

# Exoplanet Radio Emission Detection: Principles and Approaches

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**Abstract.** Radio astronomy has emerged as a promising avenue for the detection and characterization of exoplanets, offering unique insights into the physical and atmospheric properties of these distant celestial bodies. This study commences with a historical overview of the early works by Zarka that laid the groundwork for the systematic exploration of radio exoplanet detection. It analyzes the theoretical principles and mechanisms that underpin the generation of radio emissions from exoplanetary systems. Detailed analysis delves into the specific instrumental capabilities of LOFAR, nenuFAR, and FAST, elucidating their respective strengths and limitations in detecting exoplanetary radio signals. In particular, the review points out the sensitivity and frequency coverage of each telescope and their potential to characterize a diverse range of exoplanets. Finally, this paper discusses the future prospects and potential synergies in advancing exoplanet radio detection. It concludes with an outlook on the role of radio astronomy in the exploration of exoplanetary systems and the exciting possibilities that lie ahead in understanding the diversity of exoplanets in the universe.

**Keywords:** Radio astronomy, exoplanets detection, LOFAR, nenuFAR, FAST.

## 1. Introduction

In the past few decades, traditional methods for detecting extrasolar planets are mainly indirect. Taking transit photometry as an example, the passage of a planet across a star reduces the observed brightness of that star, the magnitude of dimming indicates the diameter of the planet besides [1]. In contrast, radio astronomy offers a direct probe into the radio emissions from the exoplanets themselves, enabling direct information about the physical properties and characteristics of these planets.

For past research endeavors, attempting direct measurements of exoplanets used to be thought exceedingly challenging due to the vast interstellar distances involved. It appears to be arduous to directly image celestial bodies which are relatively small and dim (i.e., planets) in proximity to shining stars within an extragalactic system using optical techniques [2]. Direct imaging is a suitable for conditions where the star system is in close to our Earth, and the exoplanet exhibits significant size (considerably larger than Jupiter), significant separation from its host star, and elevated temperatures which allowing the production of detectable infrared radiation.

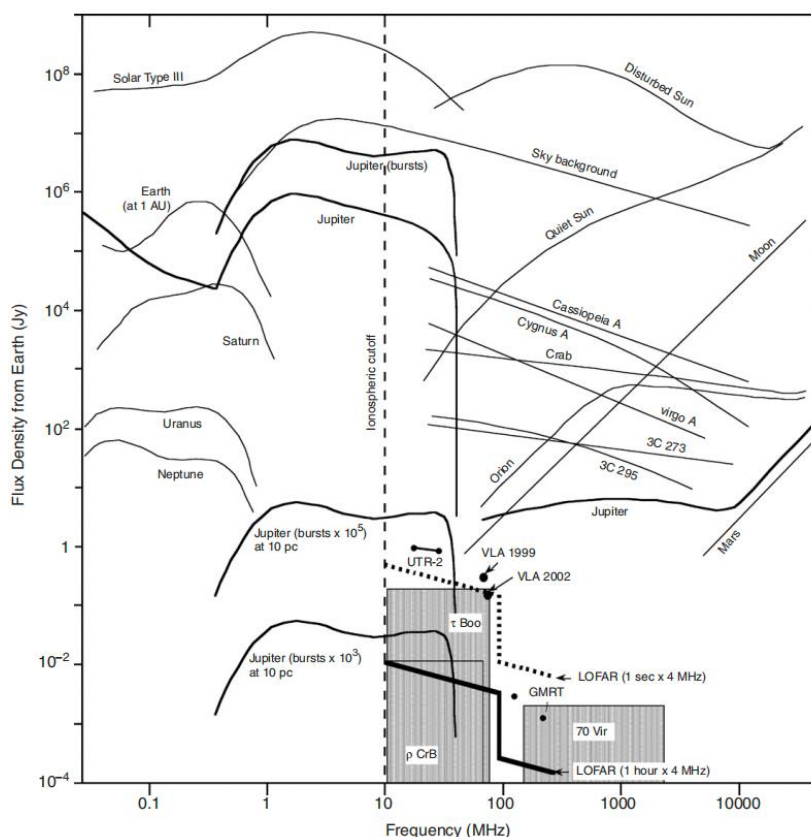
Under this harsh circumstance, the detection of radio waves emitted by planets bring new possibilities - it holds the potential to eliminate the need for reference objects in the accurate detection process. This method designs to looking for exoplanets which generate intense nonthermal radio radiations, and the highest contrast between a Jupiter-size planet's emissions are similar to solar radio bursts, that is, a stellar-planet contrast  $\sim 1$  [3].

The initial systematic discussion on the potential of detecting radio emissions from exoplanets was conducted by Philippe Zarka in 2007. Building upon his ideas, Grießmeier further analyzes four models to estimate auroral radio radiation of confirmed extrasolar planets and insists that exoplanet detection by analyzing radio emission are technically achievable [4], but the abundance of such emissions may not be very promising. Subsequently, lots of published works estimating the magnetic field intensity via different scaling laws and the induced magnetospheric radio emission from a number of currently known exoplanets [5-7]. The radio fluxes extrapolated from currently collected

exoplanets are contrasted with the wavelength ranges and sensitivities of all present and upcoming observatories [8].

Numerous articles have made efforts to quantify the radio flux density of exoplanets. These estimates have large uncertainties since different analyzed models applied, but can be employed to assess the feasibility of detecting exoplanetary auroral radio emissions using a specific radio telescope and observational configuration [9]. The majority of low-frequency radio telescopes observe exoplanets through interferometric images which are quite expensive, while excluding problematic antennas or dishes from the analysis even during offline processing. On the other hand, beam-formed observations are more cost-effective but lack the reliability to detect continuous or slowly varying emissions [9].

The goal of this study is to systematically explain this emerging observational methodology and present state-of-art advancements in research. Sec. 2 show the theoretical principles of planet radio emission, with reference to the data collected from Jupiter as an example. The primary factors and sources of the radio wave are also included. A clear comparison with the features of radio detection and IR imaging is also presented. Sec. 3 presents the feasibility of this method in practical application. Sec. 4 will focus on probable development direction and the main technical challenges to overcome in the future.



**Fig. 1** Flux density as a function of Frequency.

## 2. Descriptions

### 2.1. Theoretical Backgrounds and Comparative Studies

Within the solar system, the most obvious radio generation process that can be detected by human being is the decameter-wave burst originating from Jupiter's magnetosphere [10]. The cyclotron maser instability (CMI) used to be identified as the certain mechanism that causes this intense radiation from these magnetospheres [3, 11]. This theory show that the CMI can arise from an electron propagation with either a loss-cone anisotropy or a maximum at big pitch angles. The CMI occurs

when charged particles in the plasma move at speeds proximate to the local electron cyclotron frequency [12]. The emission frequency is contingent upon the local cyclotron frequency, which scales proportionally with the magnetic field amplitude. Electrons experience periodic changes in gyration radius and velocity as they gyrate around magnetic field lines with varying strengths. When an external or self-generated electromagnetic wave resonates with the cyclotron frequency, it interacts with gyrating electrons, resulting to the emission of coherent, highly polarized, and monochromatic radiation known as cyclotron maser emission [10].

Therefore, the radio emissions originating from Jupiter are produced through the interaction between Jupiter's satellites (i.e., Io and Ganymede) and the surrounding plasma near its orbit [13]. Jupiter exhibits an average flux density of approximately  $10^6$  Jy, with peak flux densities around  $10^7$  Jy during short periods. The Jovian flux density is more intense than that of the quiet sun, sometimes even exceeding the sun radio bursts, which means Jupiter is sometimes as bright as our sun at decameter ranges [9].

In terms of the CMI mechanism, the fundamental conditions for generating radiation from Jupiter are the existence of an intense magnetic field in the surrounding region and the existence of satellite bodies at relatively close distances. The interaction between these surrounding satellite and the plasma itself in the intense magnetic effect generates radio emissions. Extrapolating to star-planetary systems, it can be theorized that they would produce radiation on orders of magnitude greater. It is plausible to speculate that there may be stellar systems in the universe that meet these conditions, allowing for their detection in the radio spectrum. An essential evidence supporting the detectability is that even if Jupiter were placed at a significantly distant location, one may still have the capability to observe it using LOFAR (i.e., Dutch-led Low Frequency Array radio telescope). Fig. 1 shows the emitted spectra lines detected from Sun, Jupiter, and other solar planets. The bottom part illustrates the flux range expected to be observable by LOFAR, which enables the detection of objects including Jupiter at a distance of 10 parsecs. With the exception of Jupiter's decametric emissions, the auroral planetary spectra lines are situated below the Earth's ionospheric cut-off [3]. Subsequently, the giant extension survey of LOFAR, nenuFAR, and FAST survey are also designed to detect magnetized exoplanets via radio methodology. More relevant details will be discussed in the following section.

## 2.2. Predictions for Magnetized Exoplanets

Based on the Jovian system, then extrapolating to hot Jupiters, Zarka in 2019 mentioned that low frequency radio fluxes that could be up to  $10^3$  to  $10^5$  times greater than that of Jovian output, for planets rotating very quick in orbit around stars with a prominent UV-X-ray luminosity [14]. Drawing on the principles of magnetosphere-ionosphere mutual effect, the concept of the Ganymede-Jupiter induced interaction is extended to terrestrial planets orbiting white dwarfs, thereby forecasting a significant radio emission at frequencies more than 1 GHz. In these case, those apparent physical characteristics of magnetized exoplanets seem to allow for radio detectability.

## 2.3. Unique Information Gained via Radio Detection

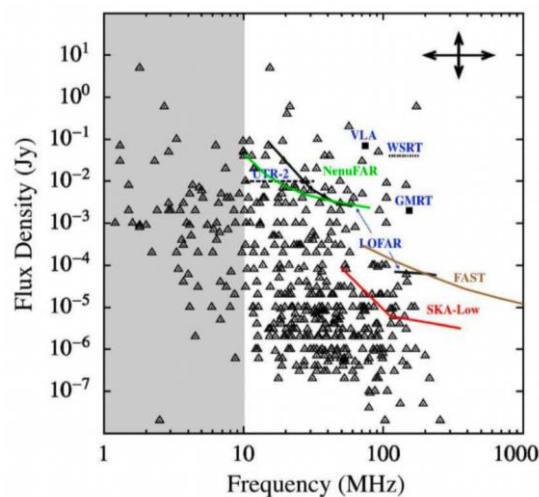
Zarka hold the view that magnetospheric radio emissions reveal distinct insights into the amplitude and tilt of planetary magnetic fields [14], thereby shedding light on the planetary dynamo [15] and possible internal structure [16, 17]. Additionally, such emissions may unveil the presence of satellites interacting with the planetary magnetic field (eg, analogous to Io-Jupiter system). As demonstrated by Zarka, radio emissions further enable researchers to investigate planetary orbit inclination, as well as Solar Planetary Interaction (SPI) on a larger scale. Lastly, the trace of planetary nonthermal LF radio emission is likely to be the only way to unequivocally identify exoplanetary magnetic characteristics [18]. Moreover, radio astronomy can play a key role in the search for potential habitable exoplanets and the exploration of extraterrestrial life. Certain radio emission signatures, such as those indicating interactions between exoplanets and their parent stars, could be indicators of habitability and the presence of Earth-like environments conducive to life [7, 19].

### 3. Analysis Methods

Referring to precise simulation data on the laser emission intensity from magnetized exoplanets, it becomes imperative to investigate an extensive set of objectives with the utmost continuum sensitivity, preferably focusing on long wavelength and conducting circular polarization or full Stokes observations. The author thus selects two detection approaches: nenuFAR and its complementary FAST.

#### 3.1. LOFAR Observation and Its Extension NenuFAR

According to Zarka's initial conjecture, LOFAR's (Low Frequency Array) detection wavelength would be consistent with that of exoplanets [3]. It can observe from 10-90 MHz and even higher. Following his anticipation, Turner analyzes the Jovian emission using Stokes-I and Stokes-V with LOFAR-LBA, and in OFF-beam 1 with Stokes-I and V. The results show that LOFAR is able to observe extrasolar planets with signals around  $10^{6-7}$  times the intensity of Jupiter's flux. This implies the presence of either a gas giant planet (i.e., Jupiter) located at a distance of 13,000 AU or an exoplanet with mean radio flux  $10^5$  times greater than Jupiter's, capable of emitting intense burst emissions. at a distance of 5 pc. This means radio emissions from planets as close as 55 Cnc (12 pc), Upsilon Andromedae (13 pc) and Tau Boötis (16 pc) can be observed if their real-time flux radiation could achieve  $10^5$  times greater than those exhibited by Jovian decametric burst emission [9].



**Fig. 2** Illustration of the anticipated peak radiation frequency and flux density for known exoplanets, represented by triangle symbols. Additionally, the approximate sensitivities of several instruments are depicted [14].

In addition to the ideal foreground of LOFAR in higher frequency band (about 100 to 250 MHz), there is a requirement for an exceptionally sensitive radio observatory operating in a LF range, spanning between the Earth's ionospheric 10 MHz cutoff [3] and the FM band. NenuFAR, aimed at act as a large-scale low frequency supplement of LOFAR in the low-frequency range, aimed at fulfilling this need. NenuFAR will be more sensitive than LOFAR for below 35 MHz, which is exactly the frequency range that researchers think with the highest probability of being emitted by most exoplanet systems [9]. NenuFAR is a LF radio telescope currently commissioning at the Nançay Radioastronomy Observatory. It is designed to deliver the most precise observations yet, within the frequency range of 10-85 MHz [20]. Figure 2 shows the detecting range of various instruments, as well as predicted peak emission density and radio flux of extrasolar planets.

#### 3.2. FAST Observation

The FAST radio telescope offers a wide frequency range, including observations down to 70 MHz with full polarization measurements [21]. Comparing FAST's sensitivity with typical flux density during Jovian bursts about 35 MHz (approximately  $40 \mu\text{Jy}$  within a 10 pc range), it is evident that

FAST possesses the capability to detect moderately strong exoplanetary radiations, supplied the emission frequency above 70 MHz, corresponding to sources with magnetic field amplitudes  $> 25$  G emitting cyclotron radiation. As such, FAST is well-suited for searching for SPI emissions, including those from terrestrial planets around white dwarfs, down to moderate intensities. Conversely, emissions from magnetospheric exoplanets are more likely to be targeted by low-frequency radio arrays, such as LOFAR. For the conformity of FAST in the realm of exoplanetary radio searches and studies, the ability to conduct numerous multi-epoch target observations and wide-polarization surveys will be crucial. For instance, encompassing all observable stellar systems within a 10 pc distance, including 200 determined stars and 35 extrasolar planet systems, will be of utmost importance [14]. As shown in Fig. 2, it profits from a contrast window for exoplanet and SPI radio search, complementing the declination range covered by LOFAR and NenuFAR.

#### 4. Limitations and Prospects

In reality, it should be noted that the identification of a radio signal originating from an star-exoplanetary interaction represents just the initial stage in the investigation. Although the planetary emission is estimated to be substantially intense, it is still necessary to ensure that the detected signal produces from the exoplanet itself, instead of its host star. Possible way to address this issue could potentially draw inspiration from the transit method, where the planetary emitted flux will disappear briefly during eclipses. In addition, it becomes necessary to look for periodicity in the observed signal and contrast its period with the rotation period of host star. Furthermore, if available, comparing the detected signal's period with the planetary rotation period can provide valuable insights.

In summary, identifying and characterizing radio signals from exoplanetary systems involves a multi-faceted approach, encompassing not only signal detection but also careful analysis and comparison with various parameters to establish the true origin of the emissions. However, LF radio observations are faced with significant limitations, including strong galactic background luminosity, intense natural and artificial electromagnetic interference. Consequently, current instruments are primarily constrained to detecting star radio bursts that are several orders of magnitude more intense than solar bursts.

While radio exoplanet detection has not yet been used on a large scale, there are reasons for optimism. In the near future, a new astronomical instrument, Square Kilometer Array, is expected to cover a broader range of auroral emissions. SKA is a wide-bound radio telescope boasting an anticipated flux sensitivity of approximately  $10 \mu\text{Jy}$ . It is a remarkable improvement in sensitivity of approximately 30 times compared to LOFAR [22]. SKA will solely analyze frequencies over 50 MHz; however, in certain scenarios, exoplanetary radio emissions are expected to extend to few hundreds MHz which is particularly applicable to young and massive exoplanets [9], making the Square Kilometer Array a highly promising instrument for conducting radio studies of exoplanets.

#### 5. Conclusion

The investigation of radio emissions from exoplanets and the correlation between stars and planets represents a promising and expansive new domain for exploration, with a well-established theoretical framework in place. Taking Jupiter, a celestial body within our solar system with a well-defined magnetic field and radio emission, as a reference point, one infers the potential detection of hot Jupiters and other celestial objects capable of emitting nonthermal radiation in extraterrestrial systems. Human beings have ample evidences to acknowledge the reliability of LOFAR, nenuFAR, SKA, and FAST for exoplanetary observations in the low frequency range. They approximately cover the frequency range of 10-250 MHz. Indeed, there are certain limitations in the equipment conditions currently, such as the need to mitigate radio interference originating from the host star and the Earth's environment, as well as identifying regular periodic variations. The author believes that radio detection remains a promising avenue for exploration. Not only does radio exoplanet detection enable

us to directly analyze the structure and chemical composition of the planets themselves, but it also holds the potential to contribute to the future search for potentially habitable exoplanets.

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