Hydrogen Epoch of Reionization Array

This proposal targets the Mid-Scale Science Projects category of the Mid-Scale Innovations Program solicitation.

The major stages in the history of our Universe are written in the phases of hydrogen. The Hydrogen Epoch of Reionization Arrays (HERA) roadmap is a staged program that uses the unique properties of redshifted 21 cm neutral hydrogen emission to study the birth of the first stars and galaxies. HERA was given the "top priority in this [Radio, Millimeter, and Sub-millimeter] category of recommended new facilities for mid-scale funding" as part of the *New Worlds, New Horizons of Astronomy and Astrophysics* decadal survey, (**?**; hereafter Astro2010).

The HERA roadmap envisioned a series of radio interferometers constructed throughout the decade, starting with the PAPER and MWA instruments (Donald C. Backer Precision Array for Probing the Epoch of Reionization; Murchison Widefield Array) aimed at detailed characterization of the foregrounds and first efforts to detect the Epoch of Reionization (EoR) power spectrum, a second-generation instrument to measure the EoR power spectrum in detail and reveal how early structure in the universe formed, and a third-generation instrument late in the decade to image the EoR.

Using the advances spearheaded by the MWA and PAPER experiments, we are proposing to build the second-generation HERA instrument to extract the exciting science offered by 21 cm observations of the first stars and galaxies.

In §1 we describe the science HERA will enable. Section 2 then reviews the breakthroughs in our understanding the EoR foregrounds from PAPER and MWA, and the techical heritage which allows HERA to perform the science envisioned in the decadal survey at significantly reduced cost. The full HERA instrument and timeline is described in §3, followed by the impacts on the US scientific and national community in §5.

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" (**?**). Observations of Gunn-Peterson absorption by the IGM toward the most distant quasars (**?**), kinetic Sunyaev-Zel'dovich features in the CMB (**?**), and CMB anisotropy and polarization (**??**) 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 (**?**): "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."

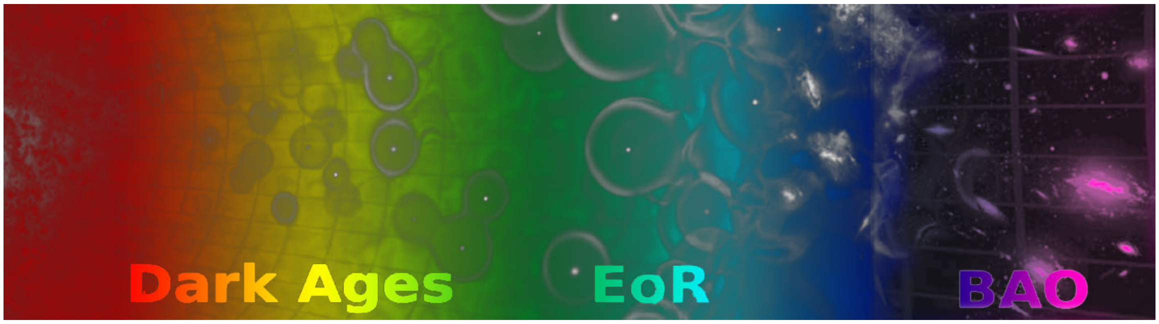

Fig. 1.— The 21cm hyperfine line of neutral hydrogen represents the next frontier in precision cosmology. Following recombination (left edge), the spin temperature of 21cm emission is sensitive to the density and temperature of the intergalactic medium (IGM) through the Dark Ages, evolves with the heating 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 (**???**).

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-spectrum" understanding of the mechanism for how instrumental responses modulate foregrounds on spectral scales of cosmological interest (**?**), 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.

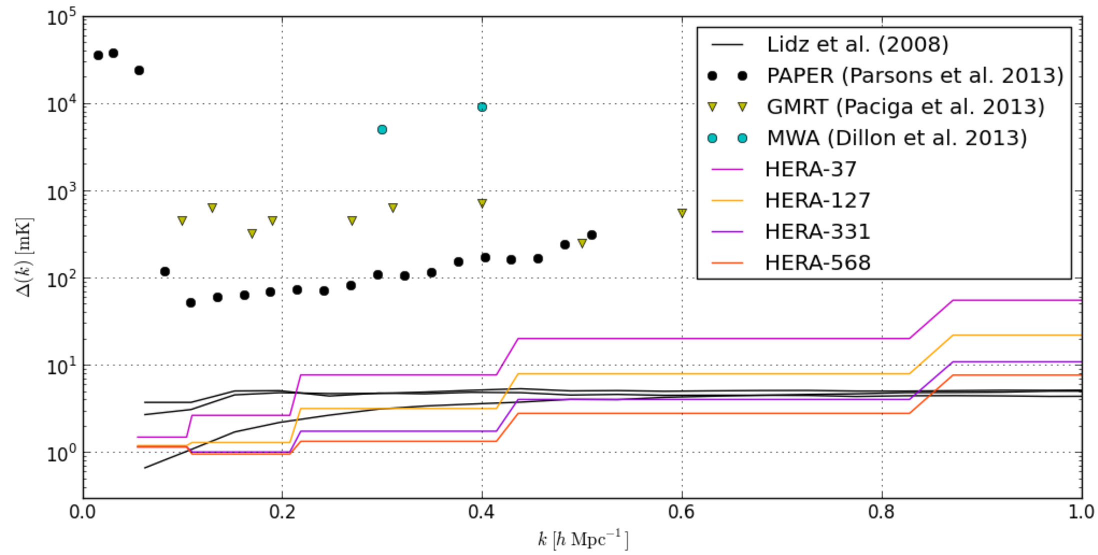

Fig. 2.— Current best upper limits on the power spectrum of 21cm emission from reionzation at $z = 7.7$, made with a 32-antenna deployment of the PAPER experiment (**?**). Black indicates the final measurements with 2σ confidence intervals. The yellow triangles indicate the previous best 2σ upper limits at $z = 8.6$ (**?**). Magenta illustrates a fiducial 50% ionization model (**?**). 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.

2. Lessons learned from PAPER and MWA

Talk about the window and current limits.

3. Project Description

This proposal outlines a staged build out to a 568-antenna array in South Africa that incorporates the lessons learned from the first generation EoR observatories. It features a 14 m zenith pointing dish optimized for spectral smoothness, a dense hexagonal core to enable redundant baseline calibration and delay-spectrum analysis, and a distribution of outrigger antennas to provide complete uv coverage to ~700 m for foreground imaging and mitigation. HERA draws on the technical heritage of the MWA, PAPER, and EDGES. Specific examples include the spectrally smooth feed and antenna based on PAPER, receiver node and field digitization at baseband from the MWA, absolute radiometric calibraion from EDGES, the delay-spectrum analysis from PAPER, and the precision imaging and foreground removal software from the MWA.

The HERA antenna shown in Figure 5 is an illustrative example of how the HERA design has been optimized based on our current understanding. The key antenna figure of merit is the spectral smoothness and stability of the response because it determines the precision to which astrophysical foreground emission can be separated from the cosmological 21 cm emission. HERA uses the PAPER dipole feed—modified slightly for wider bandwidth—suspended over a 14 m parabolic dish. The short (~5m) focal height of the dishes is central to limiting the path length of reflections whose time-delay gives rise to chromatic antenna sensitivity. The zenith pointing enhances the stability of the antenna response (PAPER), short cables to in-field digitizers limit the length of cable reflections (MWA), and absolute calibration (EDGES) are all designed to provide an extremely plots/MWApretty.png

Fig. 3.— High dynamic range imaging of foregrounds with the MWA towards galactic center utilizing the Fast Holographic Deconvolution software package developed at the University of Washington. Vela and Puppis SNRs are in the lower right, and the image is approximately 30° in diameter. Analysis includes direction dependent beam and polarization effects, and routinely achieves $< 0.5\%$ polarization leakage across the field. Subtracting precision maps of smooth spectrum and polarized foregrounds will enable HERA to enlarge the EoR window.

stable and smooth spectral response. Similarly the antenna layout uses the dense core, outriggers, and symmetric configuration of the MWA, combined with redundant baselines within the core (PAPER). Together these advances enable HERA to have the science reach envisioned in the decadal survey while fitting within the MSIP funding envelope.

HERA follows a staged build-out plan. 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 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 allows key aspects of 21 cm reionization science to be addressed. The timeline of HERA development, along with the associated science products, is outlined below.

Year 1–Infrastructure and First 37 Antennas (FY 2015).

- Infrastructure installation. Using the new 'K3' site approximately 10 km from the current PAPER site at the Karoo Radio Observatory in South Africa. Includes ground leveling, power and basic network connectivity.
- Move existing PAPER-128 antennas, correlator, and EMC container to K3 site.
- Install first 37 HERA antennas and instrument with existing PAPER feeds and electronics.
- Begin development of wider bandwidth HERA baluns, receivers, feeds, and nodes using the PAPER and MWA techical heritage () and the development of in-situ antenna calibration system based on EDGES (). Continue development of delay-spectrum () and Fast Holographic Deconvolution software (FHD;).

Year 2–Hardware Commissioning and Deep Foreground Survey (FY 2016).

- Commissioning observations using a hybrid array of 37 HERA antennas in a close-packed hexagon surrounded by 91 PAPER antennas in an imaging configuration.
- Perform a deep polarized foreground survey using unique hybrid antenna capability of FHD. Will directly determine on-sky beam response of HERA antennas and enable future subtraction of sources in HERA sidelobes.
- Finalize site infrastructure (high-bandwidth optical network, surveying, trenching).
- On-antenna commissioning of new feeds, receivers, nodes, and antenna calibrations systems in Green Bank and South Africa.
- Build out to 127 HERA antennas starts.

Year 3–HERA 127 and Detecting the Rise and Fall of Reionization (FY 2017).

plots/Pober_wedge.pdf

Fig. 4.— The EoR window as measured by PAPER. Blue represents a region containing EoR signal but no foreground contamination.

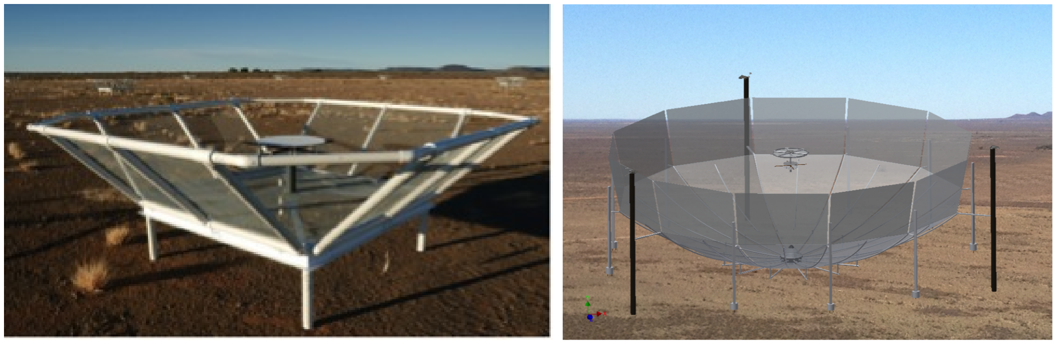

Fig. 5.— The PAPER element (left) provides a clean instrumental response as a function of frequency (**??**), which is crucial to the foreground isolation shown in Figure 2. A 14 m dish designed around the same feed (right) dramatically improves sensitivity while constraining the path length and amplitude of reflections to ensure that foreground isolation is not substantially degraded.

- Construction of HERA-127 completes, and science observations begin in Oct. 2016, again using the PAPER correlator.
- Analysis begins on a dataset capable of constraining the timing and duration of reionization. Analysis focuses on current techniques based on PAPER individual baseline analysis, with exploration of subtracting bright and polarized foreground sources.
- Deployment of HERA 331 begins. 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).
- Science papers from HERA-37 are published.
- Additional data storage infrastructure is installed in the KAPB. The UPenn data analysis cluster is upgraded.

Year 4–HERA 331 and Measuring the Evolution of the First Galaxies (FY 2018).

- Construction of HERA 331 completes, and science observations begin in Oct. 2017.
- Science observations with HERA 331 complete in Apr. 2018, and analysis begins on a dataset capable of characterizing the redshift evolution the power spectrum shape—measuring the development of the first galaxies.
- Continued analysis and software development with an emphasis on opening the EoR window (removing contamination at low $k_{\|}$).
- HERA 127 results are published.
- Build out to 568 antennas begins, including outrigger antennas to fascilitate imaging and better foreground removal.
- Pipelines for EoR processing of HERA 568 complete.

Year 5–HERA 568, Imaging Reionization and Constraining the Development of Structure at $z > 11$ (FY 2019).

- Construction of HERA 568 completes, and science observations begin in Oct. 2018.
- Analysis push to enable imaging of the largest structures and extracting the full sensitivity of the instrument (including partially coherent baselines).

3.1. The Transformative Science enabled by HERA

4. Broader Impacts and Benefit to the Community

4.1. Developing Young Instrumentalists (shorten)

Aspiring instrumentalists in radio astronomy face a challenging path, in part because the fundamental nature of radio astronomy instrumentation is changing. Because the capabilities of radio telescopes are directly tied to the Moore's Law growth in the capabilities of digital electronics, new science opportunities are constantly being opened up, while existing facilities rapidly fall into obsolescence. Furthermore, the breakneck pace of technological development places a premium on rapid development. The faster an instrument incorporating new technology can be deployed, the earlier that new science goals can be reached.

All of this combines to mean that aspiring radio astronomy instrumentalists must acquire a very broad set of skills in a short amount of time. A sampling of the skills required includes the practical application of antenna design, optics, 3D modeling, machining, circuit design, soldering, DSP algorithms, FPGA/GPU programming, network management, computing systems, kernel optimization, interferometry, synthesis imaging, astrometry, statistical methods, linear algebra, high-performance computing, laboratory methods, and many, many others. While some of these skills are taught in undergraduate and graduate curricula, many are not, and exposure varies tremendously between majors. In particular, many students who arrive at graduate school in astronomy and physics lack preparation in practical engineering, programming, and laboratory skills. Students with talent in physics, math, and astronomy, but with a practical bent are often siphoned off in other directions.

One aspect of the broader impact of this proposal addresses the loss of talented scientists with practical skills from applications in astronomy instrumentation, and to address the gap between the preparation afforded by an undergraduate education and the breadth of skills required to succeed as an aspiring (radio) instrumentalist in graduate school. This will be done by funding a one-year junior specialist position in the RAL, offered annually over the course of this grant, to a person to who will gain practical experience working alongside professional RAL engineers and scientists on all aspects of the HERA instrumentation development at UC Berkeley, with the goal of acquiring the practical skills required for pursuing research in instrumentation in a graduate program.

4.2. Developing African Scientists

(Carilli)

4.3. Benefits to the Community: Data Products (needs work!)

(Carilli) benefit/synergy with JWST, WFIRST, CMB pol stuff, etc. Data products disseminated at MIT. Products include: integrated data products, made available after 2 years; high-speed continuum images, generated as part of operational data analysis by MIT; wide-field sky maps (made with 91 PAPER antennas in first 2 years), database of metadata for asscoiated with data products, access to calibrated, compressed visibilities upon request. deep (foreground subtracted) image products for use with other surveys & instruments

5. 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, Furlanetto, Hewitt, Morales, Tegmark) Advisory Boards advise Parsons. A Site Manager will supervise and manage construction activities executed by local contractors at the South African site, and reports to DeBoer. A SKA-SA Liaison (supported by SKA-SA) interacts with DeBoer, the Site Manager and the SKA-SA board to coordinate HERA, Meerkat and SKA site activities.

An external advisory board evaluates the baseline design based on existing components in a Preliminary Design Review in Year 1. A Critical Design Review in Year 2 evaluates the production design, incorporating improvements to the analog system and feeds (Bradley), the node and correlator (Werthimer), and the data storage system (Aguirre), and analysis software (Morales). Fabrication of sub-systems (electronics, antenna sub-assemblies and antenna assembly) are contracted to industry, both in the US and South Africa. Construction on site proceeds with 2-3 teams of local contractors and laborers, managed by the UCB-appointed site manager. Observing proceeds autonomously without local observers; SKA-SA provides occasional site support as necessary.

Project risk and contingency are handled primarily by de-scoping along the axes of scale, time and new capability. Baseline designs using existing hardware establish a low-risk path to basic functionality yielding new science. 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.