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Emission of cyclotron radiation by interstellar planets

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ABSTRACT

In the solar system all planets that have significant magnetic fields also emit electron cyclotron radiation, usually near the auroral regions around the magnetic poles. In this study we use scaling laws based on solar system data to estimate the power and frequency of the auroral cyclotron emissions from interstellar planets (or sub-brown dwarfs). The emission can be powered either by motion of the planet through the interstellar plasma or by unipolar induction due to a moon. According to our results, in interstellar space the unipolar induction mechanism is potentially more effective than the motional emission mechanism. Typical emission power is around 10^{10}–10^{12} W, but significantly stronger emissions are obtained in the most optimistic estimates. We have to conclude that detection of a rogue Jupiter would be very difficult, if not impossible with the radio telescopes available now or in the near future, but in very favorable conditions a much more massive and rapidly rotating (or otherwise strongly magnetized) gas giant with a large nearby moon could be detected up to ~ 57 pc distance with the square kilometer array. There may be a few thousand large enough interstellar planets this close to the solar system. For reference, we point out that according to previous studies some known hot Jupiters are expected to emit up to 10^{14}–10^{16} W of cyclotron radiation, orders of magnitude more than the typical interstellar planets discussed here. However, these emissions have not yet been detected.

1. Introduction

In the solar system all planets that have significant magnetic fields also emit electron cyclotron radiation, usually near the auroral regions around the magnetic poles (e.g. Zarka, 1998). Frequency and power of the emission depend on the characteristics of the planetary magnetic field and its interaction with the surrounding plasma. Theoretical estimates, based on semi-empirical scaling laws observed in the solar system, have been made for emissions from exoplanets orbiting main sequence stars (Farrell et al., 1999; Lazio et al., 2004; Grießmeier et al., 2007; Zarka, 2007) and white dwarfs (Willes and Wu, 2005). These radio sources have not yet been detected (Bastian et al., 2000; Zarka, 2007), but new facilities for low frequency radio astronomy increase the likelihood significantly (Farrell et al., 2004).

In this study we apply the same scaling laws to estimate the strength of cyclotron emission from interstellar planets or sub-brow dwarfs, that do not orbit any star. In the following we use the term "interstellar planet" for any object below $\sim 13M_J$ (Jupiter mass), whether they are kicked out from stellar systems (e.g. Papaloizou and Terquem, 2001) or formed in interstellar space (Boss, 2001). Due to their small size, lack of reflected light and weak thermal emission, interstellar planets are difficult to detect. Direct optical or infra-red imaging (e.g. Zapatero Osorio et al., 2000; Lucas and Roche, 2000; Luhman et al., 2005) is limited to hot (young) planets, while gravitational microlensing (e.g. Han et al., 2004) would give only one-time signal from each detected object. Detection of auroral radio emission would complement these observations by giving direct information about the planet's magnetic field, rotation rate and plasma environment.

In interstellar space the energy source for auroral cyclotron emission is either (1) motion of the planet through the surrounding plasma or (2) unipolar induction by moons moving through the co-rotating magnetospheric plasma, like Io in the Jovian system (e.g. Zarka, 2007). The first option is analogous to the stellar wind flowing past planetary magnetospheres, while emission from the unipolar induction mechanism we assume to be independent of the external environment.

In the solar system Jupiter is the strongest emitter of auroral cyclotron radiation, with 10^{10}–10^{11} W in frequencies < 40 MHz, and in the decameter range it is approximately as bright as solar radio bursts (Zarka, 1998, 2007). For reference, a hot Jupiter orbiting close to its parent star could emit as much as 10^{14}–10^{16} W in frequencies up to ~ 200 MHz (Lazio et al., 2004; Farrell et al., 2004; Grießmeier et al., 2007).

In the following sections we first review selected scaling laws for the magnitude of the planetary magnetic dipole moment, size of the magnetosphere and conversion of kinetic or magnetic energy flux into cyclotron radiation. We then discuss the aspects of radio emission from planetary motion and from unipolar induction in separate sections. At the end of the article we

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consider the possibility of detecting radio emission from interstellar planets with present or planned radio telescopes.

2. Scaling laws

In this section we present some simple scaling laws for estimating power and frequency of the auroral cyclotron emission in various situations. These calculations should be considered as order-of-magnitude estimates, rather than exact derivations.

2.1. Size of the magnetosphere

The characteristic size of a planetary magnetosphere can be derived from pressure balance in the bow direction. For example, Arridge et al. (2006) study the size and shape of Saturn's magnetosphere, while Petrinec and Russell (1997) discuss different cases of pressure balance at planetary magnetopauses. We determine the characteristic size from relation

$$p_{ms} = p_{dyn} + p_{mag} + p_{ther}, \tag{1}$$

where magnetospheric pressure p_{ms} must match the dynamic, magnetic and thermal pressure of the external plasma. Inside the magnetosphere magnetic pressure is much larger than the thermal pressure (see, e.g. Russell, 2001), but in the interstellar plasma all three pressures may have similar magnitude.

The magnetospheric pressure is caused by the planetary dipole field and field generated by magnetopause currents. Together these give pressure (Grießmeier et al., 2004)

$$p_{ms} \approx \frac{\mu_0 f_0^2 \mathcal{M}^2}{8\pi^2 R_{mp}^6}, \tag{2}$$

where $\mathcal{M}$ is the magnetic dipole moment, R_{mp} the magnetopause distance and $f_0 \approx 1.16$ an empirical form factor. We ignore the effects of internal magnetospheric currents, which may increase the magnetopause distance significantly (up to 10 s of planetary radii at Jupiter, Russell, 2001). The dynamic, magnetic and thermal pressures of the external plasma are

$$p_{dyn} = n_e m_p V^2,$$

$$p_{mag} = \frac{B^2}{2\mu_0},$$

$$p_{ther} = 2 n_e k_B T. \tag{3}$$

We have to specify the temperature T, magnetic field and electron number density n_e, as well as the speed V of the interstellar planet. In the expressions for p_{dyn} and p_{ther} we assume that the plasma consist of ionized hydrogen.

2.2. Motional energy flux and emission efficiency

We estimate the energy flux to the magnetosphere simply as

$$F_* = \pi R_{mp}^2 V p_*, \tag{4}$$

separately for the dynamic, magnetic and thermal pressure components. The input energy is consumed in particle acceleration and ionospheric Joule heating or leaves through the tail (e.g. Koskinen and Tanskanen, 2002). A fraction of the kinetic energy of accelerated electrons is converted into coherent radiation by the cyclotron maser mechanism, usually in the acceleration regions above the auroral ionosphere (Zarka, 1998). We write the total emitted power as

$$P_{emit} = \alpha F_{dyn} + \beta F_{mag} + \gamma F_{ther}, \tag{5}$$

where α, β and γ are conversion efficiencies for the different types of input energy. According to Zarka et al. (2001) reasonable estimates based on solar system data are $\alpha = 10^{-6} \ldots 10^{-5}$ and $\beta = 10^{-3} \ldots 10^{-2}$, while Farrell et al. (2004) suggest $\beta = 10^{-2} \ldots 10^{-1}$. Zarka et al. (2001) point out that in the planet–solar wind interaction we cannot reliably distinguish which energy source, dynamic or magnetic, is really driving the cyclotron emission. However, in the unipolar induction case (planet–moon interaction) magnetic energy flux is dominant due to the small magnetospheric plasma density (Zarka, 2007). Conversion efficiency for the thermal energy flux is not really known, as it is not important in the solar system, so we assume $\gamma = 0$.

2.3. Emission due to a moon

In the unipolar induction mechanism movement of a moon across the planetary dipole field converts magnetic energy into kinetic energy of accelerated particles and thereof into cyclotron radiation. We follow Zarka (2007) and write the emitted cyclotron power as

$$P_{emit} = \beta p_{dip} \Delta V \pi R_{eff}^2, \tag{6}$$

where the conversion efficiency β is the same as in Eq. (5). Pressure due to the planets dipole field is approximately

$$p_{dip} = \frac{\mu_0 \mathcal{M}^2}{32\pi^2 r^6}, \tag{7}$$

where r is the mean orbital radius. We assume that the magnetospheric plasma co-rotates with the planet up to 10 s of planetary radii, as in the Jovian and Kronian systems (Russell, 2001). Further assuming that the moon orbits in the planet's rotation direction, the speed difference between the moon and the magnetospheric plasma is

$$\Delta V = \left| \sqrt{\frac{GM}{r}} - \omega r \right|, \tag{8}$$

where M is the mass of the planet and ω its angular rotation frequency. The effective radius R_{eff} is either radius of the solid surface or, if the moon has significant atmosphere or magnetic field, the exospheric or magnetospheric radius (Zarka, 2007).

2.4. Magnetic dipole moment

In order to explore the possible range of the magnetic dipole moment $\mathcal{M}$, we would like to estimate it from the mass and rotation period of the planet. Farrell et al. (1999) and Grießmeier et al. (2004) discuss several different scaling laws of the form

$$\mathcal{M} \propto M^a \omega^b, \tag{9}$$

where the exponents vary in the range $a = 1 \ldots 2$ and $b = 0.5 \ldots 1$. Perhaps a more reliable estimate could be obtained by solving parameters of the dynamo region from an equation of state as done by Grießmeier et al. (2007), but for the sake of simplicity we will use Eq. (9), with exponents $a = 1.5$ and $b = 0.75$ in the middle of the plausible range. We normalize the scaling law to Jupiter, so that

$$\mathcal{M} = 1.5 \times 10^{27} \left(\frac{M}{M_J}\right)^{1.5} \left(\frac{\omega}{\omega_J}\right)^{0.75} \text{A m}^2. \tag{10}$$

2.5. Oblateness

Oblateness is defined in terms of the equatorial (R_{eq}) and polar (R_p) radius as

$$\eta = \frac{R_{eq} - R_p}{R_{eq}}. \tag{11}$$