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PROPOSAL COVER SHEET

V5.0

Cycle 8 Call for Proposals: LWA1 Radio Observatory

Submit to: lwa@unm.edu by November 1, 2019

Project title: Radio emission from Tau Bootis: following up a tentative signal

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

Almost since its discovery, the giant exoplanet Tau Bootis b has been predicted to be the one of the best candidates for exoplanetary radio emission. Our group has performed LOFAR beamformed polarized observations of this planet. With this project, two observations of Tau Bootis show a tentative signal in circular polarization. We propose to follow-up on these signals and try to confirm their astrophysical origin. In order to be able to draw solid conclusions even from weak signals, we will conduct near-continuous observations with LOFAR, NenuFAR, and UTR-2. If our tentative signal is confirmed, this would constitute the first firm detection of an exoplanetary radio signal. Unique physical information will be obtained on the observed system: the exoplanetary magnetic field, rotation, orbital inclination, and the physics interaction of the planet with its host star. Including calibration, **we ask for 214 hours** of observing time, with 3 simultaneous beams in full polarization. **The minimum observing time required is 40h.** Nighttime conditions are essential; for this reason, the observations should take place between late January and early June.

Project Investigators:

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

PI Contact Information

[redacted] [redacted]

Phone number: [redacted]

Requested mode([redacted]

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

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

LWA1 only time request:	hrs/beam:	214	nr of beams:	3
LWA-SV only time request:	hrs/beam:		nr of beams:	
LWA1+SV interferometer time request:	hrs:		–	–
Repeated observations: length of each block (hrs):	8			
frequency of blocks (or when):	At certain phases of the planet			
Restrictions in observing time (time of day):	Night time			
Restrictions in observing time (time of year):	January – June			

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

In order to observe the planet at the correct orbital phase, careful scheduling is required. We will provide a list of potential observing windows.

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	Tau Bootis	(MHz)		(MHz)		(MHz)		(MHz)	
RA (hh.h)	13:47:17.0	ν_1	25.5	ν_1	25.5	ν_1	25.5	ν_1	
Dec (dd.d)	+17:27:22	BW	19.6	BW	19.6	BW	19.6	BW	
LST beg (hh.h)	9	ν_2	43.1	ν_2	43.1	ν_2	43.1	ν_2	
LST end (hh.h)	19	BW	19.6	BW	19.6	BW	19.6	BW	
Source 2		**Beam 1**		**Beam 2**		**Beam 3**		**TBN**	
Name	PSR B0809+74	(MHz)		(MHz)		(MHz)		(MHz)	
RA (hh.h)	08:14:59.50	ν_1	25.5	ν_1	25.5	ν_1	25.5	ν_1	
Dec (dd.d)	+74:29:05.7	BW	19.6	BW	19.6	BW	19.6	BW	
LST beg (hh.h)	3	ν_2	43.1	ν_2	43.1	ν_2	43.1	ν_2	
LST end (hh.h)	15	BW	19.6	BW	19.6	BW	19.6	BW	
Source 3		**Beam 1**		**Beam 2**		**Beam 3**		**TBN**	
Name	Jupiter	(MHz)		(MHz)		(MHz)		(MHz)	
RA (hh.h)	00:00:00.00	ν_1	14.8	ν_1	14.8	ν_1	14.8	ν_1	
Dec (dd.d)	+00:00:00.00	BW	19.6	BW	19.6	BW	19.6	BW	
LST beg (hh.h)		ν_2	27.4	ν_2	27.4	ν_2	27.4	ν_2	
LST end (hh.h)		BW	19.6	BW	19.6	BW	19.6	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	

Radio emission from Tau Bootis: following up a tentative signal

The direct detection of exoplanetary magnetic fields has been an elusive hunt despite decades of searching. All the planets in our Solar System, except Venus, have or used to have a magnetic field (Stevenson, 2003), and theoretical scaling laws predict that many exoplanets might have one as well (e.g. Sánchez-Lavega 2004). Measuring the magnetic field of an exoplanet will give valuable information to constrain its interior structure (composition and thermal state), its atmospheric escape, and the nature of any star-planet interaction (Hess & Zarka, 2011; Zarka et al., 2015; Grießmeier, 2015, 2017, 2018). Additionally, the magnetic field of Earth-like exoplanets might help contribute to their sustained habitability by deflecting stellar wind particles and cosmic rays.

The most promising method to detect exoplanetary magnetic fields is via radio emission observations because unlike the other methods it is not susceptible to false positives (Grießmeier 2015). Assuming the anisotropic beaming of exoplanetary radio emission is similar to that of Jupiter (Zarka et al. 2004), we would expect the emission to be be visible from Earth only 10% of the time. Therefore, radio emission from exoplanets is expected to be phase-dependent (e.g. Hess & Zarka 2011). Also, the intensity of the radio emission is expected to vary as the planet encounters different plasma conditions (particle density, magnetic field) along the orbit (e.g. Fares et al. 2009).

Over the past years, a number of international teams have tried to detect low-frequency radio emission from exoplanets, but as of today no unambiguous detection has been achieved. Some hints have been obtained on a few planets (Lecavelier des Etangs et al. 2013; Sirothia et al. 2014; Vasylieva 2015; Bastian et al. 2018) but a reliable, confirmed detection that will open the observational study of star-planet plasma interactions and comparative exo-magnetospheric physics remains to be obtained. A complete overview of the situation is given in the SKA book chapter (Zarka et al. 2015), and in Grießmeier (2015, 2017, 2018). This subject remains an extremely hot topic.

Observational searches have been (and are being) carried in imaging mode with the VLA, GMRT, OVRO-LWA and LOFAR. As an alternative to imaging observations, beamformed searches have been carried by our team with LOFAR (Turner et al. 2017, 2019a). Our observations were performed at low frequencies from 15–62 MHz with full polarization and consisted of three simultaneous beams (one ON beam and two OFF beams). During this campaign, we have observed four exoplanetary systems including Tau Bootis.

Specific analysis tools for beamformed data were developed during the PhD thesis of I. Vasylieva (Vasylieva, 2015), and a full pipeline (`BOREALIS`) was developed during the PhD thesis of J. Turner (Turner et al. 2017, 2019a). This pipeline includes custom-built RFI mitigation, data reduction, computation of observables, comparison of multiple beams, and has been flux-calibrated using Jupiter observations (Turner et al. 2019a). `BOREALIS` is general and so far has been successfully applied to LOFAR, UTR-2, and NenuFAR beamformed data.

Recently, the previously acquired LOFAR datasets have been fully analyzed (Turner et al. 2017, Turner et al. 2019b, submitted). From our LOFAR campaign, two observations of Tau Bootis show tentative detections (Turner et al. 2019b, submitted, Figures 1 and 2 below) at two different orbital phases (Figure 3). As seen in the Figure 3, phase coverage is 25% of the planetary orbit. Therefore we cannot exclude that we have missed radio emission concentrated at specific orbital phases.

We suggest to follow-up these tentative detections of radio emission from Tau Bootis b. The proposed LWA observations will be part of a multi-telescope campaign with LOFAR, NenuFAR, and UTR-2. Observing at multiple sites will help to give good orbital coverage without having to wait for dozens of days, during which the local plasma conditions might change along the orbit. The LWA observations will be near-continuous with a 4-hour gap between observations taken by LOFAR and NenuFAR. Observing the entire orbit of the planet is necessary since planetary emission may have been missed due to the beaming effect. A detected signal by multiple telescopes would constitute a simultaneous detection and confirmation without needing extra telescope time. The unambigous confirmation of radio emission from this nearby exoplanetary system would constitute a highly significant and visible result rapidly publishable in a high-impact journal.

Technical Requirements

Previous observations: No previous observations with LWA1 were taken.
Telescope, beams, polarization: We request to use LWA1 with three beams (one ON beam and two OFF beams). This setup will be similar to the tentative detections found with LOFAR that also had three beams. We request to observe in all polarizations (IQUV).
Sensitivity: The tentative detections of Tau Bootis were seen with an intensity of $\sim$430 mJy between 21 – 30 MHz. The sensitivity of LWA1 with a bandwidth of 4 MHz and 10 min integration time is 88 mJy. Therefore, a $\sim 4\sigma$ detection is possible if a similar signal as the tentative detections is seen.
Observing constraints: Our experience with LOFAR data shows that RFI is significantly stronger during daytime than during nighttime in this frequency range. We know that there is more pressure on night-time, but high data quality is essential for the detection of the faint signal sought in this project. Tau Boo is observable at night between between late January and early June. It transits the LWA meridian at 12:20 UT on 2020-02-01, at 10:20 UT on 2020-03-01, at 8:20 UT on 2020-04-01, at 6:20 UT on 2020-05-01, and at 4:20 UT on 2020-06-01. The planetary system is observable each night in good conditions (elevation $>30°$) for $\pm$4 hours from the meridian transit. With this, mid April is optimal (8h of observations around meridian transit during nighttime).
Observation duration: Considering the previous tentative signal, we propose a deep exploration of the planet with a good orbital coverage. We suggest observing sessions of 8h each. We propose to cover all orbital phases of the planet (3.3 days, i.e. 79 hours) twice and the two orbital phases of the tentative signals three times. This amounts to 206 hours of observing time. In addition, we request 6h of Jupiter observations to allow a flux-calibration of our pipeline. We have done this with LOFAR LBA data (Turner et al. 2019a) and would like to perform the same experiment with LWA. We thus request at total of 212h of observing time (+2h for calibration). The minimum observing time for a meaningful result (cover the two orbital phases of the tentative signals twice) is 32+6h (+2h for calibration).
Scheduling: In order to observe the planet at the correct orbital phase, careful scheduling is required. We will coordinate with the LWA staff to provide a list of potential observing windows.
Calibration: Before each observation, we would observe a bright pulsar (e.g. PSR B0809+74) for 10 minutes (for a total of 2h, included above), with exactly the same settings as for the

exoplanet observation. This will allow to test the data quality. In addition, we ask for an observation of Jupiter during Jovian S-burst and L-burst emission (2*3h, for a total of 6h, included above). This will allow to quantify to which level our algorithm can pick up low-intensity, sporadic radio bursts using the method outlined in Turner et al. (2019a). It is important that these observations are taken in exactly the same mode as the exoplanet observation. Jupiter's radio emission is predictable, with ∼three observing windows of a few hours per month. We will be in contact with the LWA staff and provide a list of potential observing windows at the start of the semester.

Frequency selection: The tentative detections for Tau Bootis extend from 14–30 MHz. Therefore, we request one receiver tuning of 15.7–35.3 MHz with a bandwidth of 19.6 MHz. Assuming the actual usable bandwidth due to band edges is 15.68 MHz (80% of usable bandwidth), we can get a usable bandwidth from 17.7–33.3 MHz thus covering the frequency of the tentative detections. The other receiver tuning will be from 33.34–52.94 MHz allowing for good continuous wavelengths coverage from 17.7–52.94 MHz. Both tunings will allow us to cover the majority of the frequency range of the LOFAR observations.

Time and frequency resolution: We wish to process the data using using filter 7 of the digital receiver. We request a frequency resolution of ∼612.5 kHz and a time resolution of ∼10 ms. This will allow us to use the full bandwidth of 19.6 MHz for each of the two detector tunings.

Simultaneous ON/OFF observations: We require simultaneous ON/OFF-observations with one beam on source and two beams on an empty patch of sky all with the same frequency tunings. Coordinates of the OFF-beams will be provided in due time.

Combined observation: We have requested and been granted observations of Tau Bootis with UTR-2 (multiple beams,10-32 MHz) and NenuFAR (4 beams, 10-85 MHz). We also have a follow-up LOFAR proposal currently under consideration. Due to the spurious nature of the expected radio signal, measurements done by multiple facilities are essential to firmly validate a detection. The LWA data will be complimentary to the NenuFAR and UTR-2 data because it will allow for near-continuous observations of the Tau Bootis system.

Timeline: The LWA observations will be downloaded by our team and stored at the Nancay data center. The data will be analyzed by J. Turner and J.-M. Grießmeier using the existing pipeline (Turner et al. 2017, 2019a). The results of this study will be rapidly published in a high-impact journal alongside the observations of LOFAR, NenuFAR, and UTR-2.

References:

Bastian, T. S., et al., 2018, ApJ, 857, 133; Fares, R., et al. 2009, A&A, 398, 1383; Grießmeier, J.-M. 2017, PRE VIII, 285–300; Grießmeier, J. M. 2018, Future Exoplanet Research: Radio Detection and Characterization, 159; Hess, S. L. G. Zarka, P. 2011, A&A, 531, A29; Lecavelier des Etangs, A, et al. 2013, A&A, 552, A65; Sánchez-Lavega, A. 2004, ApJl, 609, L87; Sirothia, S. K., et al. 2014, A&A, 562, A108; Stevenson, D. J. 2003, EPSL, 208, 1; Turner,J. D., Grießmeier, J.-M., Zarka, P., & Vasylieva, I. 2017, PRE VIII, 301–313; Turner, J. D., Grießmeier, J.-M., Zarka, P., Vasylieva, I. 2019a, A&A, 624, A40; Turner, J. D., Zarka, P., Grießmeier, J.-M., et al. 2019b, A&A, Submitted; Vasylieva, I. 2015, Theses, Paris Observatory; Zarka, P., Cecconi, B., Kurth, W. S. 2004, JGR, 109, A09S15; Zarka, P., Lazio, J., Hallinan, G. 2015, Advancing Astrophysics with the Square Kilometre Array (AASKA14), 120

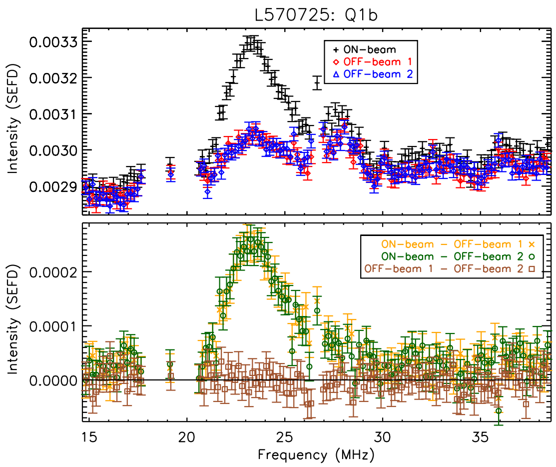

Figure 1: Tentative detection of slowly variable circularly polarized emission from Tau Bootis in LOFAR observation L570725 (Turner et al. 2019b, submitted). Plotted: signal from the ON-beam minus signal from the OFF-beam. The emission is visible as an excess between 21 and 27 MHz with a statistical significant of 8.6σ.

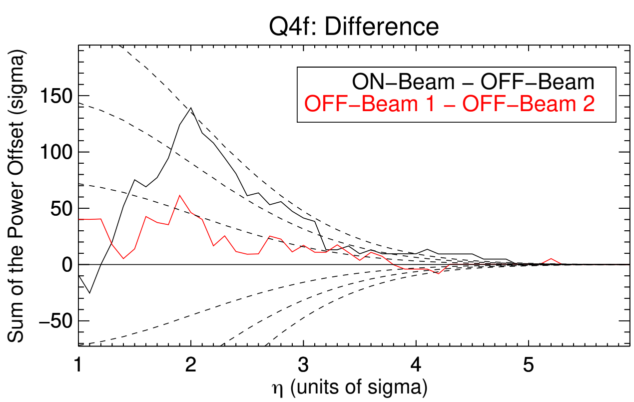

Figure 2: Tentative detection of circularly polarized bursty emission in LOFAR observation L569131 (Turner et al. 2019b, submitted). The statistics of indicator 'Q4f' show an excess of short bursts in the ON-beam over the OFF beam with a statistical significant of 3.2σ.

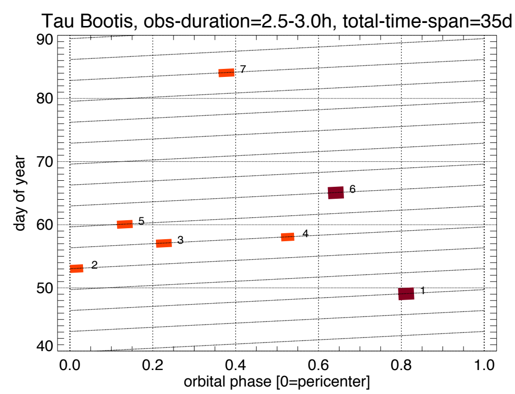

Figure 3: Orbital coverage of Tau Bootis from our LOFAR observations (Turner et al. 2019b, submitted). Not all orbital phases have been covered. The tentative detections (Figures 1 and 2) have been recorded during observations 6 (phase $\sim$0.6) and 1 (phase $\sim$0.8), respectively. Both these phases should be covered multiple times, with other phases with no detected emission for comparison.