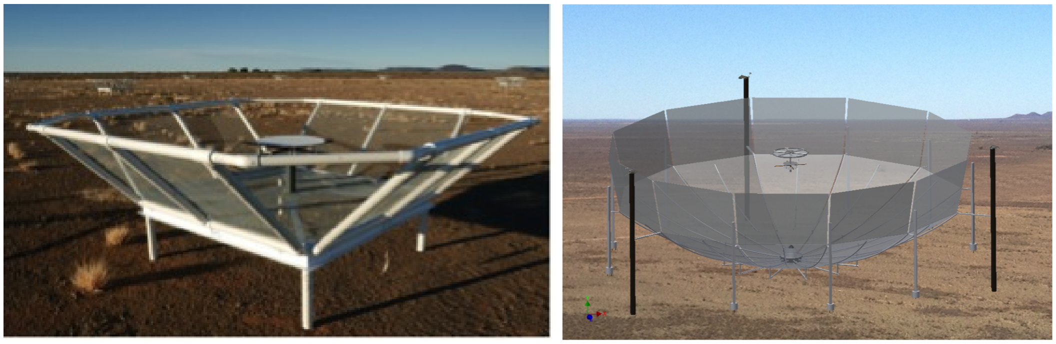

Fig. 3.— The PAPER element (left) provides a clean instrumental response as a function of frequency (Parsons et al. 2010, 2012), which is crucial to the foreground isolation shown in Figure 2. A 14m dish designed around the same feed (right) dramatically improves sensitivity while constraining the path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

extremely compact array of 14m parabolic dishes with PAPER-style dipole feeds (see Figure 3. The short (4.5m) focal height of these dishes is central to limiting the path length of reflections whose time-delay gives rise to chromatic instrumental systematics.

The size of HERA dishes 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 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 products, is outlined below.

Year 1 (FY 2015). Develop infrastructure (ground leveling, power, basic network connectivity) at a new 'K3' site ∼10 km from the current PAPER site in South Africa. Upon completion of PAPER-128 observations in Apr. 2015, migrate PAPER antennas, correlator, and EMC container to the K3 site, and combine with 37 hexagonal-packed prototype HERA dishes based on existing PAPER feeds and electronics. Students, engineers, and local interns handle physical construction. Begin development activities for improving HERA baluns, receivers, node electronics, and feeds from PAPER designs. Begin exploratory development of *in situ* antenna calibration subsystems, the spatial FFT correlator, and the various software analysis pipelines.

Year 2 (FY 2016). Perform HERA-37 commissioning observations, along with 91 PAPER elements, using the existing PAPER correlator. Verify HERA dish performance; calibrate beam patterns against PAPER beam responses; check for problematic spectral structure from reflections. Perform science observations Oct. 2015 to Apr. 2016 that, because HERA-37 has ∼10 times the sensitivity of PAPER-128, have a high probability of detecting the peak levels of the 21cm EoR power spectrum. Finish site infrastructure (high-bandwidth optical network, surveying, trenching). Finalize and fabricate improved HERA feeds and receivers in Jan. 2016. Local contractors handle physical construction (trenching, pole installation, assembly) of a 127-element HERA array featuring new feeds and a refined dish design, replacing existing 37 elements.

Year 3 (FY 2017). Perform HERA-127 science observations from Oct. 2016 to Apr. 2017 using the PAPER correlator. Publish HERA-37 science papers. Finalize and fabricate node and correlator designs. Analyze the HERA-127 dataset to constrain the timing and duration of reionization. Contractors expand HERA-127 to a 331-element array from May to Sep. Install node electronics in the field and a new GPU correlator in an off-site building, with optical links carrying digitized data. Install data storage infrastructure. Upgrade the UPenn data analysis cluster.

Year 4 (FY 2018). Perform HERA-331 science observations from Oct. 2017 to Apr. 2018. Publish HERA-127 results. Fabricate nodes and antenna parts. Analyze HERA-331 dataset to characterize the slope of the power spectrum and distinguish between sources of ionizing photons. Deploy HERA-568, following the same Year 3 pattern. Optionally repurpose FX correlator hardware for the spatial FFT correlator, with real-time calibration.

Year 5 (FY 2019). Perform HERA-568 science observations from Oct. 2018 to Apr. 2019. Publish HERA-331 results. Prepare and test final imaging and power-spectrum software pipelines. Analyze the HERA-568 dataset to produce images of bright EoR structures, and extend power-spectrum analysis to lower frequency bands.

4. Project Management Plan

This project strikes a balance between the light-weight management structure of HERA-I activities and the more formal structure required for larger-scale projects. Building on PAPER's excellent track record and the resources of UC Berkeley's Radio Astronomy Laboratory (RAL), this proposal consolidates responsibility and management of the core HERA fabrication and construction activities at RAL. Parsons serves as Project Director/Scientist; DeBoer serves as Project Manager/Engineer. Executive (Aguirre, Bradley, Hewitt, Morales, Werthimer) and Scientific (Aguirre, Bowman, Carilli, Hewitt, Morales, Tegmark) Advisory Boards advise Parsons. Site Manager Goeke (MIT) supervises and manages construction activities executed by local contractors at the South African site, and reports to DeBoer. SKA-SA Liason Walbrugh (supported by SKA-SA) interacts with Goeke, DeBoer and the SKA-SA board to coordinate HERA and SKA site activities.

An external advisory board evaluates the baseline design based on existing components in a Preliminary Design Review at project inception. A Critical Design Review in Year 3 evaluates the production design, incorporating improvements to the analog system and feeds (Bradley), the node and correlator (Werthimer), and the data storage system (Aguirre). Software development, calibration, power-spectral analysis, and imaging responsibilities are shared across institutions, coordinated at NRAO, MIT, UCB, and U. Washington, respectively. Fabrication of electronics systems is contracted to, e.g., Digicom Technologies; antenna component fabrication is contracted to, e.g., Burns Industries, including delivery to site. Construction on site proceeds with 2-3 teams of local contractors and laborers, managed by Goeke. As with PAPER, observing proceeds autonomously without local observers; SKA-SA provides occasional site support as necessary.

Project risk and contingency are handled primarily by de-scoping. Baseline designs using existing hardware establish a low-risk path to basic functionality. Improved functionality results from successful development activities or is otherwise de-scoped. Cost excesses and schedule slips are absorbed by reducing build-out, with associated de-scoping of science capabilities.

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