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Predicting low-frequency radio fluxes of known extrasolar planets

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Close-in giant extrasolar planets ("Hot Jupiters") are believed to be strong emitters in the decametric radio range. We present the expected characteristics of the low-frequency magnetospheric radio emission of all currently known extrasolar planets, including the maximum emission frequency and the expected radio flux. We compare the different predictions obtained with all four existing analytical models for all currently known exoplanets. We also take care to use realistic values for all input parameters. The four different models for planetary radio emission lead to very different results. The largest fluxes are found for the *magnetic* energy model, followed by the *CME* model and the *kinetic* energy model (for which our results are found to be much less optimistic than those of previous studies). The *unipolar interaction* model does not predict any observable emission for the present exoplanet census. Our results show that observations of exoplanetary radio emission are feasible, but that the number of promising targets is not very high. The catalog of targets will be particularly useful for current and future radio observation campaigns (e.g. with the VLA, GMRT, UTR-2 and with LOFAR).

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1. Introduction

In the solar system, all strongly magnetised planets are known to be intense nonthermal radio emitters. For a certain class of extrasolar planets (the so-called Hot Jupiters), an analogous, but much more intense radio emission is expected. In the recent past, such exoplanetary radio emission has become an active field of research, with both theoretical studies and ongoing observation campaigns.

Recent theoretical studies have shown that a large variety of effects have to be considered, e.g. kinetic, magnetic and unipolar interaction between the star (or the stellar wind) and the planet, the influence of the stellar age, the potential role of stellar CMEs, and the influence of different stellar wind models. Until recently, there was no single publication in which all of these aspects are put together and where the different interaction models are compared extensively [1]. The detectability of exoplanetary radio emission will be hampered when the local plasma frequency in the source system is higher than the frequency of the emitted radiation. We have taken this into account by investigating the local stellar wind parameters for every system. It turned out that several planets were impossible to observe for this reason. A complete discussion of these and other issues can be found elsewhere [1].

The first observation attempts go back to 1977 [2] or perhaps even earlier. At the beginning, such observations were necessarily unguided ones, as exoplanets had not yet been discovered. Later observation campaigns concentrated on known exoplanetary systems. So far, no detection has been achieved. A list and a comparison of past observation attempts can be found elsewhere [3]. Concerning ongoing and future observations, studies are performed or planned at the VLA [4], GMRT [5, 6], UTR2 [7], and at LOFAR [8]. To support these observations and increase their efficiency, it is important to identify the most promising targets.

The target selection for radio observations is based on theoretical estimates which come from the prediction of the main characteristics of the exoplanetary radio emission. The two most important characteristics are the maximum frequency of the emission and the expected radio flux. The first predictive studies (e.g., [9, 10]) concentrated on only a few exoplanets. A first catalog containing estimates for radio emission from a large number of exoplanets was presented a few years ago [4]. This catalog included 118 planets (i.e. those known as of 2003, July 1) and considered radio emission energised by the kinetic energy of the stellar wind (i.e. the *kinetic model*, see below). Here, we present a much larger list of targets (i.e. 197 exoplanets found by radial velocity and/or transit searches as of 2007, January 13, taken from http://exoplanet.eu/) and compare the results obtained by all four currently existing interaction models, not all of which were known at the time of the previous overview.

To demonstrate which stellar and planetary parameters are required for the estimate of exoplanetary radio emission, some theoretical results are briefly reviewed (section 2). In section 3, we present our estimations for exoplanetary radio emission. Section 4 closes with a few concluding remarks.

2. Exoplanetary radio emission theory

In principle, there are four different types of interaction between a planetary obstacle and the ambient stellar wind, as both the stellar wind and the planet can either be magnetised or unmagnetised. As was discussed by [11], for three of these four possible situations intense nonthermal radio emission is possible. Only in the case of an unmagnetised stellar wind interacting with an unmagnetised body no intense radio emission is possible.

In those cases where strong emission is possible, the expected radio flux depends on the source of available energy. In the last years, four different energy sources were suggested: a) In the first model, the input power P_{input} into the magnetosphere is assumed to be proportional to the total *kinetic energy* flux of the solar wind protons impacting on the magnetopause [12, 9, 10, 13, 8, 4, 14, 15, 16, 17] b) Similarly, the input power P_{input} into the magnetosphere can be assumed to be proportional to the *magnetic energy* flux or electromagnetic Poynting flux of the interplanetary magnetic field [13, 8, 18, 19, 11]. From the data obtained in the solar system, it is not possible to distinguish which of these models is more appropriate [13] so that both models have to be considered. c) For unmagnetised or weakly magnetised planets, one may apply the *unipolar interaction* model. In this model, the star-planet system can be seen as a giant analog to the Jupiter-Io system [13, 18, 19, 11]. Technically, this model is very similar to the magnetic energy model, but the source location is very different: Whereas in the kinetic and in the magnetic model, the emission is generated near the planet, in the unipolar interaction case a large-scale current system is generated and the radio emission is generated in the stellar wind between the star and the planet. Thus, the emission can originate from a location close to the stellar surface, close to the planetary surface, or at any point between the two. This is possible in those cases where the solar wind speed is lower than the Alfvén velocity [20]. Previous studies have indicated that this emission is unlikely to be detectable, except for stars with an extremely strong magnetic field [13, 18, 19, 11]. Nevertheless, we will check whether this type of emission is possible for the known exoplanets. d) The fourth possible energy source is based on the fact that close-in exoplanets are expected to be subject to frequent and violent stellar eruptions [22] similar to solar coronal mass ejections (CMEs). As a variant to the kinetic energy model, the *CME* model assumes that the energy for the most intense planetary radio emission is provided by CMEs. During periods of such CME-driven radio activity, considerably higher radio flux levels can be achieved than during quiet stellar conditions [16, 17]. For this reason, this model is treated separately. For all models we assume that any unfavourable beaming geometry at some point in time will improve sufficiently after a number of observations.

For the *kinetic energy* case, the input power was first derived by [12], who found that it is given by

$$P_{input,kin} \propto n v_{eff}^3 R_s^2. \tag{2.1}$$

In eq. (2.1), n is the stellar wind density at the planetary orbit, v_{eff} is the velocity of the stellar wind in the reference frame of the planet (i.e. including the aberration due to the orbital velocity of the planet, which is not negligible for close-in planets), and R_s denotes the magnetospheric standoff distance.

The *magnetic energy* case was first discussed by [13]. Here, the input power is given by

$$P_{input,mag} \propto v_{eff} B_{\perp}^2 R_s^2 \tag{2.2}$$

In eq. (2.2), v_{eff} is the velocity of the stellar wind in the reference frame of the planet, $B_{\perp}$ if the component of the interplanetary magnetic field (IMF) perpendicular to the stellar wind flow in the reference frame of the planet, and R_s denotes the magnetospheric standoff distance.

For the *unipolar interaction* case [13], the input power is given by

$$P_{input,unipolar} \propto v_{eff} B_{\perp}^2 R_{ion}^2 \tag{2.3}$$

Eq. (2.3) is identical to eq. (2.2), except that the obstacle is not the planetary magnetosphere, but its ionosphere, so that R_s is replaced by R_{ion}, the radius of the planetary ionosphere.

CME-driven radio emission was first calculated by [16]. In that case, the input power is given by

$$P_{input,kin,CME} \propto n_{CME} v_{eff,CME}^3 R_s^2. \tag{2.4}$$

Eq. (2.4) is identical to eq. (2.1), except that the stellar wind density and velocity are replaced by the corresponding values encountered by the planet during a CME.

A certain fraction ε of the input power P_{input} given by eq. (2.1), (2.2), (2.3) or (2.4) is thought to be dissipated within the magnetosphere:

$$P_d = \varepsilon P_{input} \tag{2.5}$$

Observational evidence suggests that the amount of power emitted by radio waves P_{rad} is roughly proportional to the power input P_{input}, see, e.g., [11]. This can be written as:

$$P_{radio} = \eta_{radio} P_d = \eta_{radio} \varepsilon P_{input} \tag{2.6}$$

As P_d cannot be measured directly, one correlates the observed values of P_{radio} with the calculated (model dependent) values of P_{input}. Thus, one replaces P_{input} by P_{radio} on the left-hand side of the proportionalities given by (2.1), (2.2), (2.3) and (2.4). The proportionality constant is determined by comparison with Jupiter. The analysis of the jovian radio emission allows to define three values for the typical radio spectrum: (a) the power during *average conditions*, (b) the average power during periods of *high activity*, and (c) the *peak power* [21]. In this work, we will use the average power during periods of high activity as a reference value for all four cases, with $P_{radio,J} = 2.1 \cdot 10^{11}$ W.

The radio flux Φ seen by an observer at a distance s from the emitter is related to the emitted radio power P_{radio} by [17]:

$$\Phi = \frac{P_{radio}}{\Omega s^2 \Delta f} = \frac{4\pi^2 m_e R_p^3 P_{radio}}{e\mu_0 \Omega s^2 \mathscr{M}}. \tag{2.7}$$

Here, Ω is the solid angle of the beam of the emitted radiation, and Δf is the bandwidth of the emission. We use $\Delta f = f_c^{max}$ [17], where f_c^{max} is the maximum cyclotron frequency. Depending on the model, P_{radio} is given by eq. (2.1), (2.2), (2.3) or (2.4). The maximum cyclotron frequency f_c^{max} is determined by the maximum magnetic field strength B_p^{max} close to the polar cloud tops [10]:

$$f_c^{max} = \frac{eB_p^{max}}{2\pi m_e} = \frac{e\mu_0 \mathscr{M}}{4\pi^2 m_e R_p^3} \approx 24\,\mathrm{MHz}\,\frac{\widetilde{\mathscr{M}}}{\widetilde{R_p}^3}. \tag{2.8}$$

Here, m_e and e are the electron mass and charge, R_p is the planetary radius, μ_0 is the magnetic permeability of the vacuum, and $\mathscr{M}$ is the planetary magnetic dipole moment. $\widetilde{\mathscr{M}}$ and $\widetilde{R_p}$ denote the planetary magnetic moment and its radius relative to the respective value for Jupiter, e.g. $\widetilde{\mathscr{M}} = \mathscr{M}/\mathscr{M}_J$, with $\mathscr{M}_J = 1.56 \cdot 10^{27}$ Am^2, see [23], and $R_J = 71492$ km.

The radio flux expected for the four different models according to eqs. (2.1) to (2.7) and the maximum emission frequency according to (2.8) are calculated in [1] for all known exoplanets.

PoS(Dynamic2007)007

3. Expected radio flux for known exoplanets

3.1 The list of known exoplanets

Table 1 [1] of [1] shows what radio emission we expect from the presently known exoplanets (13.1.2007). The results of table 1 are visualized in figure 1 (for the *magnetic energy* model), figure 2 (for the *CME* model) and figure 3 (for the *kinetic energy* model). The predicted planetary radio emission is denoted by open triangles (two for each "potentially locked" planet, otherwise one per planet). The typical uncertainties (approx. one order of magnitude for the flux, and a factor of 2-3 for the maximum emission frequency) are indicated by the arrows in the upper right corner. The sensitivity limit of previous observation attempts are shown as filled symbols and as solid lines (a more detailed comparison of these observations can be found elsewhere [18, 3, 24]). The expected sensitivity of new and future detectors (for 1 hour integration and 4 MHz bandwidth, or any equivalent combination) is shown for comparison. Dashed line: upgraded UTR-2, dash-dotted lines: low band and high band of LOFAR, left dotted line: LWA, right dotted line: SKA. The instruments' sensitivities are defined by the radio sky background. For a given instrument, a planet is observable if it is located either above the instrument's symbol or above and to its right. Large differences in expected flux densities are apparent between the different models. On average, the *magnetic energy* model yields the largest flux densities, and the *kinetic energy* model yields the lowest values. The *unipolar interaction* model does not yield any observable emission for the currently known planets. Depending on the model, between one and three planets are likely to be observable using the upgraded system of UTR-2. Somewhat higher numbers are found for LOFAR. Considering the uncertainties mentioned above, these numbers should not be taken literally, but should be seen as an indicator that while observations seem worthwhile, the number of suitable candidates is rather low. It can be seen that the maximum emission frequency of many planets lies below the ionospheric cutoff frequency, making earth-based observation of these planets impossible. A moon-based radio telescope however would give access to radio emission with frequencies of a few MHz [11]. As can be seen in figures 1, 2 and 3, this frequency range includes a significant number of potential target planets with relatively high flux densities.

Figures 1, 2 and 3 also show that the relatively high frequencies of the LOFAR high band and of the SKA telescope are probably not very well suited for the search for exoplanetary radio emission. These instruments could, however, be used to search for radio emission generated by *unipolar interaction* between planets and strongly magnetised stars.

3.2 A few selected cases

According to Table 1 of [1], the best candidates are:

- HD 41004 B b, which is the best case in the *magnetic energy* model with emission above 1 MHz. Note that the mass of this object is higher than the upper limit for planets ($\approx 13 M_J$), so that it probably is a brown dwarf and not a planet.
- Epsilon Eridani b, which is the best case in the *kinetic energy* model.

[1]This table is available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/

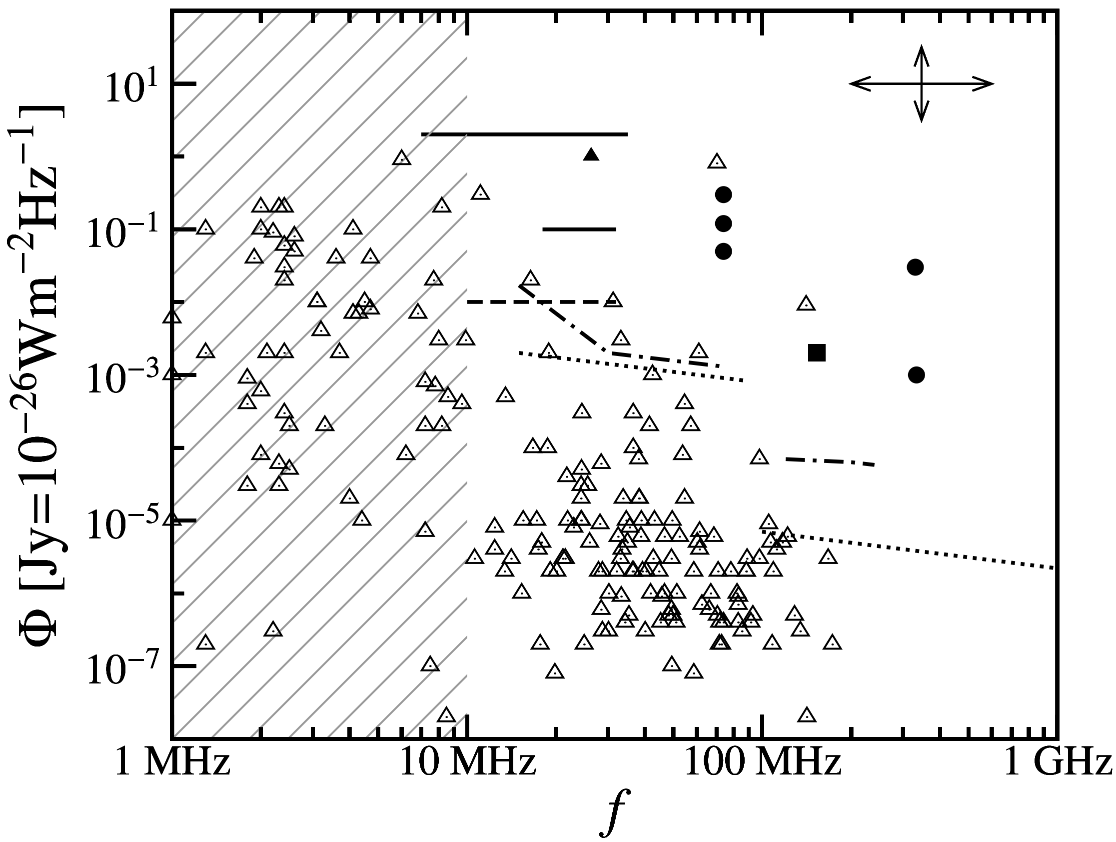

Figure 1: Maximum emission frequency and expected radio flux for known extrasolar planets according to the *magnetic energy* model, compared to the limits of past and planned observation attempts. Open triangles: Predictions for planets. Solid lines and filled circles: Previous observation attempts at the UTR-2 (solid lines), at Clark Lake (filled triangle), at the VLA (filled circles), and at the GMRT (filled rectangle). For comparison, the expected sensitivity of new detectors is shown: upgraded UTR-2 (dashed line), LOFAR (dash-dotted lines, one for the low band and one for the high band antenna), LWA (left dotted line) and SKA (right dotted line). Frequencies below 10 MHz are not observable from the ground (ionospheric cutoff). Typical uncertainties are indicated by the arrows in the upper right corner.

- Tau Boo b, which is the best case in the *magnetic energy* model with emission above the ionospheric cutoff (10 MHz).
- HD 189733 b, which is the best case in both the *magnetic energy* model and in the *CME* model which has emission above 1 MHz.
- Gliese 876 c, which is the best case in the *CME* model with emission above the ionospheric cutoff (10 MHz).
- HD 73256 b, which has emission above 100 mJy in the *magnetic energy* model and which is the second best planet in the *kinetic energy* model.

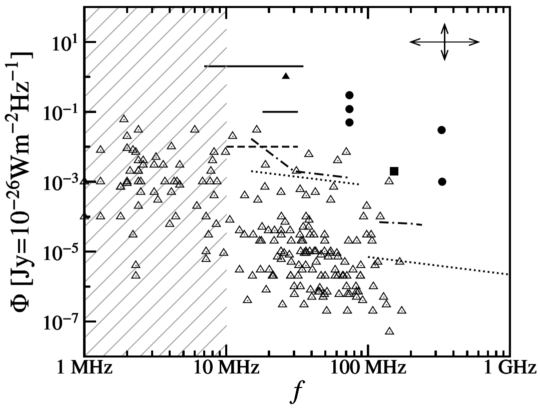

Figure 2: Maximum emission frequency and expected radio flux for known extrasolar planets according to the *CME* model, compared to the limits of past and planned observation attempts. Open triangles: Predictions for planets. All other lines and symbols are as defined in figure 1.

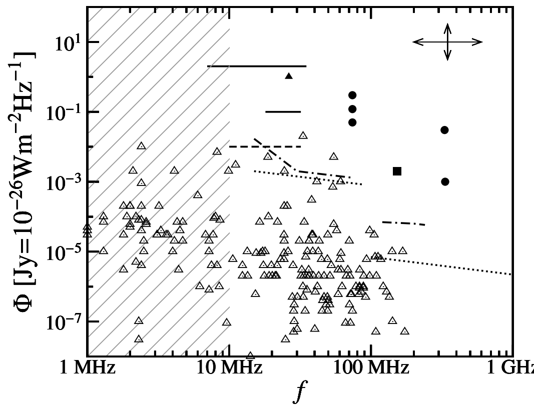

Figure 3: Maximum emission frequency and expected radio flux for known extrasolar planets according to the *kinetic energy* model, compared to the limits of past and planned observation attempts. Open triangles: Predictions for planets. All other lines and symbols are as defined in figure 1.

- GJ 3021 b, which is the third best planet in the *kinetic energy* model.

4. Conclusions

Predictions concerning the radio emission from all presently known extrasolar planets were presented. We compared the results obtained with various theoretical models. Our results confirm that the four different models for planetary radio emission lead to very different results. As expected, the largest fluxes are found for the *magnetic* energy model, followed by the *CME* model and the *kinetic* energy model. The results obtained by the latter model are found to be less optimistic than by previous studies. The *unipolar interaction* model does not lead to observable emission for any of the currently known planets. As it is currently not clear which of these models best describes the auroral radio emission, it is not sufficient to restrict oneself to one scaling law (e.g. the one yielding the largest radio flux). Once exoplanetary radio emission is detected, observations will be used to constrain and improve the model.

These results will be particularly useful for the target selection of current and future radio observation campaigns (e.g. with the VLA, GMRT, UTR-2 and with LOFAR). We have shown that observations seem worthwhile, but that the number of suitable candidates is relatively low. The best candidates appear to be HD 41004 B b, Epsilon Eridani b, Tau Boo b, HD 189733 b, Gliese 876 c, HD 73256 b, and GJ 3021 b. The observation of some of these candidates is in progress.

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