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Electromagnetic Tornado in the Vacuum Gap of a Pulsar

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Abstract—The solution for an electromagnetic tornado that describes the motion in the discharge filament of breakdown in the vacuum gap of a pulsar has been obtained. This solution can serve as an explanation of the observed circular polarization of giant pulses from pulsars.

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The so-called giant pulses (GPs) whose properties differ significantly from those of ordinary ones are observed in a small number of rapidly rotating pulsars [1]. The very short duration of some GPs (as short as a few nanoseconds) suggests that they can arise during discharges [2] in a vacuum gap [3] in the process of primary electron acceleration to Lorentz factors of $\sim 10^7$. Indeed, relativistic aberration in the primary beam narrows the emission cone opening to angles $\delta\varphi \sim 10^{-7}$, while rotation with millisecond periods P leads to nanosecond pulse durations $\delta t \approx (P/2\pi)\delta\varphi$ in this case. This explanation is also consistent with the fact that GPs are observed precisely in rapidly rotating pulsars.

The observation of circular polarization of GPs from pulsars [4], which reaches 100% in certain cases, poses a serious problem for researchers. Indeed, in a pulsar's relativistic strongly magnetized plasma, the eigenmodes of electromagnetic waves are linearly polarized [5–7]. At the same time, the high GP energy densities [8], comparable (in millisecond pulsars) to the magnetic energy density near the magnetic poles, suggest that GPs arise near the stellar surface and not on the periphery of the magnetosphere, where the field is relatively weak. At present, there is no explanation of the circular polarization of GPs from pulsars. The proposed model of an electromagnetic tornado in the inner vacuum gap of a pulsar opens a new approach to solving this problem. Tornado quantization in a pulsar's superstrong magnetic field also allows the observed bands in the GP spectrum to be explained.

We will show that the observed circular polarization of both signs of GPs from pulsars is naturally explained by peculiarities of the breakdown in a vacuum gap (see the monograph [9] and references therein). The Coulomb field of charge repulsion in the discharge channel (bunch) produces a radial electric field orthogonal to the magnetic one. This, in turn, leads to the rotation of the discharge jet around its axis due to drift in the crossed fields and, accordingly, to the possible appearance of circular polarization of the generated waves [10]. Owing to the drift, the discharge channel turns into a peculiar kind of a vortex. The essentially two-dimensional field pattern leads to an approximately constant velocity circulation in this vortex resembling well-known tornados. However, in contrast to the hydrodynamic nature of ordinary tornados, the tornados in a vacuum gap are purely electrodynamic in origin.

A logarithmic potential $\phi \propto \ln r$ and a radial electric field $E_r \propto 1/r$, which is inversely proportional to the distance from the charge (filament), are known to correspond to a point charge on a plane or an infinitely thin charged filament in space. Accordingly, the drift velocity $V_\varphi \propto 1/r$ will behave in the same way. In this case, the velocity circulation is constant, $I = 2\pi r V_r \approx$ const (V_r is the radial velocity), i.e., the motion exactly reproduces the motion in a hydrodynamic potential vortex [11]. (Given the solid-body rotation at small distances from the axis, the solution obtained resembles a Rankine vortex.)

Consider a cylindrical segment of an axially symmetric electron bunch elongated along the magnetic field (Fig. 1). The Coulomb field E of charge repulsion in the bunch is assumed to be radial with respect to the axis.

From the equation for the radial Coulomb field

$$\mathrm{div}\mathbf{E} = 4\pi\rho \quad (1)$$

in the local coordinate system in the case of a radial space charge distribution of the form[1]

$$\rho(r) = \rho_0 \frac{r_0^4}{r_0^4 + r^4} \quad (2)$$

[1] Such a distribution ensures density finiteness on the axis and a fairly rapid decrease with increasing distance from it, which corresponds to total charge finiteness. A more rapid decrease has an effect only on the value of the numerical coefficient, of the order of unity, in the expression for the field asymptotics. A quadratic decrease would lead to a logarithmic divergence of the charge and the field.