HERA: Illuminating Our Early Universe

For the Mid-Scale Science Projects category of the Mid-Scale Innovations Program (MSIP)

The Hydrogen Epoch of Reionization Array (HERA) uses the unique properties of the 21 cm line of neutral hydrogen to probe the Epoch of Reionization (EoR) and the preceding Cosmic Dawn. During these epochs, roughly 0.3 to 1 Gyr after the Big Bang, the first stars and black holes heated and reionized the Universe. By directly observing the large scale structure of reionization as it evolves with time, HERA will profoundly impact our understanding of the birth of the first galaxies and black holes, their influence on the intergalactic medium (IGM), and cosmology.

HERA was ranked the "*top priority in the Radio, Millimeter, and Sub-millimeter category of recommended new facilities for mid-scale funding*" by the Decadal Survey. We have advanced the project aggressively over the last five years. Using the Donald C. Backer Precision Array to Probe the Epoch of Reionization (PAPER), the Murchison Widefield Array (MWA), and the MIT EoR experiment (MITEoR), the HERA team has characterized the strong foregrounds masking the 21 cm signal and has developed powerful techniques for overcoming them in power spectral measurements of reionization. We are now perfecting these techniques with the HERA prototype — a 19-element array of 14 m parabolic dishes in the South African Karoo Radio Astronomy Reserve.

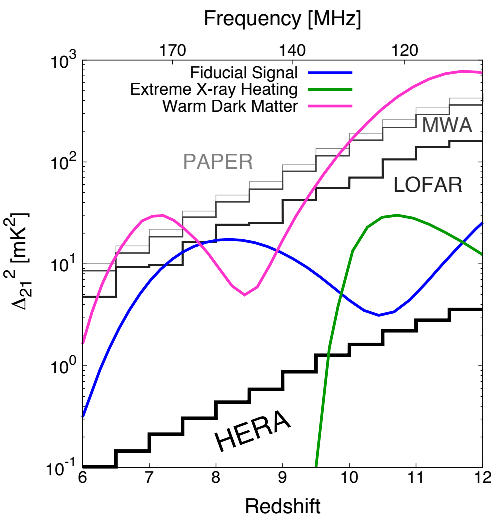
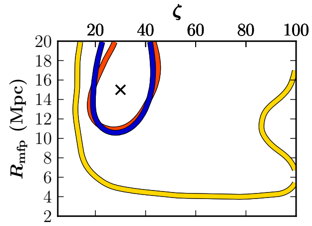


Fig. 1.— 1σ thermal noise sensitivities at $k = 0.2\,h\,\mathrm{Mpc}^{-1}$ with 1080 hours of integration (black) compared with fiducial heating and reionization scenarios (colored).

Based on this experience, we propose to build a 352-element HERA science array in South Africa. This array is an optimized 21 cm cosmology engine capable of high SNR measurements of the 21 cm power spectrum at redshifts $z = 6$ to 13 (*Planck* data suggest $z \approx 9$ for instantaneous reionization). These measurements are uniquely capable of characterizing the evolution of the cosmic ionization field, exposing the nature of the first ionizing sources and tracking the growth of structures in the "cosmic web." In combination with other probes of our early universe, HERA provides a comprehensive picture of reionization and breaks measurement degeneracies in fundamental cosmological parameters. HERA also advances the interests of the broader astronomical community by providing data cubes for cross-correlating with other high-redshift probes (e.g. JWST; CMB maps; CO, CII, and Ly$-\alpha$ intensity mapping), releasing deep multi-frequency imaging surveys for galactic and extra-galactic science, and acting as a hardware platform for other timely science instruments targeting, e.g., 21 cm tomography of the pre-reionization epoch, fast radio bursts, and auroral emission from exoplanets.

1. Primary Scientific Justification: Precision Constraints on Reionization

HERA's primary scientific goal is to understand the processes driving the evolution of the 21 cm brightness temperature in the IGM during cosmic reionization. First generation experiments, including LOw Frequency ARray (LOFAR), MWA, and PAPER, are pushing hard on systematic effects and hoping for a first detection of the EoR signal. As shown in Figure 1, these experiments may only achieve marginal detections in some models; HERA is capable of making a high-SNR detection of virtually any realistic ionization scenario to precisely constrain the astrophysics of reionization. Figure 2 shows the results of a Markov Chain Monte Carlo (MCMC) pipeline for fitting models to multi-redshift 21 cm power spectrum data. Based on the excursion-set formalism of Furlanetto et al. (2004) and the 21cmFAST code (Mesinger et al. 2011), this code models the astrophysics of reionization with three free parameters (see Figure 2 for details). While the most sensitive existing experiment, LOFAR, faces large uncertainties, HERA delivers ∼10% constraints on these parameters, which are currently essentially unconstrained by observations. HERA is optimized for 21 cm power spectrum measurements, delivering comparable reionization constraints to the SKA at a fraction of the cost and within an earlier timeframe to help inform SKA design.



Instrument (multi-z)	Parameter (% error) $\frac{\zeta}{\zeta_{\rm fid}}$	$\frac{R_{\rm mfp}}{R_{\rm fid,mfp}}$	$\frac{\log_{10}(T_{\rm vir}^{\rm min})}{\log_{10}(T_{\rm vir,fid}^{\rm min})}$
LOFAR	1.55 (43.29)	0.89 (31.11)	1.06 (6.05)
HERA	1.03 (12.00)	1.01 (12.37)	1.00 (1.95)
SKA	1.02 (9.36)	1.04 (13.50)	1.00 (1.28)

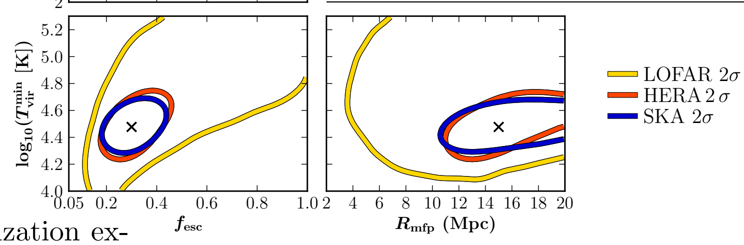


Fig. 2.— Likelihood contours from an MCMC analysis for astrophysical parameters of reionization. Constrained parameters are $T_{\rm vir}^{\rm min}$ (minimum virial temperature of ionizing galaxies); $R_{\rm mfp}$ (mean free path of ionizing photons in ionized HII regions); and ζ_0 (ionizing efficiency of ionizing galaxies). Also shown are constraints on the derived parameter $f_{\rm esc}$ (escape fraction of ionizing photons).

Complementary probes of reionization exist today and include measurements of the optical depth to last scattering in the CMB, QSO spectra, Ly-α absorption in the spectra of quasars and gamma ray bursts and the demographics of Ly-α emitting galaxies (Figure 3). Constraints from these probes are still weak: Ly-α absorption saturates at very small neutral fractions; galaxy surveys directly constrain only the bright end of the luminosity function and depend on an unknown escape fraction of ionizing photons to constrain reionization; CMB measurements probe an integral quantity subject to large degeneracies. Even when these observations are combined into a single 95% confidence region, the bounds remain weak. For example, x_{HI} spans almost the entire allowable range of [0,1] at $z = 8$. 21 cm reionization experiments place much tighter constraints on ionization, with the red band showing the forecasted 95% confidence region derived from HERA data, after marginalizing over astrophysical and cosmological parameters.

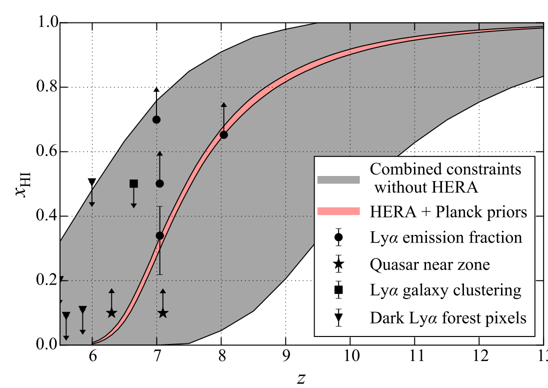


Fig. 3.— Ionization history constraints based on current high-redshift observational probes (black points). With *Planck* priors, the inferred 95% confidence region (gray) reduces to the red region by adding HERA constraints.

2. Additional Scientific Objectives: Reionization Imaging and Precision Cosmology

Breaking CMB Degeneracies: HERA power spectra, by advancing our understanding of reionization astrophysics, improve CMB constraints on fundamental cosmological parameters. As a direct probe of reionization, HERA observations remove the optical depth τ as a nuisance parameter in CMB studies. This breaks the degeneracy between the amplitude of matter fluctuations (expressed in Fig. 4 in terms of σ_8) and τ that arises when only CMB data are used. HERA effectively reduces error bars on σ_8 by more than a factor of two (Liu et al., in prep.), potentially elucidating current tensions between cluster cosmology constraints and those from primary CMB anisotropies. Improved constraints on the fluctuation amplitude also improve CMB lensing studies, since theoretical predictions for lensing power spectra currently have larger error bars than the measured spectra from *Planck*.

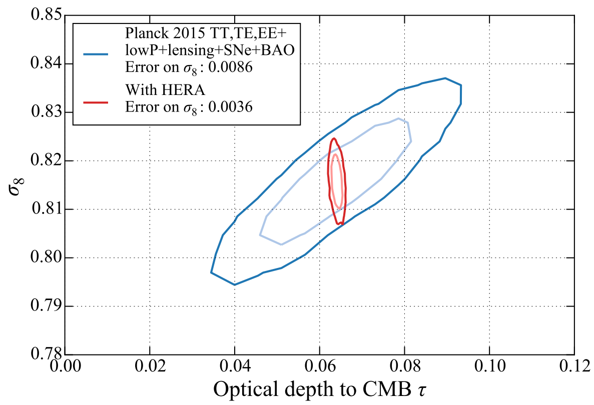


Fig. 4.— Likelihood contours (68% and 95%) for σ_8 and τ using *Planck* constraints (blue) and adding HERA data (red). The 21 cm constraints break the CMB degeneracy between the amplitude of density fluctuations and the optical depth, improving constraints on both.

First EoR Images: With a nearly completely sampled aperture over 800 m across and a dense 300 m core, HERA has the collecting area of Arecibo and 500 times its survey speed. As Fig. 5 shows, a complete season of HERA observing has the raw sensitivity to detect the largest HII structures at an SNR$>$ 10, even after conservative foreground excision. These tomographic images can unlock rich astrophysics at high redshifts.

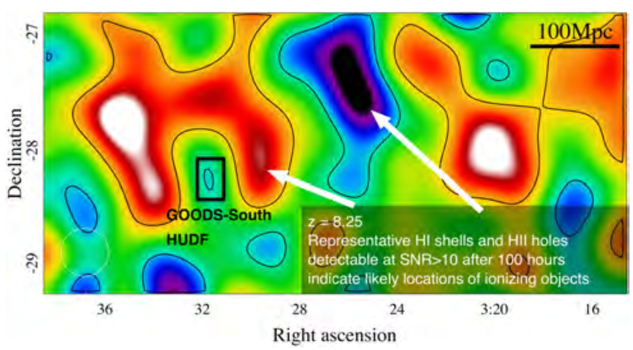


Fig. 5.— HERA can measure the ionization state around galaxies in, e.g., the GOODS-South field that contains half of all known $z > 8$ galaxies. Contours indicate 10σ detections of a simulated reionization field (McQuinn et al. 2007) for a 100-hour HERA imaging observation.

Probing early galaxies is a primary goal of ALMA, JWST, and many other observatories. HERA complements these efforts by probing the effect of early galaxies on the IGM. The GOODS-South field—one of the most panchromatically studied regions of the sky, site of the Hubble UDF, and home to half of all discovered $z > 6$ galaxies—lies in the HERA FoV. With a redshift resolution of 0.05, and sensitivity from Mpc to Gpc scales, HERA images provides crucial large-scale information about the environment of these galaxies that can elucidate their statistical properties. These maps are also powerful as cross-correlation studies with other large scale mapping projects such as CO, NIRB (e.g. WFIRST), Ly-α (e.g. SPHEREx, Doré et al. 2014), and galaxy surveys.

3. Benefits and Opportunities for the Broader Astronomical Community

21 cm Science Beyond the EoR: The detectable 21 cm signal extends to much higher redshifts and probes other astrophysical processes, though systematics become increasingly challenging at lower frequencies. complementary science during an earlier period during the Cosmic Dawn when the IGM is thought to have been heated by the first stellar mass black holes and hot ISM generated by the first supernovae (Mesinger et al. 2013). Experiments of this kind are the only practical probe of the star formation in the first galaxies and their high-energy astrophysical processes.

Fast Radio Burst Followup: HERA could be triggered by nearby, higher frequency telescopes for Fast Radio Burst (FRB) followup, saving baseband data and keeping full sensitivity to all dispersion measures. The burst reported in Masui et al. (2015) significantly strengthened the case for low-frequency transient searches. With HERA, the burst should have been at least 5–10σ and similar bursts should be seen hourly. Observations at HERA frequencies are very sensitive to the physics of the intervening medium, particularly deviations from λ^2 dispersion. Detecting deviations would rule out broad classes of models and could indicate whether FRBs are at cosmological distances.

Searching for Exoplanetary Radio Bursts: HERA could be an powerful tool in the search for bright, highly polarized auroral bursts from exoplanets (Treumann 2006; Hallinan et al. 2015). These distinctive, minutes-long bursts occur periodically with the planetary rotation, which cannot otherwise be measured. A burst from a terrestrial planet could point toward habitability, since it implies a powerful magnetic field protecting the atmosphere and perhaps the biosphere from energetic stellar wind particles (Tarter et al. 2007). HERA's collecting area, large FoV, long wavelengths, and precise calibration are all well-suited for discovering exoplanetary radio bursts.

Data Products for the Astronomical Community: HERA's $\sim 10°$ FoV drift scan will produce full-Stokes spectral image cubes, including of the Galactic center. These publicly available data products, along with our foreground models, will enable galactic and extragalactic astronomy, e.g. studies of steep spectrum radio relics, galactic magnetic fields, cosmic rays, and supernova remnants. HERA's deep, foreground-cleaned image cubes, spanning 800 Mpc by 18 Gpc at at redshift intervals of <0.05, are ideal for cross-correlation with many other public datasets.

4. Challenges and the Current State of the Art

Sensitivity Challenges: The 21 cm EoR signal is intrinsically very faint and a detection requires a large instrumental collecting area and a long, dedicated observing campaign. Pathfinder experiments like PAPER and the MWA lack the collecting area to make a conclusive detection (see Table 1), but have spurred the development of new techniques for maximizing sensitivity. PAPER, in particular, explored redundant array configurations boosting the sensitivity to particular modes of the power spectrum (Parsons et al. 2012a). An instrument like HERA is necessary to measure the EoR power spectrum to high significance, regardless of the efficacy of foreground removal.

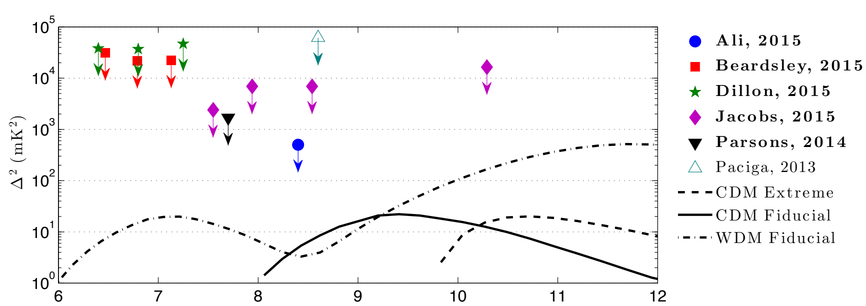


Fig. 6.— The current best published 2σ upper limits on the 21cm EoR power spectrum. Papers generated by HERA collaborators are indicated with solid symbols, and bold text in the legend. For reference are 21cmFAST-generated models at $k = 0.2\,h\,\mathrm{Mpc}^{-1}$.

The current upper limits shown Fig. 6 show how HERA precursors have been leading the charge toward a detection and have made considerable progress. These measurements have already placed meaningful constraints on the reionization epoch; Parsons et al. (2014) provided evidence of high-z IGM heating, and improved limits from Ali et al. (2015) enabled constraints on the spin temperature of intergalactic hydrogen at a $z = 8.4$ in Pober et al. (2015).

Foreground Challenges: Mitigation of foreground emission $\sim$5 orders of magnitude stronger than the 21 cm signal is one of the most important analysis challenge for 21 cm cosmology. In principle, spectrally smooth foregrounds are restricted to low k modes along the line of sight, $k_\parallel$, due to their smooth spectral nature. However, the Fourier modes probed by an interferometer are functions of frequency, creating a chromatic PSF and imparting spectral structure to foregrounds. In cylindrically-binned 2D power spectra, we see a clear division between inherently foreground dominated regions, the instrumental chromaticity "wedge," and a foreground-free region, the "EoR window" (see Fig. 7). The wedge/window division has been solidified in recent years through both theoretical and observational work (Morales et al. 2012; Parsons et al. 2012b; Vedantham et al. 2012; Datta et al. 2010; Hazelton et al. 2013; Pober et al. 2013; Liu et al. 2014a,b).

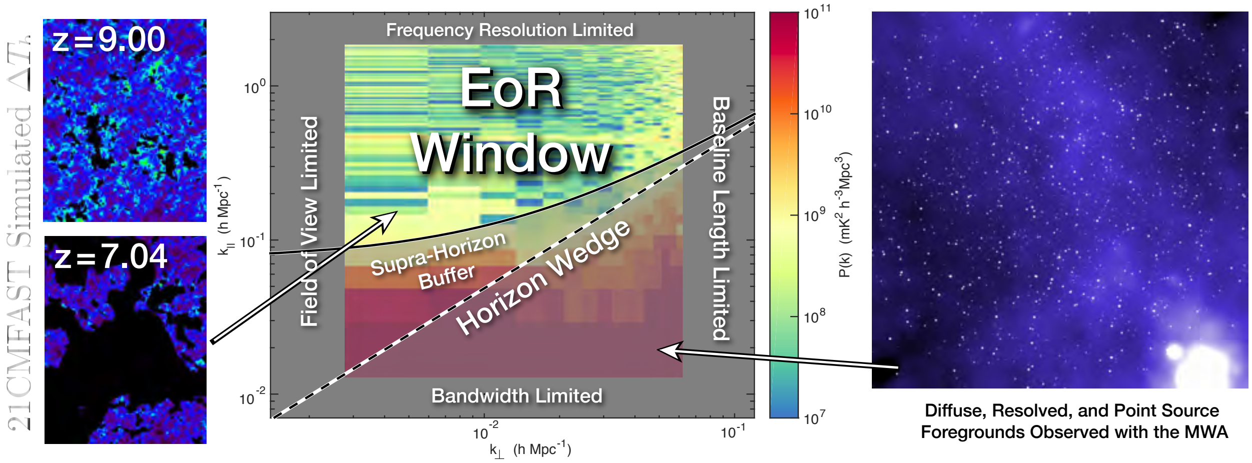


Fig. 7.— Foregrounds are a primary challenge facing 21 cm cosmology experiments. HERA leverages a "wedge" in Fourier space (center panel; Dillon et al. 2015) where window functions from a chromatic interferometer response interact with smooth-spectrum foreground (right panel) ∼12 orders of magnitude brighter in $P(k)$ than fiducial EoR models (left panel; Mesinger et al. 2011). PAPER sensitivity limits are within 1 order of magnitude of these models (Ali et al. 2015) and show the "EoR Window" to be foreground-free. HERA's dish and configuration optimize wedge/window isolation and to direct sensitivity to low-$k_\perp$ modes where EoR is brightest.

Previously, it was thought that image-based model subtraction would be required to overcome foregrounds (Liu et al. 2008; Bowman et al. 2009; Harker et al. 2009). However, the simpler and more robust method of working only inside the EoR window has enabled new upper limits from the MWA (Dillon et al. 2014, 2015) and PAPER (Parsons et al. 2014; Ali et al. 2015). Our proven strategy also highlights the importance of short baselines, which probe smaller $k_\perp$ modes less contaminated by the wedge. However, foreground subtraction minimizes spectral leakage into the EoR window and potentially maximizes sensitivity (see Table 1). Fast Holographic Deconvolution (FHD, Sullivan et al. 2012) was designed to meet precise sky and instrument modeling requirements needed to work within the wedge, serving both as an end-to-end instrument simulator and as a pipeline for identifying and removing foreground sources. The right panel of Fig. 7 shows part of an FHD image in which it already identifies and removes over 7,000 sources, suppressing foreground power in the wedge by two orders of magnitude.

Calibration Challenges: Keeping the EoR window clean of foregrounds $\sim 10^5$ brighter than the 21 cm signal requires an instrument with a precisely calibrated spectral response. Standard radio interferometric calibration relies upon accurate sky models (e.g. Smirnov 2011). However, wide instrumental fields of view, beam model uncertainties, and unreliable low-frequency catalogs make this challenging (e.g. Jacobs et al. 2013a,b; Braun 2013). Still, much progress has been made in cataloging the low frequency sky (e.g. Hurley-Walker et al. 2014) and characterizing beam patterns (Pober et al. 2012; Neben et al. 2015; Sutinjo et al. 2015). Moreover, MITEoR and PAPER have developed a new approach, taking advantage of array redundancy to calibrate in a nearly sky-independent fashion (Zheng et al. 2014; Ali et al. 2015). Initial concern that imperfect polarization calibration could contaminate the EoR signal (e.g. Bernardi et al. 2010; Jelić et al. 2010; Moore et al. 2013) has been reduced by evidence that Faraday rotation-induced frequency structure of polarized sources occupies only low $k_\parallel$ modes (e.g. Bernardi et al. 2013; Moore et al. 2015) and by the development of optimal data weighting (Parsons et al. 2015) for avoiding leakage.

HERA is designed to minimize the calibration challenge. Its hexagonal configuration allows for redundant calibration, and the use of dishes (instead of complex phased arrays) maximizes sensitivity with minimum beam complexity and variability, which will be confirmed with satellite (Neben et al. 2015) and drone-based calibrators.

5. HERA System Overview and Timeline

Through our efforts with the PAPER and MWA projects, we have achieved a pivotal new understanding of how instrumental characteristics interact with foreground emission to produce the wedge of emission shown in Fig. 7. Our published results show that by projecting out wavemodes within this wedge, we are able to avoid foregrounds to the sensitivity limits of current instruments. The HERA collaboration now has the knowledge and expertise to define the requirements for HERA; an instrument that ensures foregrounds remain bounded within the wedge while delivering the sensitivity for high-significance detections of the 21 cm reionization power spectrum under the conservative assumption that wavemodes within the wedge must be projected out of our measurements. HERA's basic parameters are shown in Fig. 8.

Following this design, HERA can deliver a 25-σ detection of the 21cm EoR power spectrum, whereas current instruments are only capable of marginal detections (Table 1). Key advances in instrument design enable HERA to achieve this level of performance with a modest number of elements. One such advance is HERA's new 14-m parabolic dish, which delivers an order of magnitude more collecting area per element relative to PAPER and the MWA but features a low f/D ratio to reduce reflections at time constants affecting the EoR window (Figure 7). HERA elements are close-packed in a hexagonal grid to maximize baseline redundancy (Parsons et al. 2012a), for an additional order of magnitude improvement in sensitivity. Outrigger elements combine with the hexagonal core to yield a fully sampled aperture out to 1 km, enhancing HERA's imaging capability for foreground characterization and mitigation.

As shown in Fig. 8, the first 19 elements are under construction, and will be completed by Dec. 2015 and funds are in place to build out to 37 elements by Sept. 2016.

- **Year 1:** HERA-37 observing; build to 127. Characterize system.
- **Year 2:** HERA-127 observing; build to 271. Commission hardware, perform deep foreground survey. Deploy nodes and update infrastructure. HERA-37 results.
- **Year 3:** HERA-271 observing; build to 352. Detect EoR power spectrum in HERA-127 results.
- **Year 4:** HERA-352 observing. Characterize power spectrum, constrain EoR astrophysics in HERA-271 results.

Instrument	Collecting Area (m^2)	Foreground Avoidance	Foreground Modeling
PAPER	528	0.77σ	3.04σ
MWA	896	0.31σ	1.63σ
LOFAR NL Core	35,762	0.38σ	5.36σ
HERA-352	**50,900**	**25.53σ**	**90.76σ**
SKA1 Low Core	833,190	13.4σ	109.90σ

Table 1 Power spectrum signal-to-noise at $z = 9.5$ for various instruments (from Pober 2015). HERA leverages a filled, redundant configuration of large dishes to achieve high-significance power spectrum measurements using current foreground avoidance techniques, with further enhancements possible with likely advances in foreground modeling.

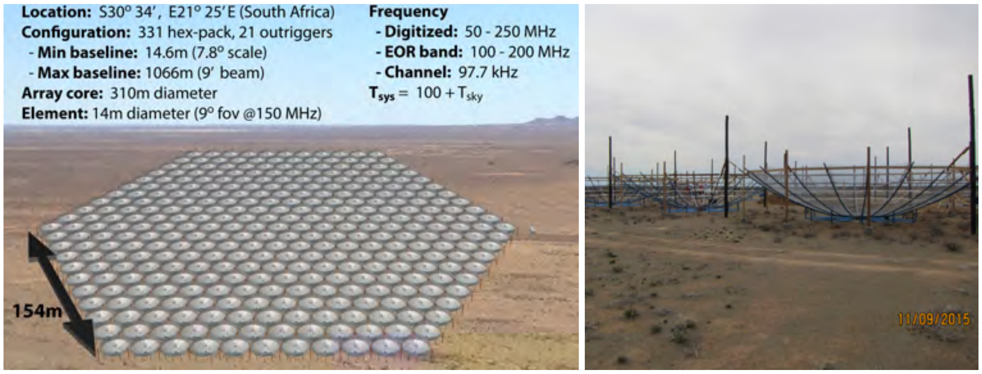


Fig. 8.— Representation of the 331 14-m core elements of the 352 array (left) and the current 19 elements (right). The location is the site of the current PAPER array in the Karoo of South Africa.

6. Broader Impacts of the Proposed Work

HERA helps train the next generation of instrumentalists by incorporating a large number of undergraduate, graduate, and postdoctoral researchers in every aspect of the experiment, from design and construction, to calibration, analysis, and science. To further broaden the impact of HERA, we propose the CAMPARE-HERA Astronomy Minority Partnership (CHAMP), which addresses the NSF goals of increasing participation of underrepresented minority (URM) groups in STEM research, improving URM retention and graduate rates, and disseminating HERA science to secondary classrooms. The two major elements of the CHAMP program are 1) a summer research program in which undergraduates selected from the CAMPARE program, together with Masters and PhD students from South Africa (SA), contribute to HERA science; and 2) an outreach program of training workshops for local teachers in southern California schools in which CHAMP undergraduates participate as both learners and presenters ("CHAMP Ambassadors").

The summer research program is based on a partnership with the highly successful California Arizona Minority Partnership for Astronomy Research and Education (CAMPARE) program. For six years, CAMPARE has engaged URM students and women in authentic research opportunities, with high success rates for graduation and placement in higher education in STEM (Figure 9). CAMPARE has a recruiting network of 22 California State University and California Community College campuses, almost all Hispanic Serving Institutions. CHAMP builds on the proven CAMPARE program, extending its reach to HERA institutions, where the PIs and postdocs provide research opportunities for the CAMPARE-selected undergraduates. In addition, CHAMP expands the SA exchange program established under the current MSIP grant, where SA Masters and Ph.D. students collaborate in summer internships at US institutions to incorporate HERA science into their theses. The CHAMP program consists of a 10-week summer experience shared by five undergraduate CHAMP Scholars and five SA graduate students each year. The first week is a "crash course" in radio astronomy, providing the science background and programming skills required for productive research. This common experience is effective cohort-building, and facilitates a powerful cultural interaction between these two groups — each underrepresented in science in their own country. The remaining 9 weeks are spent on research at HERA sites, with pairs of CHAMP Scholars and SA students working together for mutual support and continued cultural interactions. At an end-of-summer research symposium, all participants present their research to an audience of HERA mentors, other scientists, and family members of CHAMP Scholars — a form of support especially critical for URM and first-generation college students (Slovacek et al. 2012). CHAMP Scholars are provided support for presenting their research at AAS conferences, and can also take advantage of the year-round mentoring program developed by CAMPARE.

CHAMP also develops educational resources appropriate for middle or high school classrooms and provide professional development for teachers. The Center for Excellence in Mathematics and Science Teaching (CEMaST) at Cal Poly recruits high school science teachers from the home communities of CHAMP Scholars, and partners with Dr. Bryan Mendez of UC Berkeley's Multiverse educational resource group to develop a curriculum featuring HERA science appropriate for high needs classrooms, congruent with Next Generation Science Standards. Sessions hosted by CEMaST help CHAMP Scholars co-plan delivery of the curriculum, and make classroom visits to share their summer research experience. The lessons are videotaped and hosted on the CEMaST website for sharing with other classroom teachers.

Fig. 9.— CAMPARE Scholars (left), a cohort of SA exchange students under the current MSIP (center), and SA interns working on PAPER (right). In 6 years, CAMPARE has supported 62 students, more than 85% being URM, female, or both. The graduation rate among CAMPARE scholars is 97%; Bachelor's graduates have pursued graduate education in astronomy or a related field at three times the national average for URM STEM students.

7. Project Management Plan

HERA has been successfully functioning as part of an international collaboration and the project management will continue with the existing structure, which is governed by an Executive Board under a Collaboration Agreement. The Partners are: Arizona State University, Brown University, University of California Berkeley, University of California Los Angeles, University of Cambridge, Massachusetts Institute of Technology, National Radio Astronomy Observatory, University of Pennsylvania, SKA-South Africa and University of Washington. Many other Collaborators are also actively involved as part of the structure. Overall construction is managed out of Berkeley, with specific hardware, software and processing packages distributed among the collaborators. Governance, student project, and publication policies are contained within the Collaboration Agreement.

8. Why Now? Why Us?

As an international community, we have made great progress with PAPER and MWA, leading to a revolution in our understanding of how to best perform 21 cm cosmology measurements. In the past three years the HERA team has developed the EoR window paradigm to isolate the instrument chromaticity, developed advanced delay and imaging power spectrum analysis pipelines, made precision measurements of astrophysical foregrounds, and made the first deep power spectrum measurements with both PAPER and MWA. HERA's design is the direct result of these advances.

HERA is "the right instrument at the right time;" it builds on the experience and knowledge gained from first generation experiments, it has the sensitivity to precisely constrain EoR astrophysics, and it will become operational before the SKA. The HERA collaboration has a consolidated leadership in the field and is, therefore, equipped to deliver the proposed science. By building HERA, the collaboration will maintain world leadership in this key new area of cosmology.

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