A

PROPOSAL COVER SHEET

V6.0

Cycle 10 Call for Proposals: LWA1 Radio Observatory

Submit to: lwa@unm.edu by 11:59 MDT Nov. 1, 2021

Project title: A Search for the 21 cm Cosmic Dawn Absorption Signal with the LWA

Project Summary (please do not write beyond this space):

We plan to validate the published detection of the absorption profile reported by the Experiment to Detect the Global EoR Signal (EDGES) collaboration in Bowman et al. (2018: *Nature* **555**, 67-70). This absorption profile is unique to the formation of the first stars in the Universe, known as Cosmic Dawn. Bowman et al. report that this feature is centered around 78 MHz with a larger amplitude and bandwidth than cosmological models predict. We will search for validation evidence for this feature using the Long Wavelength Array.

Project Investigators:

	Name	Affiliation	Email
PI	[redacted]	[redacted]	[redacted]
Co-I	[redacted]	[redacted]	[redacted]
Co-I	[redacted]	[redacted]	[redacted]
Co-I			
Co-I			
Co-I			

PI Contact Information

Mailing address: [redacted]

Phone number: [redacted]

Requested mode(s):	Backend(s) for each requested mode:			
☐ LWA1 only	☐ DRX	☐ TBN	☐ TBW	☐ DR-Spec
☒ LWA-SV only	☐ DRX	☐ TBN	☐ TBF	☒ DR-Spec
☐ LWA1+SV Interferometer	☐ DRX			

Observing Request Information (leave fields that do not apply to your setup empty):

LWA1 only time request:	hrs/beam:		nr of beams:	
LWA-SV only time request:	hrs/beam:	200	nr of beams:	2
LWA1+SV interferometer time request:	hrs:		–	–
Repeated observations: length of each block (hrs):	1.5			
frequency of blocks (or when):	Every day during late February – mid April			
Restrictions in observing time (time of day):	None			
Restrictions in observing time (time of year):	None			

Special requirements (e.g. external trigger, outrigger dipole – describe use):

Use of the custom beamforming DRX pipelines, developed in Cycle 8, will be required in order to form achromatic beams for the planned observing campaign.

Observational Details:

Please give center frequencies (ν_1, ν_2) and corresponding bandwidth (BW) for each source. If more pointing positions are required, please attach a separate sheet with all details.

Source 1		**Beam 1**		**Beam 2**		**Beam 3** (*LWA1 only*)		**TBN**	
Name	Science Field	(MHz)		(MHz)		(MHz)		(MHz)	
RA (hh.h)	11.06	ν_1	60	ν_1		ν_1		ν_1	
Dec (dd.d)	+12.39	BW	20	BW		BW		BW	
LST beg (hh.h)	10.3	ν_2	75	ν_2		ν_2		ν_2	
LST end (hh.h)	11.8	BW	20	BW		BW		BW	
Source 2		**Beam 1**		**Beam 2**		**Beam 3**		**TBN**	
Name	Virgo A	(MHz)		(MHz)		(MHz)		(MHz)	
RA (hh.h)	12.51	ν_1		ν_1	60	ν_1		ν_1	
Dec (dd.d)	+12.39	BW		BW	20	BW		BW	
LST beg (hh.h)	11.8	ν_2		ν_2	75	ν_2		ν_2	
LST end (hh.h)	13.3	BW		BW	20	BW		BW	
Source 3		**Beam 1**		**Beam 2**		**Beam 3**		**TBN**	
Name		(MHz)		(MHz)		(MHz)		(MHz)	
RA (hh.h)		ν_1		ν_1		ν_1		ν_1	
Dec (dd.d)		BW		BW		BW		BW	
LST beg (hh.h)		ν_2		ν_2		ν_2		ν_2	
LST end (hh.h)		BW		BW		BW		BW	
Source 4		**Beam 1**		**Beam 2**		**Beam 3**		**TBN**	
Name		(MHz)		(MHz)		(MHz)		(MHz)	
RA (hh.h)		ν_1		ν_1		ν_1		ν_1	
Dec (dd.d)		BW		BW		BW		BW	
LST beg (hh.h)		ν_2		ν_2		ν_2		ν_2	
LST end (hh.h)		BW		BW		BW		BW	

A Search for the 21-cm Cosmic Dawn Absorption Signal with the Long Wavelength Array

[redacted] [redacted]
[redacted]

The search for the spectral signature of neutral hydrogen during the formation of the first stars and galaxies, known as Cosmic Dawn, is a major ongoing effort around the world. Many future observatories, including the James Webb Space Telescope (JWST), the Next Generation Very Large Array (ngVLA), and the Square Kilometre Array (SKA), have major science goals directly related to Cosmic Dawn and the subsequent Epoch of Reionization (EoR). This has been a topic of research for many years now, but efforts to detect the first stars and their remnants have been largely unsuccessful to date.

During Cosmic Dawn, the intergalactic medium (IGM) consisted mostly of neutral hydrogen gas. Neutral hydrogen can be detected via its hyperfine transition when an electron in the 1S ground state reorients from the spin-up quantum state to the spin-down. The small difference in energy between the two configurations corresponds to a photon which has a wavelength of 21.1 cm. Before Cosmic Dawn, the excitation temperature, or *spin* temperature, of the neutral hydrogen was governed by the surrounding radiation field, i.e. the cosmic microwave background (CMB). However, as the first stars formed, they radiated large amounts of Lyman α radiation which coupled the spin temperature of the neutral hydrogen to the physical kinetic gas temperature of the IGM via the Wouthuysen-Field effect. This cooled the neutral hydrogen spin temperature and allowed for the absorption of CMB photons with a wavelength of 21.1 cm. The intensity of this line is usually transformed into a relative brightness temperature with respect to the CMB, given by the expression:

$$\delta T_B \approx 27 \cdot x_{HI} \sqrt{\frac{1+z}{10}} \left(\frac{T_S - T_{CMB}}{T_S} \right) \mathrm{mK}, \tag{1}$$

where T_S is the spin temperature of the hydrogen, T_{CMB} is the temperature of the CMB, z is redshift, and x_{HI} is the fraction of neutral hydrogen. Theoretical models predict the amplitude of the absorption signal to be $\approx$ 100 mK [Pritchard and Loeb, 2012].

Once the first stars began to die, they left behind stellar remnants such as black holes whose large X-rays fluxes reheated the surrounding gas. This reheating caused the 21-cm signal to switch from absorption to emission above that of the CMB. Most of the neutral hydrogen is ionized during the Epoch of Reionization and so the 21-cm signal is no longer detectable after this point in cosmic history. The evolution of the the brightness temperature of the signal as a function of frequency and redshift is shown in Figure 1.

Both the absorption and emission signals from the neutral hydrogen have rest frequencies of 1.4 GHz, but they are redshifted to much lower frequencies. Cosmological models suggest that the turnover from absorption to emission occurs around $z \approx 17$ which corresponds to a redshifted frequency of 80 MHz [Pritchard and Loeb, 2008]. This low frequency means the Long Wavelength Array (LWA) is one of few current observatories in the world which is sensitive to this signal.

The Experiment to Detect the Global EoR Signature (EDGES) collaboration has reported a supposed detection of the absorption signal at 78 MHz [Bowman et al., 2018]. They report the amplitude of the signal to be 530 mK with a bandwidth of 18.7 MHz. These values are in contention with theoretical model predictions and could suggest either exciting new physics or a lack of understanding in current cosmological models. We plan on following up with the LWA to search for validation evidence of this detection. The sensitivity and bandwidth of the station located at Sevilleta National Wildlife Refuge (LWA-SV) should allow for a detection of the signal.

During Cycle 9, the achromatic beamforming framework developed in Cycle 8 was tested using an interferometric basket weave observation of Cygnus A. An extensive observing campaign, which utilized both achromatic beamforming and the improved observational and data analysis methodology developed in Cycle 8, was also carried out between March 10$^{\text{th}}$, 2021 and April 10$^{\text{th}}$, 2021. The observing campaign yielded over 30 hours of data which were calibrated and stacked using an iterative bootstrapping algorithm which allows for a much more statistically robust approach for representing the average observed sky spectrum. All of the improvements developed in both Cycles 8 and 9 have led to updated residual root mean squared (RMS) limits of ≈ 3 K across the entire observed band of 52–83 MHz. This work has been submitted to the Journal of Astronomical Instrumentation for publication and is currently under review [redacted]

The results of the interferometric basket weave observations of Cygnus A are shown in Figure 2. These observations used the beam–dipole mode of LWA–SV which correlates the beam of the station core with the outrigger antenna. This two element interferometer creates a fringe pattern which is a convolution of the baseline geometry, the dipole gain pattern, and the station core beam pattern. This fringe pattern resolves out the Galactic plane to better isolate the contribution to the beam from Cygnus A. The basket weave pointings allow for the beam pattern to be probed in both RA and Dec directions. The results of this test can be seen in Figure 2. It is apparent that while the beam is not totally achromatic, its shape is much more stable across the two tunings in the observations which utilized achromatic beamforming. We found an improvement in chromaticity by a factor of 2 compared to standard beamforming.

The major goals of Cycle 10 will be to further refine our methodology and push the residual RMS towards the sub–Kelvin level. This will most likely be difficult as it will require very accurate knowledge of the limiting systematics of LWA–SV. Work to better understand the additive noise response of the electronics is currently being planned which will aid in analysis of data collected during Cycle 10. We plan on exploring alternative weighting functions for achromatic beamforming which might better reduce the beam chromaticity and on conducting another extensive observing campaign during the Spring of 2022. We also plan on exploring the performance of different sky models to calibrate the data.

We request 400 beam hours, the same that was granted in both Cycles 8 and 9. This will allow for an extended observing campaign that can run from late February 2022 through mid-April 2022. This number also includes extra hours which will be used to investigate the performance of different weighting schemes for achromatic beamforming. We plan to continue to use the DRX spectrometer mode which reduces the memory overhead required to store the data from such an extended observing campaign.

References

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

Jonathan R Pritchard and Abraham Loeb. Evolution of the 21 cm signal throughout cosmic history. *Physical Review D*, 78(10):103511, 2008.

Judd D Bowman, Alan EE Rogers, Raul A Monsalve, Thomas J Mozdzen, and Nivedita Mahesh. An absorption profile centred at 78 megahertz in the sky-averaged spectrum. *Nature*, 555(7694):67, 2018.

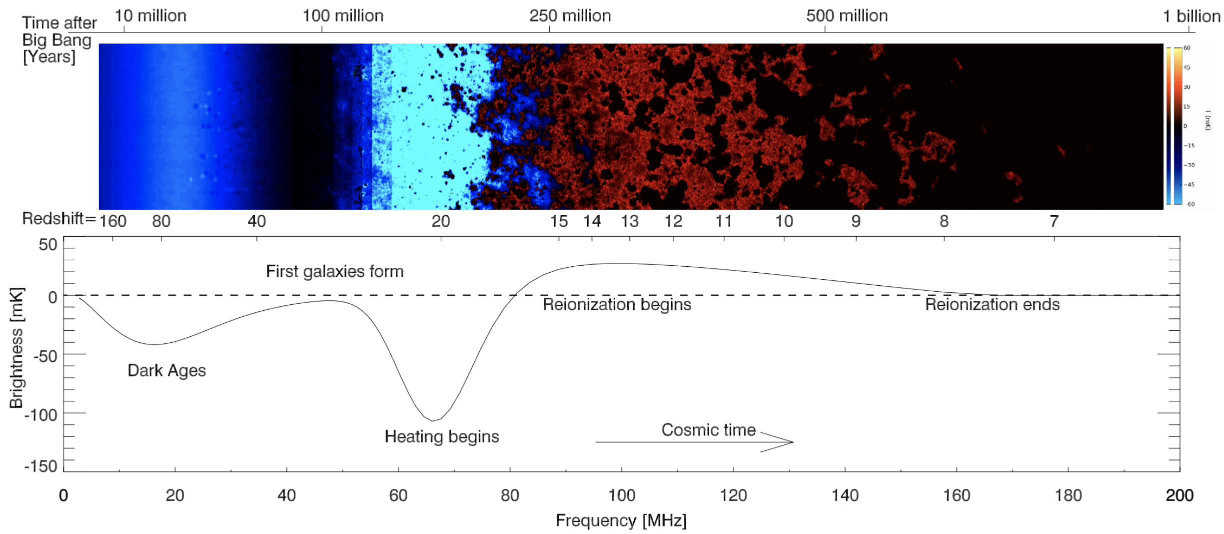

Figure 1: The evolution of the relative brightness temperature of the 1.4 GHz neutral hydrogen transition with respect to the temperature of the CMB. Source: Pritchard and Loeb [2012]

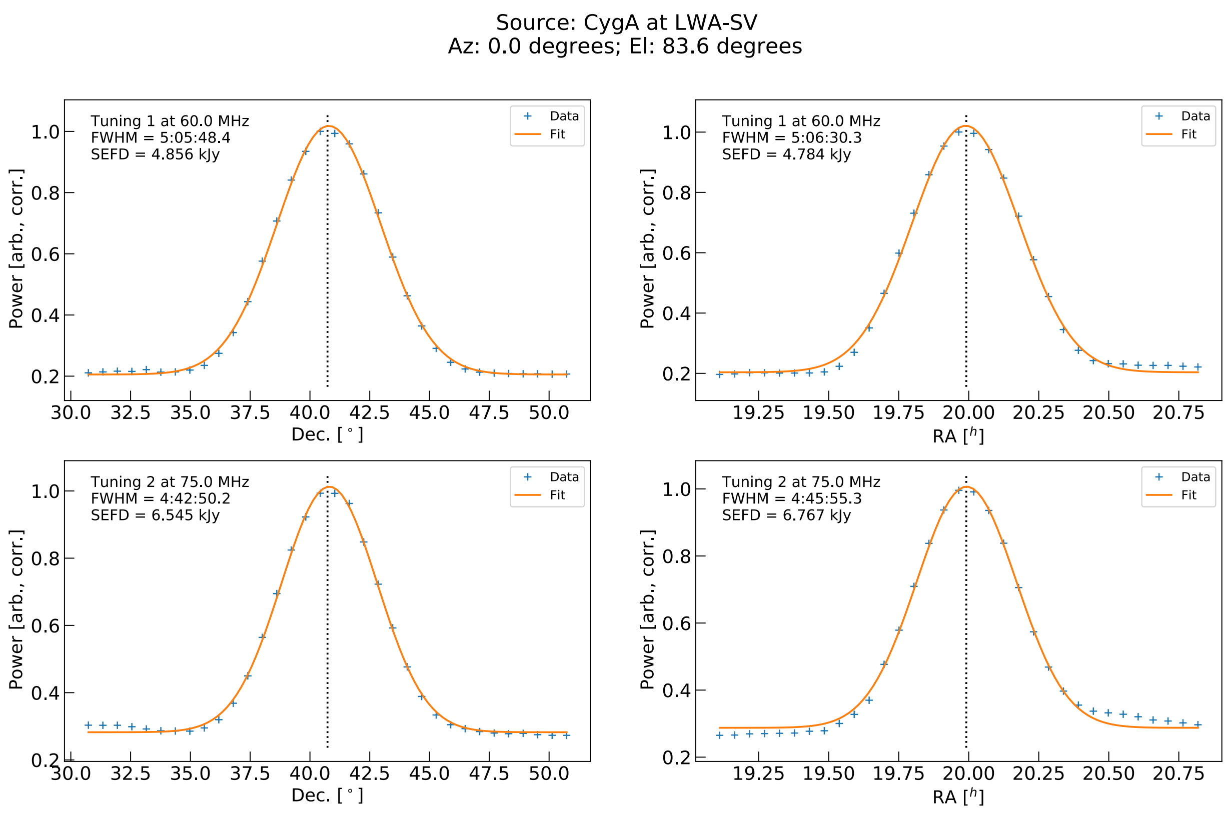

Figure 2: Results of achromatic beamforming basket weave observations. The top row shows the size of the beam in the declination and right ascension directions for the lower tuning centered at 60 MHz and the bottom row shows the same for the higher tuning centered at 75 MHz. The FWHM of the beam size is shown in each plot along with the associated SEFD.