C

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: Radio Recombination Lines with the LWA

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

We propose to use the LWA to search for carbon radio recombination lines (RRLs) in three bright sources located in the Cygnus Arm. A detection of those low frequency transitions will a) provide new information about the ionization states in these objects, and b) prove the capabilities of the LWA as a spectral line instrument. We have selected one HII region and two supernova remnants, which presumable contains large amounts of ionized gas. The project will be conducted in two stages: 1) Testing the observational setup and data reduction procedures by integrating for a few hours towards Cas A, confirming the known RRL absorption lines, and 2) Performing the scientific observations of the three targets. We will provide a report on spectral line observing with the LWA and a scientific paper after all data has been taken.

Project Investigators:

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

PI Contact Information

Mailing address: [redacted]

Phone number:

Requested mode(s): Backend(s) for each requested mode:

Requested mode(s)	Backend(s)			
☐ 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:		nr of beams:	
LWA1+SV interferometer time request:	hrs:	126	–	–
Repeated observations: length of each block (hrs):				
frequency of blocks (or when):				
Restrictions in observing time (time of day):				
Restrictions in observing time (time of year):				

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

Observational Details:

Please give center frequencies (ν1, ν2) and corresponding bandwidth (BW) for each source. If more pointing positions are required, please attach a separate sheet with all details.

ç		**Beam 1**		**Beam 2**		**Beam 3** (*LWA1 only*)		**TBN**	
Name	Cas A	(MHz)		(MHz)		(MHz)		(MHz)	
RA (hh.h)	23.7	ν_1	21.5	ν_1	21.5	ν_1		ν_1	
Dec (dd.d)	58.8	BW	20	BW	20	BW		BW	
LST beg (hh.h)	18.0	ν_2	40.5	ν_2	40.5	ν_2		ν_2	
LST end (hh.h)	05.0	BW	20	BW	20	BW		BW	
Source 2		**Beam 1**		**Beam 2**		**Beam 3**		**TBN**	
Name	DR4	(MHz)		(MHz)		(MHz)		(MHz)	
RA (hh.h)	20.4	ν_1	21.5	ν_1	21.5	ν_1		ν_1	
Dec (dd.d)	40.3	BW	20	BW	20	BW		BW	
LST beg (hh.h)	17.0	ν_2	40.5	ν_2	40.5	ν_2		ν_2	
LST end (hh.h)	23.0	BW	20	BW	20	BW		BW	
Source 3		**Beam 1**		**Beam 2**		**Beam 3**		**TBN**	
Name	DR21	(MHz)		(MHz)		(MHz)		(MHz)	
RA (hh.h)	20.7	ν_1	21.5	ν_1	21.5	ν_1		ν_1	
Dec (dd.d)	42.3	BW	20	BW	20	BW		BW	
LST beg (hh.h)	16.0	ν_2	40.5	ν_2	40.5	ν_2		ν_2	
LST end (hh.h)	02.0	BW	20	BW	20	BW		BW	
Source 4		**Beam 1**		**Beam 2**		**Beam 3**		**TBN**	
Name	HB21	(MHz)		(MHz)		(MHz)		(MHz)	
RA (hh.h)	21.5	ν_1	21.5	ν_1	21.5	ν_1		ν_1	
Dec (dd.d)	57.3	BW	20	BW	20	BW		BW	
LST beg (hh.h)	16.0	ν_2	40.5	ν_2	40.5	ν_2		ν_2	
LST end (hh.h)	04.0	BW	20	BW	20	BW		BW	

Source 1		**Beam 1**		**Beam 2**		**Beam 3** (*LWA1 only*)		**TBN**	
Name	Cas A	(MHz)		(MHz)		(MHz)		(MHz)	
RA (hh.h)	23.7	ν_1	59.5	ν_1	59.5	ν_1		ν_1	
Dec (dd.d)	58.8	BW	20	BW	20	BW		BW	
LST beg (hh.h)	18.0	ν_2	78.5	ν_2	78.5	ν_2		ν_2	
LST end (hh.h)	05.0	BW	20	BW	20	BW		BW	
Source 2		**Beam 1**		**Beam 2**		**Beam 3**		**TBN**	
Name	DR4	(MHz)		(MHz)		(MHz)		(MHz)	
RA (hh.h)	20.4	ν_1	59.5	ν_1	59.5	ν_1		ν_1	
Dec (dd.d)	40.3	BW	20	BW	20	BW		BW	
LST beg (hh.h)	17.0	ν_2	78.5	ν_2	78.5	ν_2		ν_2	
LST end (hh.h)	23.0	BW	20	BW	20	BW		BW	
Source 3		**Beam 1**		**Beam 2**		**Beam 3**		**TBN**	
Name	DR21	(MHz)		(MHz)		(MHz)		(MHz)	
RA (hh.h)	20.7	ν_1	59.5	ν_1	59.5	ν_1		ν_1	
Dec (dd.d)	42.3	BW	20	BW	20	BW		BW	
LST beg (hh.h)	16.0	ν_2	78.5	ν_2	78.5	ν_2		ν_2	
LST end (hh.h)	02.0	BW	20	BW	20	BW		BW	
Source 4		**Beam 1**		**Beam 2**		**Beam 3**		**TBN**	
Name	HB21	(MHz)		(MHz)		(MHz)		(MHz)	
RA (hh.h)	21.5	ν_1	59.5	ν_1	59.5	ν_1		ν_1	
Dec (dd.d)	57.3	BW	20	BW	20	BW		BW	
LST beg (hh.h)	16.0	ν_2	78.5	ν_2	78.5	ν_2		ν_2	
LST end (hh.h)	04.0	BW	20	BW	20	BW		BW	

Radio Recombination Lines with the LWA

November 1, 2021

[redacted]

1. Scientific Motivation

Radio recombination lines (RRLs) arise in ionized and partially ionized gas, and therefore offer valuable probes of the physical condition of the diffuse ionized interstellar medium. In particular, the size of the electron orbital increases for high quantum numbers, making the particles extremely sensitive to temperature and density of the medium.

Hydrogen and helium RRLs are seen at frequencies > 120 MHz in a variety of different regions, including HII regions, planetary nebulae, ionized stellar outflows and in the diffuse ionized interstellar medium (WIM) (e.g. Anantharamaiah 1985; Omar et al. 2002). RRLs of the fourth most abundant element, carbon, tend to trace slightly cooler regions of the interstellar medium due to its lower ionization potential. Below 120 MHz there are no hydrogen RRLs detected, and the carbon RRLs detected are seen in absorption instead of emission (Stepkin et al. 2007; Kantharia & Anantharamaiah 2001; Erickson et al. 1995). At those lower frequencies, corresponding to higher quantum numbers, the excitation temperature approaches the kinetic temperature and eventually the RRL is expected to be seen in absorption. The absorption appears to be enhanced due to a dielectronic electron capture mechanism, increasing the chance of absorption in atoms with multiple electrons, explaining why carbon is favored and no hydrogen RRLs have been detected so far in absorption (Walmsley & Watson 1982).

The carbon RRLs are often assumed to be associated with neutral hydrogen, but there are also cases where the RRLs are associated with cold molecular clouds. To understand the details of the physical conditions of the clouds producing these lines, many more detections improving the statistics are needed. Good places to search for these lines are regions where the column density is high at the same time as the background emission is strong. Locations fulfilling these criteria are along the Galactic plane, or at positions along the Cygnus Arm. At frequencies below 100 MHz, RRLs were recently detected for example using LOFAR in the case of Cas A (Asgekar et al. 2013), Cygnus A (Oonk et al. 2014), as well as toward M82 (Morabito et al. 2014). The Galactic plane has been partially searched previously (e.g. Erickson et al. 1995), while the Cygnus Arm has received less attention. In this proposal our aim is to perform a search for RRLs in the 10-88 MHz regime in the Cygnus Arm at positions where background continuum is bright.

2. Selected Targets

The targets are selected due to their location in the Cygnus Arm, in addition they should be bright at low radio frequencies and be likely to contain large amounts of ionized or partly ionized gas. We have therefore concentrated or targets to be either HII regions or supernova remnants:

DR21 is a well studied HII region, containing large amounts of ionized gas. The HII region is partially embedded in dense molecular gas (e.g. Dickel, Ho & Wright 1985). The carbon content has been investigated in molecular gas via CO, and in atomic form via [C I]. Information about the ionized carbon content in this object could help improving PDR models in DR21 and similar objects (Jakob et al. 2007).

HB21 is a large SNR ($120' \times 90'$) with an age estimated to around 6000 yr (e.g. Lazendic & Slane 2006). The environment of this SNR is likely to be dense, since it is interacting with a molecular cloud (Erkes & Dickel 1969; Byun et al. 2006). The flux density at 408 MHz is listed as 259 Jy, and with an spectral index of $\alpha = -0.27$ an interpolation implies a flux density close to 500 Jy at 26 MHz (Kothes et al. 2006).

DR4 is an SNR also also known as γ Cygni. It has a circular shape, and its spectral index implies a flux density of 1000 Jy at 26 MHz (Kothes et al. 2006).

3. Observational Setup

As demonstrated by previous LOFAR detections, observing in the interferometer mode will minimize confusion issues. At increasing quantum numbers, the spectral separation between consequent lines decreases, and at 26 MHz ($n \sim 630$) a spectral resolution of about 125 kHz is needed. At the same time, a large bandwidth is desired since then many lines can be observed at the same time, and the resulting spectra can be stacked to search for a possible detection. Using the two-station interferometer, 2 tunings of 20 MHz each, with one beam for calibration and one for the target, we will shift the frequencies of the beams allowing for spectral overlap. This way we are able to cover most of the LWA band from 12–50 and 50–88 MHz in two setups. A bandwidth of 40 MHz corresponds to almost 300 transitions at 26 MHz, and we will aim for a frequency resolution of 0.5 kHz (6 km/s).

The line to continuum ratio in the detected lines are weak, and of the order of $10^{-4} - 10^{-3}$. To test the system and our observational setup, we will start with observing the already known lines in Cas A (see Fig. 1; Stepkin et al. 2007, and the LOFAR detections by Asgekar et al. 2013 and Emig et al. 2020). Cas A is very bright, of the order of 60 kJy at 30 MHz, and has a line to continuum ratio of about 5×10^{-3}. A transition should be detectable at 5σ within 1.5 hour of integration for one tuning (3.0 hours in total for Cas A including the two frequency steps).

In other directions, along the Cygnus Arm, the unknown line to continuum ratios and flux densities may be considerably less of course, but the estimated continuum levels are above 100 Jy. Assuming line to continuum ratios of the order of 5×10^{-4}, and continuum flux densities ~ 500 Jy, a 5σ detection would require an integration time of about 2,700 hrs. This may seem a bit unreasonable, but by stacking the lines we can still make a detection. By stacking lines, the time requirement for a detection reduces dramatically: using $\sim$100 lines the time is reduced to 30 hrs. A corresponding calculation at 76 MHz yields a time requirement of 10 hours. Stacking more lines may be feasible, but as RFI may render parts of the spectrum unusable a 100 line stacking goal is more reasonable. The flux densities at 25 MHz and 76 MHz are not known for our target sources, so we request 40 hours per source (30 hrs at 26 MHz and 10 hrs at 76 MHz respectively). This allows for different sets of line stackings to be performed if a detection is made. With 3 target positions we therefore request 120 hours in total for our main target sources.

To confirm known detections and to write software preparing the data for further processing and work out RFI excision algorithms we also request 6 hours of data on Cas A (3 hours at 26 and 76 MHz respectively). In addition, these data will be used to identify any problems with the selected tuning frequencies if persistent RFI seems to exist. In a dynamic spectrum plot from 2009 the spectrum above 20 MHz seems remarkably clear (Fig. 2). The second beam will be observing nearby 3C sources for ionospheric calibration, and Cyg A will be used for bandpass calibration.

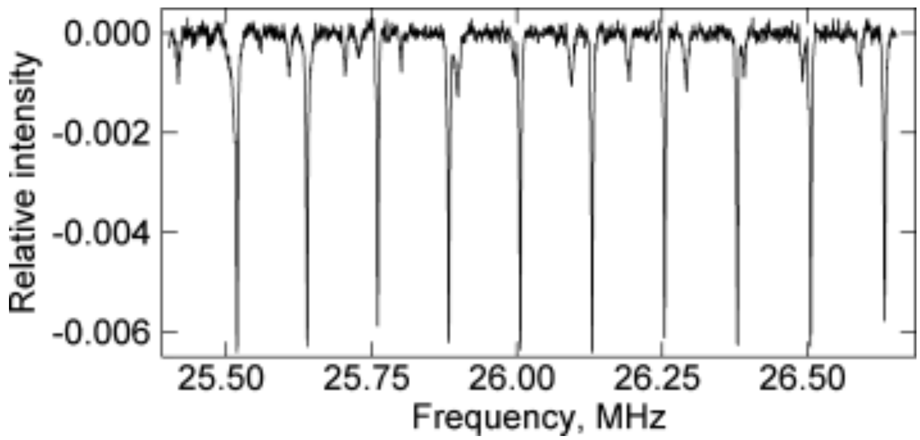

Figure 1: The spectrum of carbon at 26 MHz taken in the direction of Cas A (Stepkin et al. 2007)

4. Expected Outcomes

Our observations will be performed in two stages, starting with a proof-of-concept phase observing the known RRLs in Cas A. We will use these data to understand the data processing, in order to maximize our chances to detect new lines in our main targets. These data will further be used to test our observational setup (e.g., the required bandwidth overlap, and if any tuning frequencies need to be considered due to persistent RFI features). We will write a project report on LWA spectral observations, and plan a scientific paper on the main targets.

We are aware of the early tests performed in 2012 by Taylor and a UNM student of the Cas A recombination lines. No detection was made in their test, however, no stacking was done and we think longer integration and stacking may be needed for detections given the current sensitivity of LWA. The addition of using the LWA interferometer mode should help with confusion. Analysis will both be performed using single station beam-formed data, as well as the interferometrically correlated data combining the two LWA stations.

References

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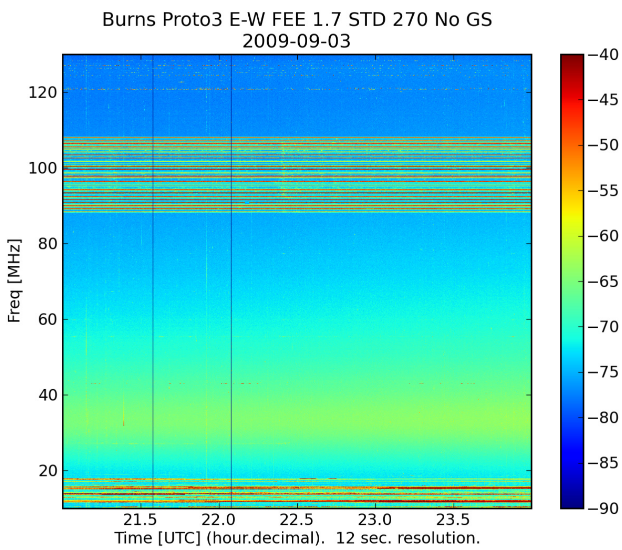

Figure 2: A 3 hour dynamic spectrum from the LWA1 site taken September 3, 2009.