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The magnetic wake of planets and small bodies in a pulsar's wind.

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Abstract

We investigate the electromagnetic interaction of a relativistic and magnetized stellar wind with a planet or a smaller body in orbit around a pulsar. This may be relevant to objects such as PSR B1257+12 and PSR B1620-26 that are expected to hold a planetary system, or to other pulsars with suspected asteroids or comets. Most models predict that, albeit highly relativistic, pulsar's winds are slower than Alfvén waves. In that case, a pair of stationary Alfvén waves, called Alfvén wings (AW), is expected to form on the sides of the planet. They are the magnetic wake of the body into the plasma flow, like the wake of a boat left into the sea (with a similar shape). The theory of Alfvén wings was initially developed in the context of the Io-Jupiter interaction. We have extended it to relativistic winds, and we have studied the possible consequences that could be relevant for observations : possible radio emissions from pulsar's planets, and a magnetic force configuration that can deeply modify the orbit of the smaller bodies (asteroids, comets).

1. The pulsar's wind

The starting point of this theory resides in a comparison of the wind's velocity, and the Alfvén velocity. The total Alfvén speed in the wind's frame is

$$V_A'^{-2} = c^{-2} + c_A'^{-2} = c^{-2} + \mu_0 \rho_0' / B_0'^2, \qquad (1)$$

where ρ_0' is the proper density of proper mass of the supposedly cold wind and B_0' is the unperturbed field observed in the wind's frame. In a class of relativistic radial MHD wind models, the wind, although extremely fast, is slower that the Alfvén velocity. In these models [Arons(2004), Kirk et al.(2009)Kirk, Lyubarsky, & Petri] the asymptotic Lorentz factor scales as

$$\gamma_\infty \sim \sigma_0^{1/3}, \qquad (2)$$

where σ_0 is the magnetization factor defined by

$$\sigma_0 = \frac{\Omega_*^2 \Psi^2}{\mu_0 f c^3}. \qquad (3)$$

where Ω_* is the star's rotation frequency, Ψ is the star's magnetic flux, and f is the flux of plasma injected into the wind. The Alfvénic Mach number $M_A' = v_0^r / V_A'$ then asymptotes to $1 - 1/(2\sigma_0^{4/3})$ and remains smaller than unity. Therefore, in spite of being relativistic, the pulsar's wind in sub Alfvénic. It means that a body into this wind is *not* isolated from it by a shock wave.

2. The Alfvén wings

Instead, a pair of electric currents are carried by two stationary Alfvénic structures called Alfvén wings, attached to the orbiting body on one side, and extending far into space in the wind plasma on the other side. The configuration of these electric currents is recalled in Fig. 1. The engine of the Alfvén wings is the convection electric field associated to the wind, that appears in the reference frame of the star's companion. The wing currents are generated by a potential drop U along the body of radius R_P,

$$U = 2 R_P E_0 = \frac{2 R_P \Omega_* \Psi}{r}, \qquad (4)$$

where $E_0 = v_0^r B_0^\phi$, directed perpendicularly to the wind flow and to the magnetic field, is the convection electric field induced by the motion of the wind into the magnetic field. This potential generates a system of currents that flow along the companion, then in space into the plasma, in a direction which depends on the wind's magnetic field and the wind's velocity. In the ultra-relativistic wind of a pulsar, the conductivity can be approximated very simply by

$$\Sigma_A \sim \frac{1}{\mu_0 c}. \qquad (5)$$

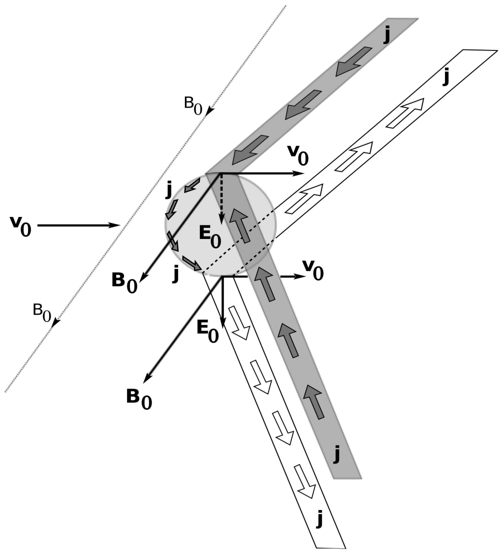

Figure 1: Schematic view of an unipolar inductor. The current $\mathbf{J}$ flowing along the planet is the cause of a $\mathbf{J} \times \mathbf{B}$ force density.

3. The Alfvén wing electric current

Adopting a simplified geometry, it is possible to estimate the total electric current. [Neubauer(1980)] gives useful expressions for the total current I flowing along an Alfvén wing. Writing R_P for the body's radius, the total electric current flowing into the Alfvén wings is

$$I = 4\,(E_0 - E_i)\,R_P\,\Sigma_A = 4\,\left(\frac{\Omega_* \Psi}{r} - E_i\right)\,R_P\,\Sigma_A \tag{6}$$

For a planet orbiting a "standard" pulsar, with a 1 second period and 10^{12} G magnetic field, within a distance of 0.2 AU, the Alfvén wing current I_{AW} would have an amplitude similar to the Goldreich-Julian current I_{GJ}... that is the basic engine of the pulsar's magnetosphere electrodynamics [Mottez & Heyvaerts(2011b)].

4. The possibility of radio emissions of planets around pulsars

We can expect that with such strong currents, the Alfvén wings are strong radio-sources. (Actually, in the much softer case of Io and Jupiter, they are.) The AW's current might be as well destabilized, and excited by transient Alfvén waves caused by the fluctuations of the pulsar's wind passing along the planet. The conjunction of the destabilized current (filamentation, blobs with mirror points, density fluctuations) and transient Alfvén waves might cause, for instance, acceleration and the production of cyclotron maser unstable distribution functions. We wave beam would be highly collimated through relativistic aberration. If we are in the right direction, there might be a chance to observe it from Earth [Mottez(2011)].

5. A magnetic thrust on the orbit of small bodies

The two Alfvén wings carry a current that, in the two branches flowing along the body -planet or comet-, generates a force density $\mathbf{j} \times \mathbf{B}$. We have estimated this force [Mottez & Heyvaerts(2011a)]. It has a component that is tangential to the orbit, and it can induce, on a time scale of , drastic changes of its orbital characteristics. If the body orbits in the same sense as the pulsar's spin, it is sent away at large distance. On the other case the body falls rapidly onto the star (10^4 years for a 1 km body).

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