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THE ELECTROMAGNETIC INTERACTION OF A PLANET WITH A ROTATION-POWERED PULSAR WIND: AN EXPLANATION TO FAST RADIO BURSTS

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Abstract. The pulsars PSR B1257+12 and PSR B1620-26 are known to host planets, and other pulsars are suspected to host asteroids or comets. We investigate the electromagnetic interaction of a relativistic and magnetized pulsar wind with a planet or a smaller body in orbit. Many models predict that, albeit highly relativistic, pulsar winds are slower than Alfven waves. In that case, a pair of stationary Alfven waves, called Alfven wings (AW), is expected to form on the sides of the body. They form a magnetic wake into the plasma flow, and they carry a strong electric current. The theory of Alfven wings was initially developed in the context of the electrodynamic interaction between spacecraft and the Earth's magnetosphere, and then of the Io-Jupiter interaction. We have extended it to relativistic winds, and we have studied the possible consequences on radio emissions from pulsar companions. We predict the existence of very collimated radio beams that are seen by an observer as very rare and brief signals. But they are intense enough to be observed from sources at cosmological distances. Thus they could be an explanation to fast radio bursts (FRB). We discuss the properties (polarisation, recurrence) that could make the difference between this model of FRB and others.

Keywords: pulsar, exoplanet, white dwarf, asteroid, magnetosphere, radio emission, Lorimer burst, fast radio bursts, radio transients, Alfvén wings

1 Introduction

Fast radio bursts (FRB) are highly transient events composed of a single radio burst lasting, at a given frequency, a few milliseconds (Lorimer et al. 2007; Keane et al. 2011; Thornton et al. 2013). As pulsar signals, FRB are dispersed in the time-frequency plane due to propagation, but their dispersion measures (DM) are so large that, if interpreted in terms of interstellar and intergalactic electron densities, they correspond to sources at cosmological distances of up to several Gpc ! This is very unlike usual pulsar signals that comme from our galaxy or its close neighbours. At odds with perytons (at first glance similar signals but identified as of terrestrial origin since their first observations), the question of FRB's origin is still open. They could result from flare stars in our galaxy or cataclysmic events, GRBs, Neutron Star mergers, very young pulsars in SuperNova Remnants, all in remote galaxies. If FRB are caused by cataclysmic events, they should happen only once for a given source. For flare stars and young SNR models, FRB would be irregularly repeatable. We propose a model that implies that FRB are periodic. This model considers FRB as a result of the interaction of pulsars and companions orbiting them.

2 Radio emissions by pulsar companions

Pulsars have companions: planets, asteroids, white dwarfs. White dwarfs orbit most millisecond pulsars (Savonije 1987). Their orbital period is typically a few days or weeks (see ATNF database). Among the five known pulsar planets, the orbital periods range from 2.2 hr to a few weeks, and $\sim$ 100 yr for the most distant (Wolszczan & Frail 1992; Thorsett et al. 1993; Bailes et al. 2011). Asteroid belts are also suspected in the vicinity of PSR B1937+21 (Shannon et al. 2013) and PSR 1931+24 (Mottez et al. 2013).

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All these companions are in the pulsar wind. A pulsar wind is an ultra-relativistic plasma flow of unknown density, flowing along the radial direction ($v_W \sim v_r$), with a Lorentz factor that might possibly reach $\gamma_{wind} \sim 10^6$. At least at close distances, a pulsar wind has a magnetic energy density larger than the kinetic energy density of the plasma: $B^2 >> \mu_0 \rho \gamma c^2$ (Michel 1969; Bucciantini et al. 2006). In that case, the Alfvén speed is larger than the plasma speed ($V_A > v_W$), although both velocities are close to c (Mottez & Heyvaerts 2011b). This could be true at the companion's distance, in which case the companion is not shielded behind a shock wave, but is instead in direct contact with the pulsar wind. Then two stationary Alfvén waves called Alfvén wings (AW) are attached to the companion, in the same way as a wake is attached to the rear of a boat on the sea (Neubauer 1980) (see Fig. 1). The AW is fed by a continuous circulation of electric current $I_{AW} \sim 4(E_0 - E_i)R_P/\mu_0 c$. For a pulsar of period $P = 1$s and an Earth-like planet at 0.2 AU, $I_{AW} \sim 10^{11}$ A. For comparision, the Goldreich-Julian current, that is the engine of pulsar magnetic activity, is $I_{GJ} = 2 \times 10^{11}$ A. Because of the high intensity of the AW currents, we can expect powerful radiative processes. For a millisecond pulsar ($P = 10$ ms), $I_{AW} \sim 10^9$ A, which is still considerable (Mottez & Heyvaerts 2011b). Such a current, crossed with the pulsar wind magnetic field, should cause orbital drifts of low mass (asteroid-like) companions (Mottez & Heyvaerts 2011a). Whatever the size of the companion, these currents are also expected to be sources of instabilities and radio waves.

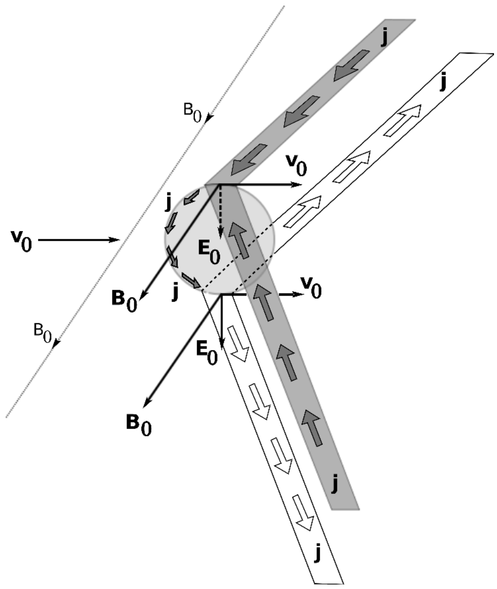

Fig. 1. Schematic view of an unipolar inductor. The unperturbed wind's magnetic field $\vec{B}_0$ and velocity $\vec{v}_0$ are almost, but not exactly, perpendicular. The electric field $\vec{E}_0$ created by the unipolar inductor is perpendicular to these two vectors; it induces an electric current (of density $\vec{j}$) along the body. This current then escapes into the surrounding plasma, forming two structures, each of them consisting of an outwards and an inwards current flow. These currents are unstable to CMI and are the source of radio waves. The angles between radio wave vectors and the current densities $\vec{j}$ mostly depend on the wind Lorentz factor γ_{wind}. When $\gamma_{wind} >> 10^3$, they become extremely narrow $\sim 1/\gamma_{wind}$.

Alvén wings do exist. The satellites Io and Ganymede have AW caused by their interaction with the rotating magnetosphere of Jupiter in which they orbit (Neubauer 1980; Saur et al. 2004). These AW have been studied with the Pioneer and Galileo spacecraft. They intersect the surface of Jupiter, contrary to what we expect with the AW of pulsar companions. It has been shown that the AW of Io and Ganymede generate auroras on Jupiter, that are signatures of plasma acceleration. Alfvén wings are also powerful sources of decametric radio waves triggered by the Cyclotron Maser Instability (CMI) (Mottez et al. 2010). The CMI is an instability that is favoured by the presence of an electric current and accelerated plasma (Freund et al. 1983; Wu 1985), which is therefore typical of Alvén wings. Therefore, we extrapoled the properties of the CMI to the environement of pulsar companions.

We have considered that the source of CMI is a volume of plasma convected by the pulsar wind that passes across the AW. Because this flux of plasma is uninterrupted, this would result in the continuous emission of radio waves, along the AW, by a source that propagates approximately with the wind velocity. Because the wind is highly relativistic, the source of radio waves would propagate, in the observer's frame, almost at the speed of light. Therefore, the emitted waves would sustain a strong relativistic aberration, so that in the observer's reference frame, almost all of the radio energy flux would be confined in a cone of angle $\theta \sim 1/\gamma_{wind}$. The main idea of this model is thus that, because of relativistic aberration with $\gamma_{wind} >> 10^2$, the signal would be produced in an extremely narrow beam, with two practical consequences : we would have very little chance of intercepting it but, when we do, the received photon energy flux would be very high. This is compatible with the rarity of FRB and the possibility of observing them from incredibly remote distances (Mottez & Zarka 2014).

More detailed computations have shown that the range of frequencies in the observer's frame would be compatible with radio frequencies, as displayed in Fig. 2. Because of the motion of the companion along its orbit, the duration of the observed signal would be very brief, compatible with typical FRB duration (5 ms) for a planet at 0.01 to 0.1 AU and $\gamma_{wind} = 10^6$. The amplitude of the radio emission in the reference frame of the source was estimated from Zarka (2007) $P_{radio} = \epsilon \frac{\pi}{\mu_0 c} {R_p}^2 r^{-2} R_*^4 B_*^2 \Omega_*^2$, where R_p is the companion radius, R_* and B_* the neutron star radius and magnetic field, and r the companion's orbital distance. The factor ϵ is estimated to $\sim 10^{-3}$ in Zarka (2007), but we have used a more conservative value $\epsilon = 10^{-4}$. Taking into account the relativistic effects, the predicted flux of the observed signal is $< F >= 4\gamma_{wind}^2 P_{radio} D^{-2} \Delta f^{-1}$, with D the distance of the pulsar and Δf the emission bandwidth. Figure 2 shows that a signal of 1 Jy could indeed be observed from a source at cosmological distances, as suggested by FRB dispersion measures.

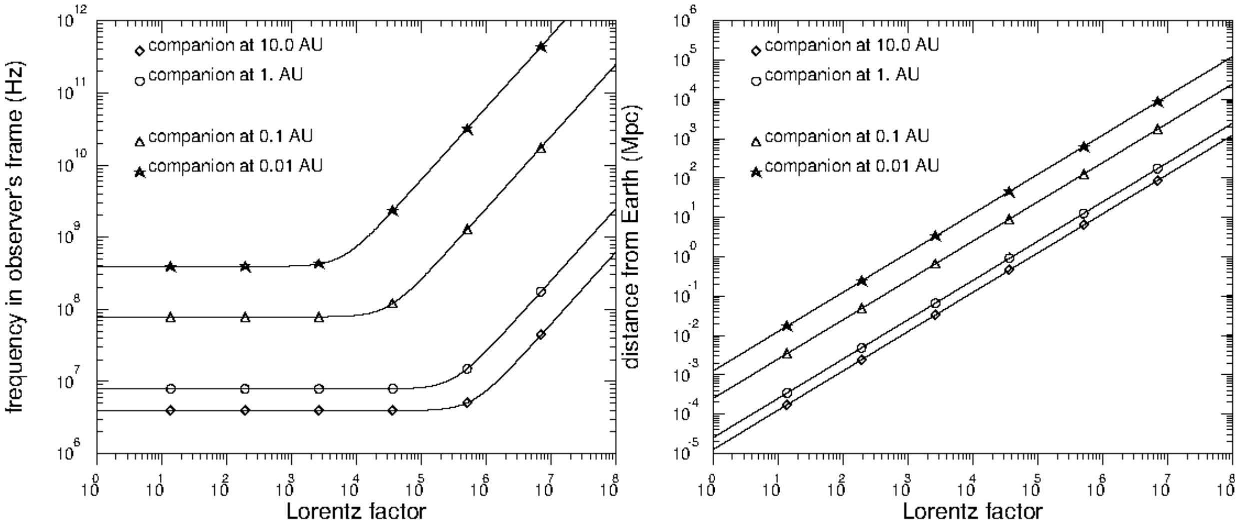

Fig. 2. Left: Frequencies vs Lorentz factor for companions of a typical $P = 10$ ms pulsar. **Right:** Distance at which the flux density of the companion-induced signal reaches 1 Jansky, expressed in Mpc, for various distances from the neutron star to its companion. The neutron star parameters correspond to a typical $P = 10$ ms pulsar.

The model of CMI in the AW of a pulsar companion shows that the shape of the signal is highly dependent on the wind's Lorentz factor. For $\gamma_{wind} \sim 10^6$ and $r \sim 0.01$ AU, the signal is composed of two pulses separated by a time interval of $\sim 1 - 5$ ms. At the time resolution of the radio surveys in which FRB have been detected, these two pulses may be merged and seen as a single pulse.

When $\gamma_{wind} \sim 10^5$ or less, four pulses can be seen, with the second and the third one very close to each other, and much brighter than the first and the fourth ones. This is actually what is seen with a transient event observed only once at the Arecibo radio telescope, and called J1928+15 (Deneva et al. 2009). This signal is composed of three pulses, the second being the most intense. The three pulses are separated by two intervals of about 1 second. We can reproduce this feature with our model and various combinations of parameters (planet distance r, pulsar period P_* and γ_{wind}). We notice that the interpulse duration would not necessarily correspond to the pulsar period P_*.

3 Observations that can help to discriminate our model from others

The following remarks about our pulsar companion model support its compatibility with FRB.

According to the present model, FRB would present the same kind of rarity as main sequence star occultations by planets (as seen with Corot or Kepler), but the aligment needs to be more "perfect" due to the strong focusing of the radio beam.

The line of sight must be in the orbital plane of the neutron star companion. It does not necessarily cross the beam of the pulsar. Even if that was the case, the pulsar signal, being much less focussed by relativistic effects, would not be detectable at cosmological distances. These are the two reasons why FRB are not associated with a regular pulsar signal.

The CMI model presented in this paper predicts only the emission of radio waves, and it is thus consistent with the lack of FRB signal in the optical, X, and γ energy ranges (Petroff et al. 2015a).

Because the CMI signal is circularly polarized in the reference frame of the source, the signal in the reference frame of the observer migh contain a part of polarized signal. This is indeed what was observed with the recent FRB 140514 (Petroff et al. 2015c). More observations of FRB polarization and detailed calculation of the expected polarization (as a function of γ_{wind}) will help to discriminate between the various models proposed to explain FRB.

The most important observation that could help to discriminate our pulsar companion model from others would be the re-occurence of a FRB at the same location and with the same dispersion measure. Up to now, follow-up observation have obtained negative results (Petroff et al. 2015b). But they do not yet constrain the lack of repeatability. A FRB typically lasts 5 ms (at a given frequency) and it might repeat only every few weeks or months. If a FRB is observed a second time, then it will be important to know if the signal is periodic. Up to now, the pulsar companion model is the only one that predicts a periodicity. If a period is found, it will correspond to the orbital period of the pulsar companion, and with that known, other parameters such as the companion's distance and the wind's Lorentz factor can be estimated. This is not only important for the physics of FRB, but for the knowledge of pulsars in general, because the Lorentz factor has never been measured, up to now, in any pulsar wind.

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