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Applications of Ohm's Law to the pulsar magnetosphere

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Abstract. We show that in the inner magnetosphere of a pulsar mildly relativistic particles can flow out steadily under two assumptions: i) all vacuum fields are completely shielded by copious amounts of particles drawn out by thermal and field emission (which is likely as shown in Jessner *et al.*, 1999) ii) particles emitted from the neutron star surface have weakly relativistic energies ($\beta\gamma \approx 1$). The results are consistent with the typical particle energies predicted in the radio emission model by Kunzl *et al.*, 1999.

1. Description of the model

Imagine a hot neutron star that constantly emits enough charged particles to shield the induced electric acceleration fields. In such cases only non-idealities in the outflowing plasma can lead to accelerating fields. Since there are no external forces in this case we can apply Ohm's law. Here we use a more general form than can normally be found and include also time variations of the current and gradients in the distribution function.

$$\frac{\partial \vec{j}}{\partial t} + \mathrm{grad}\left(\vec{v}\vec{j} + \vec{j}\vec{v} - \vec{v}\vec{v}\rho\right) = \frac{\rho e}{m_{\mathrm{e}}}\vec{E} + \frac{\rho e}{m_{\mathrm{e}} c}\vec{v} \times \vec{B} + \rho \int \vec{v}\frac{\mathrm{d}f(\vec{v})}{\mathrm{d}t}\mathrm{d}\vec{v}\,. \qquad (1)$$

This equation is valid for strong magnetic fields (= no pressure term, no currents perpendicular to the magnetic field). ρ is the (electron) charge density, the distribution function is normalized in that way that $\int f(\vec{v})\mathrm{d}^3 v = 1$. The other symbols have their usual meaning. Besides, we use the following simplifying assumptions: $\vec{v} \parallel \vec{j}$, namely $\vec{j} = \rho\vec{v}$ which is automatically fulfilled for a pure electron flow and $\frac{\mathrm{d}}{\mathrm{d}t} f(\vec{v}) = 0$ (collisionless plasma). The first term of (1) is fluctuating rapidly (approx. with ω_{pe}) and will therefore not play an important role apart from some resonant particles. The third term ($\vec{j} \times \vec{B} \perp \vec{B}$) does not contibute to the parallel (=accelerating) field and is therefore neglected as well.

Evaluating the remaining equation for the dipolar geometry and neglecting all terms proportional to v_θ we can normalize to dimensionless units (accelerating

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force → $\frac{\partial}{\partial t}(\beta\gamma) := \frac{\partial}{\partial t}\varphi)$. This yields:

$$\frac{\mathrm{d}\varphi}{\mathrm{d}x} = \beta_{\|}^2 \frac{\partial}{\partial x_{\|}} \ln \frac{\rho}{\rho_{\mathrm{GJ}}} + \beta_{\perp}\beta_{\|} \frac{\partial}{\partial x_{\phi}} \ln \frac{\rho}{\rho_{\mathrm{GJ}}} + \beta_{\perp} \frac{\partial}{\partial x_{\phi}} \beta_{\|} \tag{2}$$

where $\varphi = \beta\gamma$. The second and third term only play a role in the outer magnetosphere, so for processes inside the radio emission zone we can neglect them (they are about a factor of r/r_{LC} smaller than the first term).

2. Results

Integrating equation (2) numerically for the classical Goldreich-Julian solution we find that when we start with low relativistic particles ($\phi \approx 1$) up to a typical emission height (50 pulsar radii for normal and 8 for ms-pulsars, e.g. Kijak and Gil, 1998; Blaskiewicz *et al.*, 1991) the particles are accelerated up to Lorentz factors of about 10-15 which is close to the particle energies needed for the most intense (low frequency) radio emission in the Kunzl *et al.*, 1999 model.

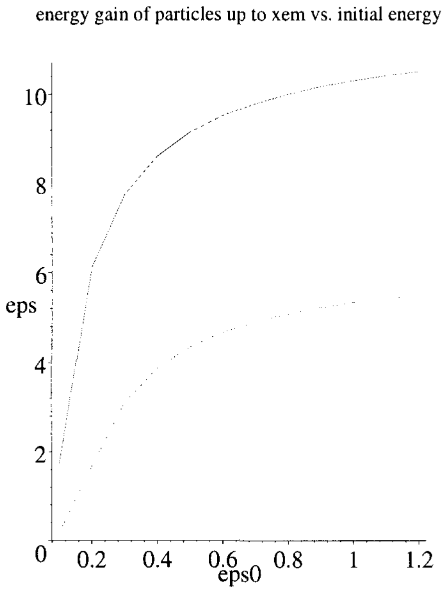

Figure 1: Dimensionless energy gain of electrons by the calculated fields for normal (lower) and millisecond pulsars (upper) versus the initial kinetic energy (in units of $\beta\gamma$). The parameters for this example are $P = 0.5\,\mathrm{s}$, emission height $x_{\mathrm{em}} = 50$ (normal pulsar) and $P = 5\,\mathrm{ms}$, $x_{\mathrm{em}} = 8$ (ms pulsar), respectively. In both cases we took a fieldline that crosses the surface at θ_{cap}.

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