THE INFLUENCE OF STELLAR CORONAL MASS EJECTIONS ON EXOPLANETARY RADIO EMISSION

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Abstract

Radio emission from extrasolar giant planets in close orbits around their host stars constitutes an active field of research, including both observational efforts and theoretical work aiming at reasonable predictions for different target planets. So far, most theoretical work focussed on steady stellar wind conditions. However, as shown by Khodachenko et al. [2005], close-in exoplanets may be under almost constant influence of coronal mass ejections. The implications of such events for the expected radio flux levels are discussed, and the resulting flux levels are compared to those expected for planets around non-flaring stars.

1 Introduction

All strongly magnetized planets in the solar systems are known to be sources of nonthermal radio emission. Although the exact emission mechanism is not fully understood, planetary radio emission is probably based on the cyclotron maser instability [Zarka, 1998]. At frequencies typical for planetary radio emission (up to several tens of MHz), the radio flux of Jupiter exceeds the radio flux of the quiet sun by several orders of magnitude [Grießmeier et al., 2005]. However, it would still be difficult to detect it from outside the solar system. With the LOFAR-detector currently under construction [Kassim et al., 2004], Jupiter-like planets could be detected up to distances of 5 lightyears. Considering that the nearest star to the solar system is 4.2 lightyears away, chances seem low ever to detect radio emission from an extrasolar twin of Jupiter. On the other hand, for extrasolar giant planets in close orbits around their host stars (the so-called "Hot Jupiters"), much higher flux densities are expected [Zarka et al., 1997; Farrell et al., 1999; Zarka et al., 2001; Lazio et al., 2004; Farrell et al., 2004; Stevens, 2005; Grießmeier et al., 2005].

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Stellar coronal mass ejections similar to solar coronal mass ejections (CMEs) are currently being discussed with respect to their influence on extrasolar planets. So far, the discussion has focussed on the possible increase of atmospheric loss caused by CMEs [Khodachenko et al., 2005]. Another possible effect of impacting CMEs is the enhancement of planetary radio emission. This is especially interesting for Hot Jupiters.

In this work we will extend the radio flux estimations of Grießmeier et al. [2005], which deal with average stellar wind conditions. We will consider conditions typical for CMEs, i.e. enhanced particle velocity and density, taking these parameters from Khodachenko et al. [2005]. One of the most promising candidate for radio detection is τ Bootes b [Stevens, 2005; Grießmeier et al., 2005]. Using this planet as an example, we will discuss the expected influence of CMEs on planetary radio emission.

This paper is organised as follows: Section 2 reviews important parameters typical for coronal mass ejections. In Section 3, planetary radio emission connected to coronal mass ejections is discussed, first for the solar system (Section 3.1), and then for extrasolar planetary systems (Section 3.2). The radio flux expected for a CME situation is compared to the radio flux connected to a steady stellar wind in Section 3.3. Section 4 closes with a few concluding remarks.

2 Stellar coronal mass ejections

2.1 Density and velocity

In this section, typical properties for coronal mass ejections are presented. The dependence of the *average* CME density n and of the *average* CME velocity v on the substellar distance d is presented.

The current knowledge on CMEs exclusively comes from the study of the Sun. The observational data on CMEs are related to two spatial domains: the near-Sun region (up to 30 solar radii, or about 0.14 AU) remote-sensed by coronagraphs; and the outer region, including the geospace and beyond, where in-situ observations are made by spacecraft. Significant impact in this study has been made by the Large Angle and Spectrometric Coronagraph (LASCO) on board of ESAs Solar and Heliospheric Observatory (SoHO), which observed more than 8000 CMEs since January 1996 [Yashiro et al., 2004]. Accumulated observational material allows to perform extensive statistical studies of the solar eruptive phenomena and draw conclusions on the main characteristics of CMEs. To connect the results of remote estimations of the CME parameters near the Sun ($<$ 0.14 AU) with those measured in-situ at distances $>$ 0.4 AU, Khodachenko et al. [2005] give two typical, interpolated limiting cases, denoted as *weak* and *strong* CMEs, respectively. These two classes have a different dependence of the (average) density on the distance to the sun d. In the following, these quantities will be labeled $n^w(d)$ and $n^s(d)$, respectively. For weak CMEs, the density $n^w(d)$ behaves as follows:

$$n^w(d) = n_*^w \left(d/d_*\right)^{-2.31} \tag{1}$$

where the density at $d_* = 1$ AU (astronomical unit) is given by $n_*^w = 4.88 \cdot 10^6$ m^{-3}.

For strong CMEs, Khodachenko et al. [2005] find:

$$n^s(d) = n^s_* \, (d/d_*)^{-2.99} \tag{2}$$

with $n^s_* = n^s(d = d_*) = 7.1 \cdot 10^6 \ \mathrm{m}^{-3}$, and $d_* = 1$ AU.

As far as the CME velocity is concerned, one finds that individual CMEs can have very different values for v. However, the *average* CME velocity v is approximately independent of subsolar distance, and is similar for both types of CMEs:

$$v^w = v^s = v = 5.26 \cdot 10^5 \, \mathrm{m/s}. \tag{3}$$

For the planet τ Bootes b at an orbital distance of 0.0489 AU, this results in a CME density in the range $5.2 \cdot 10^9 \ldots 5.9 \cdot 10^{10}$ m^{-3} and a CME velocity of $5.26 \cdot 10^5$ m/s.

2.2 Occurrence rate and solar-stellar analogy

In the solar system, CMEs impact the planets in a discrete way. For close-in extrasolar planets, however, Khodachenko et al. [2005] find that CME-planet collisions can be expected to happen much more frequently. When the CME production rate of a star exceeds a critical value (i.e. $f_{CME} > f^c_{CME}$), its close-in planets can be considered to be under continuous action of CMEs. In this case the speed and density of the stellar wind around the planet will be in fact the CME speed and density. Taking into account the angular size of CMEs, Khodachenko et al. [2005] find that $f^c_{CME} \approx 10$ day^{-1}, which is not much higher then the present-day Sun value in the activity maximum ($f_{CME} \sim 6...8$ day^{-1}). Note that while many CMEs do not reach 1 AU, all CMEs reach the orbit of Hot Jupiters. Thus, for Hot Jupiters around CME active stars, CMEs will continuously superpose the stellar wind.

In this work, the so-called solar-stellar analogy is important. It is based on the assumption that the same underlying mechanisms as in the Sun are responsible for observed stellar phenomena. The apparent association between solar CMEs and flares suggests that there is a physical link between them. However this physics is yet poorly known. Recent studies on temporal correspondence between CMEs and flares provide arguments in favor of the so-called common-cause scenario, according to which flares and CMEs are different manifestations of the same large scale magnetic process on the star [Zhang et al., 2001]. For this reason, it can be definitely stated that an intensive flaring activity of a star should be accompanied by an increased rate of CME production. Since the parameters of the stellar wind near a distant star are not known very well, we cannot get any precise values for the speed and acceleration of CMEs at particular distances from the star. The same is true for the density of the extra-solar CME material. For that reason, keeping in mind that physical mechanisms responsible for the initiation and propagation of CMEs should not be very different for different stars, we assume that the extra-solar CME parameters lie within certain boundaries (maximum/minimum), which seem reasonable in view of the similarity assumptions between the Sun and other stars.

3 Planetary radio flux

3.1 Planetary radio emission in the solar system

From the solar system, a direct connection between emitted planetary radio flux and CMEs is known to exist. Prangé et al. [1993] found indications that an event of very strong DAM-emission (at a level observed only a few times every year) was triggered by a solar wind disturbance created by a CME. Similarly, Gurnett et al. [2002] found strong HOM radiation triggered by an interplanetary shock observed by the spacecraft Cassini and Galileo. The peak of emitted intensity occurred around the time when the solar wind density reached its maximum.

At the same time, it is known that different types of planetary radio emission correlate well with solar wind parameters [Zarka 1998, and references therein]. Especially the correlation with solar wind ram pressure as found, e.g., by Desch and Rucker [1983] and Barrow and Desch [1989] is of interest in this context. In the following, we assume that the increased radio flux during a CME is simply caused by the increased ram pressure. Taking the velocity and density of a CME from Section 2.1, the increase of exoplanetary radio flux during a CME will be calculated in Section 3.2.

3.2 Exoplanetary radio emission under CME action

It is clear that the radio emission of a planet in an extrasolar planetary system can differ considerably from Jupiter's radio emission. Extrasolar planets in close orbits arount their host star probably have much smaller magnetic moments. This results from tidal locking, see Grießmeier et al. [2004]. Also, these planets will experience a much denser stellar wind. Both these effects have a strong influence on the *average* radio flux. The even higher plasma densities of CME events, on the other hand, determine the *peak* flux of a close-in planet, and the high number of CMEs gives the frequency of its occurrence. For active stars, the CME-dominated peak radio flux may even replace the average radio flux. For slightly less active stars, strong intensity variations can be expected.

The energy emitted in the radio range is estimated in the following way: the energy input P_{input} into the planetary magnetosphere is proportional to the total kinetic energy of all stellar wind particles hitting the magnetopause. Also, the amount of energy emitted by radio waves P_{rad} is assumed to be proportional to the energy input P_{input}. This argumentation was first used to estimate the radio flux of the planet Uranus in the solar system [Desch and Kaiser, 1984]. Later, it was used to predict the radio flux of extrasolar planets [Zarka et al., 1997; Farrell et al., 1999; Zarka et al., 2001; Farrell et al., 2004; Lazio et al., 2004; Stevens, 2005; Grießmeier et al., 2005]. An alternative to this *kinetic energy* model was suggested by Zarka et al. [2001, 2006]: in this case, the energy input is dominated by *magnetic energy* flux.

As mentioned above, we will apply the kinetic energy model to the situation where the energy input is determined by CMEs rather than the steady stellar wind. In that case, the total emitted radio power P_{rad} and the resulting flux density Φ_s are given by:

$$P_{\text{rad}} = \left(\frac{\mathcal{M}}{\mathcal{M}_J}\right)^{2/3} \left(\frac{n}{n_J}\right)^{2/3} \left(\frac{v}{v_J}\right)^{7/3} P_{\text{rad},J} \tag{4}$$

$$\Phi_s = \frac{8\pi^2 m_e R_p^3 P_{\text{rad}}}{e\mu_0 \Omega s^2 \mathcal{M}}. \tag{5}$$

Here, $\mathcal{M}$ corresponds to the planetary magnetic moment and n and v denote the stellar wind/CME density and velocity. $\mathcal{M}_J$, n_J, and v_J denote the corresponding values for Jupiter, with $\mathcal{M}_J = 1.5 \cdot 10^{27}$ Am^2, $n_J = 3.7 \cdot 10^5$ m^{-3}, and $v_J = 400$ km s^{-1}. P_{rad} is the radio flux emitted by Jupiter and is calculated from Zarka et al. [2004]. In the following, the average radio power during periods of high activity is used, with $P_{\text{rad}} = 2.1 \cdot 10^{11}$ W. Furthermore, m_e and e are the electrons mass and charge, μ_0 is the vacuum permeability, R_p is the radius of the planet, Ω is the solid angle of the beam, and s is the distance of the stellar system from the observer (15.6 parsec for τ Bootes). As in Grießmeier et al. [2005], $\Omega = 1.6$ is adopted, and the magnetic moment for the planet around τ Bootes is taken to be between 0.5 and 2.7 $\mathcal{M}_J$. Equations (4) and (5) correspond to eq. (10) and (14) of Grießmeier et al. [2005]. In contrast to that work, eq. (4) avoids the assumption that the density falls off as $n = n_0/d^2$.

As was discussed in section 2, “Hot Jupiters” are expected to be subject to frequent and violent CME-like events. Both the CME velocity and the CME density are higher than the respective quantitites for the stellar wind (see Table 1). Equations (4) and (5) clearly show that higher values for n and v lead to higher radio power P_{rad} and to higher flux densities Φ_s at the detector.

3.3 Radio emission driven by stellar wind and CMEs: Comparison

In Section 2, it was shown that highly different values are expected for the density and velocity of the plasma interacting with an extrasolar magnetosphere for the case of a CME when compared to the interaction with the steady stellar wind. Here, we finally compare the expected radio flux for radio emission driven by CMEs with the flux of stellar wind driven planetary radio emission.

Table 1 shows the emitted radio power P_{rad} and the flux densities Φ_{AU} (normalized to 1 AU) and Φ_s (for a distance of 15.6 parsec) for both cases: (left) stellar wind driven radio emission (corresponding to Grießmeier et al. [2005]) and (right) magnetospheric radio emission driven by a strong stellar coronal mass ejection.

In Figure 1, the lower limits for the expected planetary radio flux (corresponding to the upper limit of 2.7 $\mathcal{M}_J$ for the planetary magnetic moment, see Grießmeier et al. [2005]) are compared: a) radio emission driven by the stellar wind, and b) radio emission driven by a strong CME. One can clearly see that for a close-in extrasolar planet around a star of 4.6 Gyr age[1], radio emission driven by a CME is much stronger than stellar wind driven

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[1] Note that this does not correspond to the true age of the τ Bootes system, which is given as 1 Gyr by Fuhrmann et al. [1998]. Thus, in fact, we compare with a 4.6 Gyr old τ Bootes-b-*like* planet.

τ Bootes b	stellar wind (4.6 Gyr)	strong CME
$v(t)$ (velocity) [km/s]	400	526
$n(t)$ (density) [m^{-3}]	$4.2 \cdot 10^{9}$	$5.9 \cdot 10^{10}$
P_{rad} (emitted radio power) [W]	$0.69 \cdot 10^{14} \ldots 2.1 \cdot 10^{14}$	$0.76 \cdot 10^{15} \ldots 2.3 \cdot 10^{15}$
Φ_{AU} (flux density at 1 AU) [Jy]	$4.1 \cdot 10^{10} \ldots 9.7 \cdot 10^{10}$	$4.5 \cdot 10^{11} \ldots 10.7 \cdot 10^{11}$
Φ_s (flux density at dist. $s = 15.6$ pc) [Jy]	$0.0039 \ldots 0.0093$	$0.043 \ldots 0.10$
$f_c^{\max}$ (maximum frequency) [MHz]	$6.7 \ldots 19$	$6.7 \ldots 19$

Table 1: Comparison of stellar wind triggered radio emission with stellar coronal mass ejection triggered radio emission.

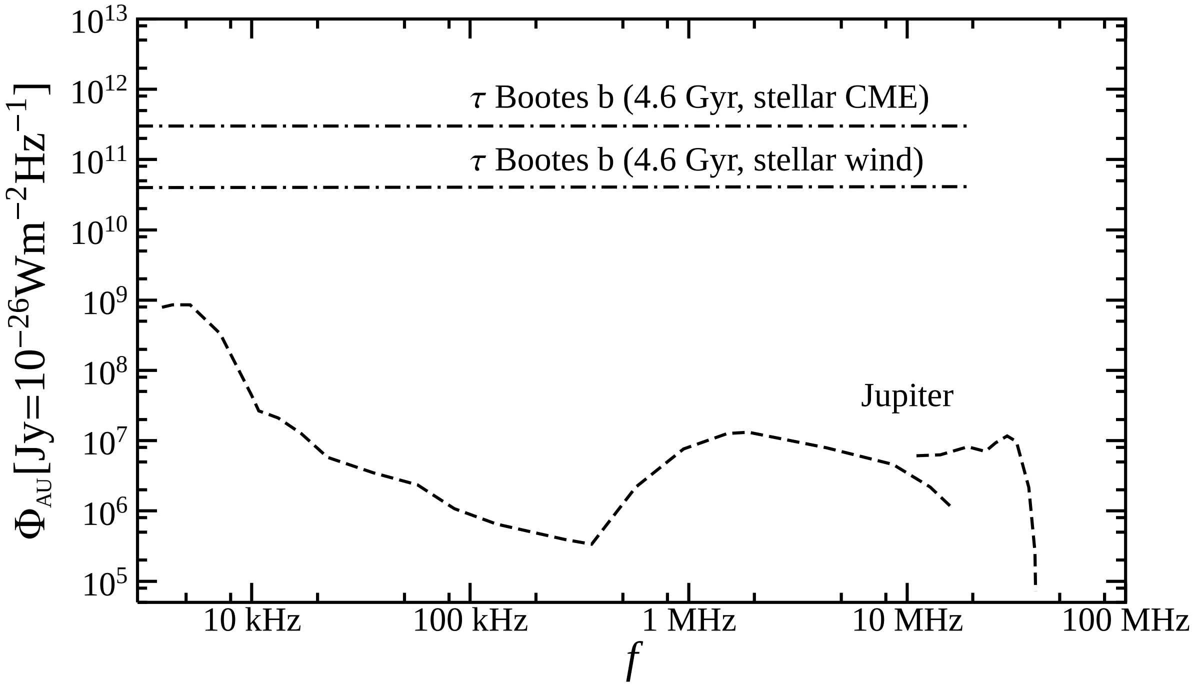

Figure 1: Radio flux expected for a planet like τ Bootes b around a 4.6 Gyr old star. Both the radio flux energized by the steady stellar wind and that triggered by CME-like stellar coronal mass ejections are compared to the radio flux observed from Jupiter as given by Zarka et al. [1995, 2004]. Note that all values are normalized to a distance of 1 AU.

radio emission. In the case presented here, both types of emission differ by a factor of 10. The comparison shows that radio emission driven by CMEs is considerably stronger than stellar wind-driven radio emission. This effect becomes even more pronounced when the dependence of the stellar wind velocity on the stellar distance is taken into account [Grießmeier et al., 2005b].

The radio fluxes Φ_s from Table 1 can also be compared to the detection limit of the planned LOw Frequency ARray LOFAR [Kassim et al. 2004], which will go into operation in 2007-2008. According to the modified instrument design plans, LOFAR will only include frequencies above 30 MHz (instead of the previously planned 10 MHz) with a sensitivity of approximately 2 mJy, see `http://www.lofar.org`. This frequency is above the expected maximum emission frequency for τ Bootes b, see Table 1. Thus, because of the modified frequency range, the detection of planetary radio emission by this instrument is uncertain.

At the UTR-2 radio array, the sensitivity will soon be improved using a new digital receiver. With the capability of the UTR-2 array to observe at low frequencies (ca. 10-35 MHz), it seems possible to detect radio emission of extrasolar planets in the near future.

4 Conclusion

The influence of coronal mass ejections on exoplanetary radio emission was studied. It was shown that stellar coronal mass ejections may trigger much stronger radio emission than the steady stellar wind.

This confirms that, when expected radio fluxes are calculated for different planets, not only the planetary parameters have to be considered. Stellar parameters like the age of the stellar system [Grießmeier et al., 2005] and the measured stellar coronal activity [Stevens, 2005] can be used to deduce the stellar mass loss rate, which in turn has a strong influence on the expected radio flux. This study shows that in addition to these parameters, the CME-activity of the star is also an important parameter and should be considered when establishing target lists for observations of extrasolar planets in the radio frequency domain.

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