Radio-loud Exoplanet-exomoon Survey: GMRT Search for Electron Cyclotron Maser Emission

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Received 2021 October 29; revised 2022 October 17; accepted 2022 October 24; published 2022 December 2

Abstract

We conducted the first dedicated search for signatures of exoplanet–exomoon interactions using the Giant Metrewave Radio Telescope (GMRT) as part of the radio-loud exoplanet-exomoon survey. Due to stellar tidal heating, irradiation, and subsequent atmospheric escape, candidate “exo-Io” systems are expected to emit up to 10^6 times more plasma flux than the Jupiter-Io DC circuit. This can induce detectable radio emission from the exoplanet-exomoon system. We analyze three “exo-Io” candidate stars: WASP-49, HAT-P 12, and HD 189733. We perform 12 hr phase-curve observations of WASP-49b at 400 MHz during primary & secondary transit, as well as first & third quadratures achieving a 3σ upper limit of 0.18 mJy beam^-1 averaged over four days. HAT-P 12 was observed with GMRT at 150 and 325 MHz. We further analyzed the archival data of HD 189733 at 325 MHz. No emission was detected from the three systems. However, we place strong upper limits on radio flux density. Given that most exo-Io candidates orbit hot Satsumes, we encourage more multiwavelength searches (in particular low frequencies) to span the lower range of exoplanet B-field strengths constrained here.

Unified Astronomy Thesaurus concepts: Natural satellites (Extrasolar) (483); Radio continuum emission (1340); Exoplanets (498); Star-planet interactions (2177)

1. Introduction

Extrasolar satellites (exomoons) have so far eluded ongoing searches due to their small size. Several investigations have exploited transit timing variations leading to the possible identification of giant exomoons (Teachey & Kipping 2018; Heller et al. 2019; Kreidberg et al. 2019). Recently, high-resolution spectroscopy has revealed that evaporating exomoons may display alkali metals in hot Jupiter/Hot Saturn atmosphere transit spectra due to their inevitable outgassing due to tidal heating and plasma-driven atmospheric sputtering (Oza et al. 2019; Gebek & Oza 2020). These exomoon candidates have been named “exo-Ios” due to their extremely large evaporation rates ~ 10^{5.2} kg s^-1 (0.2–20 lunar mass Gyr^-1) capable of catastrophic self erosion over the often unconstrained age of the star system.

One possible method of detecting these elusive exomoons is to search for signals of planet–moon interactions. In the solar system, the planet–moon interaction between Jupiter and Io leads to detectable radio emission. The Io-controlled decametric emission (Bigg 1964) is caused by the motion of Io through Jupiter’s magnetic field lines. This motion leads to magnetic field oscillations known as Alfvén waves (Belcher 1987), which lead to the generation of electric fields parallel to the jovian magnetic field line (Neubauer 1980; Crary 1997; Saur et al. 2004; Su 2009). As the electrons travel through magnetic field lines, they accelerate and gyrate, leading to radio emission powered by the electron cyclotron maser instability mechanism (ECMI; Wu & Lee 1979; Crary 1997). If a similar mechanism also operates in exomoon-exoplanet systems, then their emission might also be radio bright.

There have been several attempts at detecting star–planet interaction in the radio and UV domain (e.g., Lazio et al. 2004; Smith et al. 2009; Lecavelier Des Etangs et al. 2011; Lecavelier des Etangs, et al. 2013; Hallinan et al. 2013; Vedantham et al. 2020; Callingham et al. 2021; Narang et al. 2021a, 2021b; Pérez-Torres et al. 2021; Turner et al. 2021; Viswanath et al. 2020). However, the exoplanet–exomoon interaction has not yet been studied observationally. In this work, we present the first dedicated survey for studying the planet–moon interaction using the Giant Metrewave Radio Telescope (GMRT) to reveal hidden volcanic exo-Ios (or their exotori counterparts) as well as inform the unknown field strengths of hot Jupiters and hot Saturns. In Section 2, we describe the targets, followed by the details of the observations and the data reduction process in Section 3. We describe the results in Section 4. In Section 5, we discuss our findings, followed by a summary in Section 6.

2. Targets

To select a sample of possible exomoon candidates, we consider planets with alkali exosphere detections in high-resolution spectroscopy (Wytenbach et al. 2015, 2017; Dwivedi et al. 2019). The main target of our proposal is WASP-49. The WASP-49 system has never been observed at radio wavelengths. We also retrieve archival GMRT observations of two more exomoon candidates, HD 189733 and HAT-P 12. All three systems are candidate exo-Io systems based on the minimum sodium and potassium column densities implied...
by high-resolution visible light spectroscopy observations (Oza et al. 2019). These potentially evaporating exomoons are well within the tidal stability criterion (Cassidy et al. 2009). Evaporative transmission spectroscopy simulations of two of these systems (WASP-49, HD 189733) demonstrate that an exo-Io or exo-torus scenario is consistent with high-resolution sodium observations at present (Gebek & Oza 2020). In Table 1, we list the stellar and planetary parameters for WASP-49, HD 189733, and HAT-P 12 systems.

The system HD 189733 has been previously observed with GMRT at 150 MHz, 244 MHz, and 614 MHz (Lecavelier Des Etangs et al. 2009, 2011). At 150 MHz Lecavelier Des Etangs et al. (2011) obtained a 3σof 2.1 mJy beam<sup>−1</sup>, while at 244 MHz and 614 MHz Lecavelier Des Etangs et al. (2009) derived a 3σ upper limit of 2 mJy beam<sup>−1</sup> and 160 μJy beam<sup>−1</sup> respectively. Smith et al. (2009) observed HD 189733 between 304 and 347 MHz with the Robert C. Byrd Green Bank Telescope of the National Radio Astronomy Observatory. The reached and rms sensitivity of 26.7 mJy beam<sup>−1</sup>. No radio observations of HAT-P 12 have been carried out previously.

### Table 1

| Host star | Sp Ty | M<sub>p</sub> | R<sub>p</sub> | α<sub>p</sub> | d | Reference |
|-----------|-------|-----------|-----------|-----------|---|-----------|
| WASP 49   | G6 V  | 0.378 ± 0.027 | 1.115 ± 0.047 | 0.0379 ± 0.0001 | 193.73±0.68 | Lendl et al. 2012 |
| HAT-P 12  | K4 V  | 0.21 ± 0.01 | 0.959±0.021 | 0.0384 ± 0.0003 | 141.75 ± 0.18 | Hartman et al. 2009 |
| HD 189733 | K2 V  | 1.166 ± 0.05 | 1.142±0.036 | 0.031 ± 0.004 | 19.76±0.05 | Addison et al. 2019 |

Note. The distance d is from Gaia EDR3/DR3 Bailer-Jones et al. (2021).

3. Observations and Data Reduction

It is unlikely to know a priori the orbital period of exomoons around their parent planets. Moreover, the radio beam, due to planet–moon interaction, may be arbitrarily oriented with respect to the observer. Furthermore, the emission can also be modulated based on the phase of the planet around the star as argued by Pérez-Torres et al. (2021). To maximize the likelihood of detecting the emission, we decided to observe the WASP-49 system at four phases of the planets around the star: the first and second quadrature of the planet WASP-49b, as well as the primary and secondary transit. The WASP-49b system was observed for 12 hr (spread over four observations) with uGMRT in band 3 (250–500 MHz, proposal ID 39_015). The center frequency of the receiver was set at 400 MHz, with a bandwidth of 200 MHz. For each observation, the phase center was set at the position of WASP-49b.

The primary transit of WASP-49b was observed on 2020 October 29. We observed 3C48 as the primary flux density and bandpass calibrator. The flux calibrator was observed twice, once at the beginning of the observation and once at the end of the observation. The phase calibrator used was 0521 – 207 and was observed in a loop with 30 minutes on the science target and 5 minutes on 0521 – 207. The secondary transit was observed on 2020 November 5, while the first quadrature (phase 0.25) was observed on 2020 November 8. The observational setup for these observations was similar to the night of 2020, October 29th, with 3C48 as the primary flux density and bandpass calibrator and 0521 – 207 as the phase calibrator. The second quadrature (phase 0.75) was observed on 2021, January 17th. We used 3C147 as the primary flux density and bandpass calibrator, which was observed at the beginning as well as the end of the observation. We used 0706-231 as the phase calibrator, which was again observed in a loop of 5 minutes on the phase calibrator and 30 minutes on WASP-49.

We reduce the uGMRT data using the CASA Pipeline-cum-Toolkit for Upgraded Giant Metrewave Radio Telescope data REduction uGMRT- (CAPTURE) pipeline (Kale & Ishwara-Chandra 2021). We carry out the primary beam correction to correct for the falling sensitivity at the beam edges using the CASA task wbpghmrt<sup>8</sup> to produce the final image.

We further analyze archival GMRT observations of the exoplanet systems HAT-P 12 and HD 189733. The HAT-P 12 field was observed at 150 MHz and 325 MHz with GMRT. At 150 MHz, the system was observed for 11.6 hr (proposal ID 20).

textsuperscript{089} on 2011, April 28th. The phase center of the observation was the HAT-P 12 system. 3C48 was used as the primary flux density, and 1331 + 305 was used as the phase calibrator. At 325 MHz, the HAT-P 12 field was observed surreptitiously as part of the proposal 22.

textsuperscript{051} on 2012 September 8th. The phase center was set to the J1357 + 43, which is 24′/4 away from HAT-P 12. The system was observed for ~7 hr, with 3C286 being used as the flux calibrator and 1331 + 305 as the phase calibrator.

We also retrieve previously unpublished uGMRT observations of the system HD 189,733 at 325 MHz. The system was observed for 9.3 hr on 2009 May 26, with the phase center being HD 189733. The primary flux calibrators were used were 3C147 and 3C286, while 1924 + 334 was used as the phase calibrator. The archival GMRT observations of HAT-P 12 and HD 189733 were reduced using the Source Peeling and Atmospheric Modeling pipeline (Intema 2014). The log of the observations is given in Table 2.

4. Results

The WASP-49 field was observed with the uGMRT at 400 MHz for four nights totaling 12 hr of observation time. The four observations for the WASP-49 field at 400 MHz are shown in Figure 1. No emission was detected for each of the observations. The rms values achieved for each of the four nights are listed in Table 2. Based on these rms values, we put a 3σ upper limit of 0.18 mJy beam<sup>−1</sup> for the emission from this system.

In Figure 2, we show the archival GMRT observations for the HAT-P 12 system. At 150 MHz, we reached an rms value of 530 μJy beam<sup>−1</sup>, and at 325 MHz, we were able to reach an rms value of 95 μJy beam<sup>−1</sup>. No radio emission was, however, detected from the system at either of the frequencies. The upper limits of 1.6 mJy beam<sup>−1</sup> at 150 MHz is comparable to some of

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<sup>8</sup> https://github.com/ruta-k/uGMRTprimarybeam
the deepest limits reached at that frequency for an exoplanet field (e.g., Hallinan et al. 2013; O’Gorman et al. 2018; Narang et al. 2021b; Narang 2022). The GMRT observations of HD 189,733 325 MHz are shown in Figure 3. At 325 MHz, the rms value for the HD 189733 field is 95 μJy beam⁻¹.

5. Discussion

During our observations, we have produced some of the deepest images of an exoplanet field (e.g., Lecavelier Des Etangs et al. 2011; Lecavelier des Etangs, et al. 2013; Hallinan et al. 2013; O’Gorman et al. 2018; Narang et al. 2021b; Pérez-Torres et al. 2021; Narang 2022). There could be several reasons why no radio emission was detected from these systems. In the following subsection, we discuss some of these possible reasons.

5.1. Radio-quiet Exoplanet-exomoon Emission

If the radio emission from exoplanet-exomoon interaction is inherently quiet, in that case, our current instrumentation will not be able to detect it. A major difficulty in our experiment is the sheer distance of the targets; for instance, 2/3 of the candidate exomoon targets we analyzed in this study are located beyond 100 pc; therefore, the flux emitted may be too weak to be detected with uGMRT. Moreover, deeper observations with next-generation radio telescopes are needed to detect radio-quiet exoplanet-exomoon emissions.

5.2. Overestimation of Cyclotron Frequency and Exoplanet Magnetic Fields

The electron cyclotron maser emission is characterized by the maximum cyclotron emission frequency νc. This frequency for ECMI masers is fundamentally linked to the magnetic field strength B₀ of the emitting body at the radio source location and is given as follows:

\[ \nu_c = 2.8B_0 \]  

where B₀ is in Gauss and νc in MHz.

The observations in this work have been carried out at frequencies in the range of 150–500 MHz. This corresponds to planetary magnetic fields of ~50–180 G. If the magnetic fields of the exoplanets are lower than these values, then we could have missed the emission.

To evaluate this possibility, we apply the methods of Yadav & Thorngren (2017) to estimate the magnetic fields using evolution modeling (Thorngren & Fortney 2018) to derive the heat flux from the interiors of the planets (see Christensen et al. 2009). This gives the mean magnetic field on the dynamo surface as (from Reiners & Christensen 2010)

\[ B_{\text{rms}} \text{[kG]} = 4.8 \times 10^4(M_pL_p)^{1/6}R_p^{-7/6}, \]  

where M_p, L_p, and R_p are the mass, luminosity, and radius of the planet (all normalized to solar values).

However, the dynamo surface is not at the surface of the planet but further in at the liquid–metallic phase transition at approximately 1 Mbar (Yadav & Thorngren 2017; Chabrier et al. 2019). To best take this into account, we adopt Equation (2) of Yadav & Thorngren (2017), which uses a scaling law for the dynamo radius (which was calibrated for planets with M_p ~ 1M_J to instead use the 1 Mbar radius from our evolution models. The dipole magnetic field strength at the pole is thus

\[ B_{\text{dipole}}^{\text{polar}} = \frac{B_{\text{rms}}^{\text{dyn}}}{\sqrt{2}} \left( \frac{R_{\text{dyn}}}{R_p} \right)^3, \]  

where R_{dyn} is the dynamo radius. These equations only consider the dipole portion of the field, which is assumed to be the dominant component.

These equations should be seen as rough estimates. Following Christensen et al. (2009), we assume that the magnetic field is generated by a dynamo from the release of interior heat (rather than, e.g., rotation). If this is not the case, then magnetic fields are likely to be weaker; however, observational evidence thus far points toward the strong magnetic field case (Cauley et al. 2019). Furthermore, we are applying these relations to lower-mass planets (i.e., hot Satrums) than either Christensen et al. (2009) or Yadav & Thorngren (2017) were originally considering. We expect this is still reasonable because the intrinsic temperatures generating the dynamo are comparable, the conductive liquid-metallic region still extends to most of all our planets’ radii, and lastly, since we have used modeled dynamo depths rather than the existing scaling relation from Reiners & Christensen (2010).

For our most massive exo-Io candidate host HD 189733b, M_p = 1.16 M_J, we find B_{\text{dipole}}^{\text{polar}} = 58 G. This translates into a maximum cyclotron frequency of 162 MHz for HD 189733b. For WASP-49b (M_p=0.38 M_J) we find B_{\text{dipole}}^{\text{polar}} = 85 G, and for HAT-P-12b (M_p=0.21 M_J ) we find B_{\text{dipole}}^{\text{polar}} = 13 G. These values correspond to a maximum cyclotron frequency of 238 MHz for WASP-49 b and 36.4 MHz for HAT-P-12b. Hence more observations at lower frequencies are required to comment on the ability and presence of an exo-Io to drive ECMI emission at these systems.

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Table 2

| Target          | Frequency | Phase         | Date of Observation | Bandpass & Flux Density Calibrator | Phase Calibrator | rms this Work | rms Literature |
|-----------------|-----------|---------------|---------------------|------------------------------------|------------------|---------------|----------------|
| WASP 49b²      | 400       | Primary transit| 2020 October 30th   | 3C48                               | 521 − 207        | 79            |                |
| WASP 49b²      | 400       | First quadrature| 2021 January 18th   | 3C147                              | 0706 − 231       | 78            |                |
| WASP 49b²      | 400       | Secondary eclipse| 2020 November 5th   | 3C48                               | 521 − 207        | 72            |                |
| WASP 49b²      | 400       | Second quadrature| 2020 November 8th   | 3C48                               | 521 − 207        | 61            |                |
| HAT-P 12b      | 150       |               | 2011 April 28th     | 3C48                               | 1331 + 305       | 530           |                |
| HAT-P 12b      | 325       |               | 2012 September 8th  | 3C286                              | 1331 + 305       | 95            |                |
| HD 189733b     | 325       |               | 2009 May 26th       | 3C147 & 3C286                      | 1924 + 334       | 118           | 26,667a        |

Note. ² P.I: A. Oza ID39_015; a Smith et al. (2009).
5.3. Time Variable and Beamed Emission

Radio emissions from planets in our solar system are highly time variable (Zarka et al. 2004). The decameter emission from Jupiter due to the interaction with Io is highly modulated at scales of milliseconds to days (e.g., Zarka et al. 1996; Ryabov et al. 2014). The radio emission from the exomoon interaction could also be a time variable similar to the variability seen in the Jupiter-Io emission. Furthermore, the emission due to the interaction between Io and Jupiter is also highly beamed (e.g., Queinnec & Zarka 1998; Zarka et al. 2004; Ray & Hess 2008; Lamy et al. 2022). Similar beaming is expected from exomoon–exoplanet interactions. Long-term monitoring of these systems (WASP-49, HAT-P 12, and HD189733) would be required to rule out the variable or beamed nature of emission. The nondetection could be explained by Earth not being in the cone of emission at the time of observation.

6. Summary

We present the first dedicated search for radio emission at candidate exoplanet-exomoon systems. We analyzed uGMRT/GMRT observations for three systems, WASP-49, HAT-P 12, and HD 189733. We observed WASP-49 in band 3 (300–550 MHz) of uGMRT. We observed the first and second quadrature as well as the primary and secondary transit of the system in order to search for radio emission and its variability from the system. We do not detect any radio emission from the system but place a strong 3σ upper limit of 0.18 mJy beam$^{-1}$ at 400 MHz. We analyzed archival legacy GMRT data for HAT-P 12 at 150 MHz and 325 MHz. At 150 MHz, we obtain a 3σ upper limit of 1.6 mJy beam$^{-1}$ from the HAT-P 12 field; this is one of the deepest images at 150 MHz using GMRT. A much deeper 3σ upper limit of 0.21 mJy beam$^{-1}$ was reached at 325 MHz for this system. We further analyzed legacy GMRT observations of the HD 189733 field at 325 MHz. The 3σ upper limit of 0.36
mJy beam\(^{-1}\) at 325 MHz is 222 times deeper than the previous observation from Smith et al. (2009).

If an exomoon is present in one of these systems, we detect no radio emission due to time variables and beamed emission, overestimation of the cyclotron frequency, or overestimation of the flux density. The search for radio emission due to planet-moon interaction is an emerging field, and more observations at a lower frequency using LOFAR and GMRT band 2 (120–250 MHz) are perhaps required to detect/rule out the presence of exomoons. Indeed, based on the B-field strengths derived here for hot Saturn hosts (Yadav & Thorngren 2017), the majority of exo-Io hosts from Oza et al. (2019) would benefit from searches at lower frequencies. The possibility of evaporating exomoons continues to be tantalizing; however, limited by the characterization of extrasolar gas giant magnetospheres and their interaction with their host stars.

This work is based on observations made with the Giant Metrewave Radio Telescope, which is operated by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research and is located at Khodad, Maharashtra, India. We thank the GMRT staff for efficient support to these observations. We acknowledge support of the Department of Atomic Energy, Government of India, under Project Identification No. RTI4002. Part of this work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. K.H. is supported by the European Research Council via Consolidator Grant ERC-2017-CoG-771620-EXOKLEIN. K.H. is supported by the European Research Council via Consolidator Grant ERC-2017-CoG-771620-EXOKLEIN (awarded to Kevin Heng).

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