ON THE REQUIRED MASS FOR AN EXOPLANET TO EMIT RADIO WAVES

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Abstract

The detection of radio emission from an exoplanet would constitute the best way to determine its magnetic field. Indeed, the presence of a planetary magnetic field is a necessary condition for radio emission via the Cyclotron Maser Instability. The presence of a magnetic field is, however, not sufficient. At the emission site, the local cyclotron frequency has to be sufficiently high compared to the local plasma frequency. As strong stellar insolation on a low-mass planet can lead to an extended planetary atmosphere, the magnetospheric plasma frequency depends on the planetary mass, its orbital distance, and its host star. We show that an extended planetary atmosphere can quench the radio emission. This seems to be true, in particular, for an important fraction of the planets less massive than approximately two Jupiter masses and with orbital distances below ∼0.2 AU. Most of the best candidates suggested by radio scaling laws lie in this parameter space. Taking this effect quenching into account will have important implications for the target selection of observation campaigns. At the same time, this effect will have consequences for the interpretation of observational data.

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1 Introduction

In the solar system, planets with a magnetic field emit low-frequency, coherent, polarized radio emission via the so-called Cyclotron Maser Instability (CMI, see e.g., Zarka, 1998; Farrell et al., 1999; Ergun et al., 2000; Treumann, 2006). For exoplanets with a sufficiently strong magnetic field, the same type of emission is expected. Such exoplanetary radio emission is expected to be detecable with the latest generation of radio telescopes (see, for example, Grießmeier, 2018; Lazio, 2018; Zarka, 2018).

When setting up observation campaigns, the typical approach is to use the known exoplanetary parameters, and to estimate, planet by planet, the maximum frequency of the emission (based on an estimate of the planet's surface magnetic field strength) and the flux density of the radio emission received at Earth. This basic approach has been used at least since the seminal articles of Zarka et al. (1997) and Farrell et al. (1999). It immediately leads to several criteria which make a planet a potentially detectable source of radio emission: in order to have a maximum emission frequency above the terrestrial ionospheric cutoff, a certain magnetic moment is required; massive planets are more likely to have strong magnetic fields, which leads to better chances to detect their radio emission. Also, close-in planets are frequently assumed to be favorable for radio emission, as their proximity to the star leads to a larger energy flux into the planetary magnetosphere. Assuming that a fixed fraction of that input power is converted to radio power, close-in planets are usually among the favored targets.

Over the years, more accurate planetary parameters have been obtained, approximations have been refined, some models have been added, and other models have been improved. It is in this line of work that the previous implementation of the radio prediction code (Grießmeier et al., 2007) is currently being replaced by the unified exoplanetary radio prediction code PALANTIR (Prediction Algorithm for star-pLANeT Interactions in Radio), which will be at the same time more user-friendly and easier to upgrade in the light of future theoretical work (Mauduit et al., 2023).

As our understanding of planetary radio emissions has grown, and as the number of known planets has literally exploded, the initially simple approximations have not only become more complex, but also include more physical mechanisms. One of the physical effects that has, so far, only been investigated on a case-by-case basis, but which should be investigated in a more systematic way, is the relation between the expected plasma conditions in the vicinity of the planet and the detectibility of that planet via radio emission. Indeed, for low mass planets, strong stellar insolation can lead to an extended planetary atmosphere and thus a high local plasma density. If the plasma density, relative to the cyclotron frequency, is too high, the radio emission is quenched. For higher planetary masses, however, the planetary atmosphere is hydrostatic even for close-in orbits, and radio emission remains possible. This effect will be detailed in Section 2. Section 3 will review previous studies. Based on these studies, Section 4 presents a parameter space where quenching can prevent radio emission from planets which might otherwise be considered good targets. Section 5 closes with concluding remarks and future perspectives.

2 Plasma conditions at the emission source site

Theoretical and observational work has shown that the CMI requires specific plasma conditions to be able to operate. More precisely, for the CMI to operate, the local electron plasma frequency f_p has to be smaller than the local electron cyclotron frequency f_c by a certain factor. Theoretical work suggests a critical ratio of 0.4, i.e. CMI emission can only operate if $f_p/f_c < 0.4$ (e.g., Le Quéau et al., 1985; Hilgers, 1992; Zarka et al., 2001).

In other words, the CMI requires regions of low plasma density and strong magnetic field. This condition is usually assumed to be fulfilled for exoplanets. For example, Grießmeier et al. (2007) stated that the detectability of exoplanets are unlikely to be affected by high plasma density (including both stellar wind plasma and the planetary environment).

However, for extremely close-in planets, specific conditions can arise. Indeed, the upper atmosphere is heated by the high X-ray and extreme ultraviolet flux of the host star. In some cases, this can result in expanded upper atmospheres. In this case, the ionized gas can prevent the generation and/or escape of radio emission. This effect has already been demonstrated by numerical simulations (Daley-Yates & Stevens, 2017, 2018) as well as by analytical calculations (Weber et al., 2017a,b, 2018; Erkaev et al., 2022).

3 Previous case studies

In the literature, only a handful of cases have been studied so far:

- In the case of low mass Hot Jupiters (with a mass similar to that of Jupiter, or less), strong stellar insolation (i.e. close orbital distance), can lead to an extended atmosphere, and planetary radio emission is probably not possible. Weber et al. (2017a,b) show that this is the case, for example, for the exoplanets HD 209458b (with a planetary mass of $0.69\,M_J$) and HD 189733b (with a planetary mass of $1.14\,M_J$). For HD 209558b-like planets, the critical orbital distance (i.e. the orbital distance below which this effect becomes important) seems to be somehere between 0.2 and 0.5 AU.

- For high mass Hot Jupiters, the atmosphere is "compact", i.e. strongly bound to the planet, and radio emission is possible even for planets at close orbital distances. This is the case, for example, for the exoplanet τ Bootis b (with an estimated planetary mass of $5.84\,M_J$), as discussed by Weber et al. (2018).

- The case of υ Andromedae b is particularly interesting. The planet is known from radial velocity observations. As a consequence, the true planetary mass is unknown. Instead, the measurements only yield the projected mass, which serves as a lower limit to the true planetary mass. The planetary mass being unknown, Erkaev et al. (2022) have performed atmospheric models for different values of the planetary mass. They find that no radio emission should be visible if the planetary mass M is lower than $2.25M_J$ (where M_J is Jupiter's mass). On the other hand, planetary radio emission is possible if the planet is more massive, i.e. if $M > 2.25M_J$. This argument can also be turned around: if radio emission is detected from this planet, this would be a strong indication that the planetary mass is $> 2.25M_J$. It should be noted that both τ Bootis and υ Andromedae have been part of recent radio observations using LOFAR (LOw Frequency ARray) and NenuFAR (New Extension in Nançay Upgrading LOFAR) (Turner et al., 2021; Turner et al., 2023).

Clearly, the differences between planets are striking, and a coherent picture seems to start to emerge, which should briefly be compared to the results of the typical approach (which ignores this atmospheric expansion effect). In the simplified approach, a high planetary mass is favorable for radio detection, as it leads to a high maximum emission frequency (as mentioned above, ground-based detection required at least $f_c^{min} = 10$ MHz). The simplified approach also favors close-in planets, where the power input into the magnetosphere is high.

Taking into account the effect of potential quenching by a planetary expanded upper atmosphere, the picture slighty changes. A high planetary mass still is favorable for radio detection (as it decreases the ratio f_p/f_c). In addition, a high planetary mass leads to a more strongly bound planetary atmosphere. Only for a low planetary mass the atmosphere can be extended, and lead to radio quenching. On the other hand, small orbital distances are only favorable within limits: if the orbital distance is below a critical value, the atmosphere becomes highly heated and expands, leading to radio quenching.

4 Parameter space for radio quenching

A detailed case-by-case calculation for each planet is beyond the scope of this work and is left for future work. Here, we estimate for which region in the parameter space spanned by the planetary mass and orbital distance this effect can become important, in the sense that it can prevent the generation of radio emission for otherwise good candidates. First, for the lower mass limit, we note that exoplanets with masses as low as 0.01 Jupiter masses (and sometimes less) are sometimes considered as good candidates for the search for planetary radio emission (Mauduit et al., 2023). In principle, planets considerably less massive will be impacted even more strongly, but they are usually not considered as good candidates for radio emission. We thus adopt $M_{\min} = 0.01M_J$ for our parameter space. Second, based on the case of υ Andromedae b (cf. Section 3, we assume that most planets with a mass above $\sim 2M_J$ are protected against radio quenching, and set $M_{\max} = 2M_J$ for our parameter space. Third, we set a conservative lower limit of 0.2 AU for orbital distances where radio quenching may become important (based on the case of HD209458 b, cf. Section 3). The region delimited by these three criteria is depicted in Figure 1.

Figure 1 shows that these criteria lead to a large parameter space where an extended atmosphere may prevent planetary radio emission (see Figure 1). This parameter space currently includes 780 of the currently know 5332 exoplanets. More importantly, many of the good candidates suggested by radio scaling laws will fall into this parameter space.

In relaity, of course, both parameters are not independent, and the minimum planetary mass required to prevent an extended planetary atmosphere will depend on the orbital distance, which will lead to a more complex shape than that shown in Figure 1. The precise borders of the region in the parameter space spanned by planetary mass and orbital distance that is favorable for planetary radio emission still need to be determined. As additional parameters, this "radio-favorable" region will, also depend on the planetary radius, the stellar mass and the stellar age. This parameter space will be systematically explored in future work.

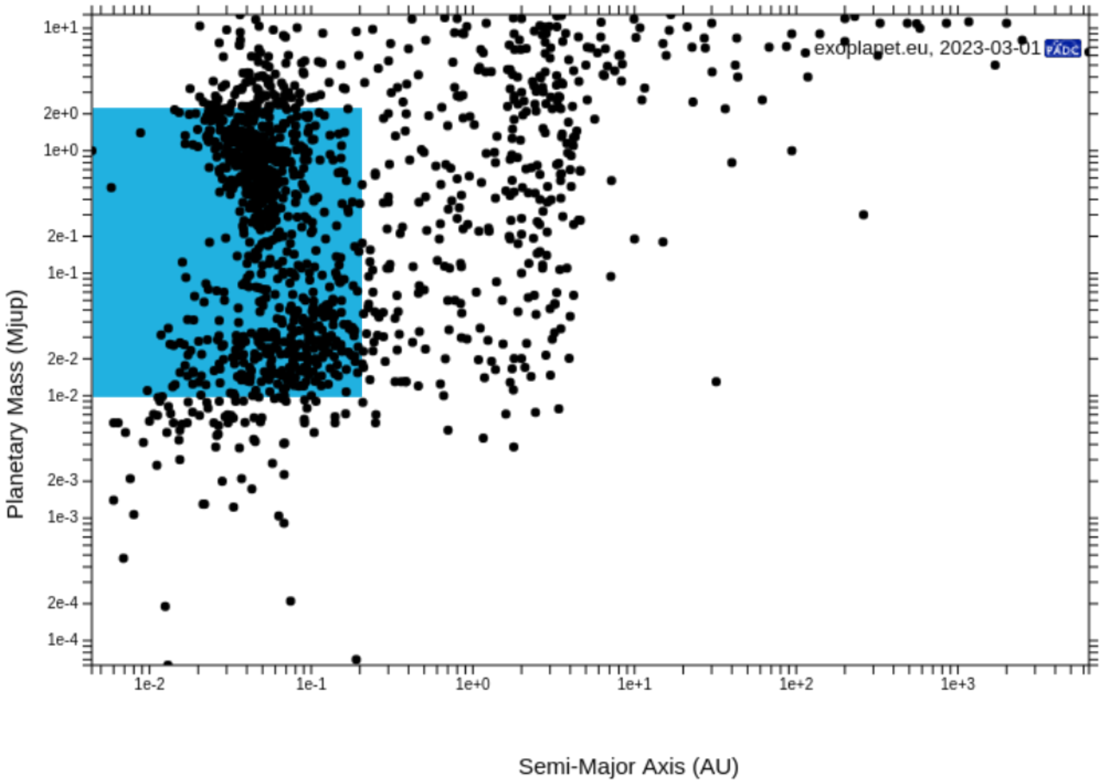

Figure 1: *Known explanets (as of 2023-03-01), based on* `exoplanet.eu` *(Schneider et al., 2011). Blue area: Planets with an orbital distance $d < 0.2$ AU, and a planetary mass M in the range $0.01 < M \leq 2M_J$). In this parameter space, an extended planetary atmosphere could potentially lead to radio quenching.*

5 Perspectives

The importance of the planetary mass for the efficient generation of an intrinsic planetary magnetic field, and thus for the generation of planetary radio emission has long been realized. However, it becomes increasingly clear that a high planetary mass is important for a second reason: with a high mass, the planet can maintain its evaporating atmosphere at close distance, and thus avoid conditions where an extended ionized atmosphere can trap, or quench, the planetary radio emission. The minimum required mass will depend on the planetary orbital distance and the characteristics of its host star.

So far, this effect has only beeen studied for isolated cases. We plan to perform a systematic study of the parameter space that is favorable for the generation and emission of planetary radio emission. We also aim at including this criterion to the radio-prediction and target selection code PALANTIR (Mauduit et al., 2023), which will allow to optimise the target selection for observational campaigns with low frequency radio telescopes, such as the one currently ongoing at NenuFAR (Turner et al., 2023).

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