On high brightness temperature of pulsar giant pulses

V. M. Kontorovich

Institute of Radio Astronomy of National Academy of Sciences of Ukraine; V.N.Karazin National University, Kharkov
vkont1001@yahoo.com, vkont@ri.kharkov.ua

Abstract

Giant pulses observed in a number of pulsars show a record brightness temperature, which corresponds to the high energy density of $U \approx 10^{15}\text{erg/cm}^3$. Comparable densities of energy in the radio-frequency region are attainable in a cavity-resonator being the pulsar internal vacuum gap. Emission of energy through the breaks accidentally appearing in the magnetosphere of open field lines corresponds to the giant pulses. The emitted energy is determined by the break area, which causes a power dependence of break occurrence probability. The observed localization of the giant pulses relative to the average pulse is explained by the radiation through a waveguide near the magnetic axis or through a slot on the border of the open field lines. Separate discharges may be superimposed on the radiation through the breaks, thus forming the fine structure of giant pulses with duration up to some nanoseconds. Coulomb repulsion of particles in the puncture spark in the gap leads to spark rotation around its axis in the crossed fields, which provokes the appearance of observed circular polarization of the giant pulses. The correlation between the giant pulse phase and the phase of the hard pulsar emission (X-ray and gamma) is naturally explained as well.

Thus, a wide range of events observed at the giant pulses can be explained from the viewpoint that the internal vacuum gap is a cavity-resonator stimulated by discharges and radiating through the breaks in the magnetosphere.

Keywords: pulsars – giant pulses, vacuum gap, cavity-resonator, spark rotation; tornado – electromagnetic

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Introduction

Giant pulses (GP), sporadically observed in a small number of pulsars, are a riddle which has not yet been solved (see reviews\textsuperscript{1−5}). GP is characterized by enormous flux density\textsuperscript{6}, extremely small pulse duration (down to a few nanoseconds)\textsuperscript{7}, presence of circular polarization of both directions\textsuperscript{8}, power distribution by energies\textsuperscript{9}, mainly location in the narrow window with respect to the average pulse position\textsuperscript{10} and correlation between the GP phase and the phase of the hard pulsar emission (X-ray and γ-ray)\textsuperscript{11−12}. All these features fundamentally distinguish GPs from ordinary pulses\textsuperscript{2}. Nevertheless, GP seems to be "a frequent, but rarely observed phenomenon inherent in all pulsars"\textsuperscript{10}. A number of pulsars emits anomalously intensive pulses\textsuperscript{13} which by their properties seemingly do not differ from GPs. Trying to explain GPs by plasma mechanisms in magnetosphere in which different variants of two-stream instability are realized\textsuperscript{14} needs considering strongly nonlinear effects such as modulation instability\textsuperscript{15−16}, Zakharov plasma wave collapse (the more popular!)\textsuperscript{8}, reconnection of the magnetic field lines\textsuperscript{17,18}, induced scattering in narrow beams\textsuperscript{19}, etc. (see references in the reviews\textsuperscript{5}).

When explaining the GPs in these works, we have seen that the pulsar is regarded as a "plasmic generator", a "device", in which the radiation processes are governed by different (nonlinear) processes in the magnetosphere plasma.

In work\textsuperscript{10} it is indicated that GPs are characterized by the extremely high energy density of order $10^{15}$ erg/cm\textsuperscript{3}, which appears as a key moment and forms the basis of this study.

It should be emphasized, and this is the main subject-matter of this work, that in the similar terms the pulsar can be thought of as a "vacuum device", in which the magnetospheric plasma acts as the walls, limiting the cavity and the waveguides as well the breaks in the magnetosphere, through which the radiation of GPs is transmitted. The radiation itself arises at discharges in the vacuum gap.

Thus we proceed from the idea that the pulsar internal vacuum gap\textsuperscript{20}, where the particle acceleration processes occur in the longitudinal electric field\textsuperscript{21}, is a cavity-resonator (with respect to the low-frequency radiation\textsuperscript{22,23}).

\textsuperscript{1} Crab (B0531+21), B1937+21, B1821-24, B0540-69, B1112+50, B1957+20, J0218+4232, J1823-3021A, B0031-07, J1752+2359, B0656+14\textsuperscript{6,31,33−35,37−42}

\textsuperscript{2} See also the recent works\textsuperscript{43−48}.

\textsuperscript{3} B0809+74, B0823+26, B0834+06, B0943+10, B0950+08, B1133+16
In the work\textsuperscript{22} the idea of resonator was illustrated by analogy with the resonator "earth-ionosphere" excited by the lightning discharges: "We live in a resonant cavity bounded below by the earth and above by the ionosphere. Lightning strikes excite low-frequency electromagnetic Schumann resonances in this cavity, as predicted by Schumann (1952), with a fundamental frequency of about 8 Hz. Such behaviour should also occur above the magnetic poles of pulsars due to the well-defined boundaries\textsuperscript{4} found there"\textsuperscript{22}. The modes of the cylindrical resonator were used in\textsuperscript{22} to describe such feature as a "carusel" structure of the pulsar micro pulses, and, as seen from the quotation above, the analogy with Schuman resonance in the spherical "earth-ionosphere" resonator (see e.g. the book\textsuperscript{24} of P.Bliokh and his collaborators) was discussed.

In the work\textsuperscript{23} another aspect of the problem is brought to the foreground: the stationary random process of discharges on the polar cap surface and, as a result, formation of a stable average shape of the pulse. That was demonstrated with the aid of the toy dice model. The idea of the resonator and waveguides was also formulated and then used in the context of pulsar radio and hard radiation\textsuperscript{25} from the polar gap. Owing to this idea the radiation emanates from the gap through the waveguides in the neighborhood of the magnetic axis and through the slots\textsuperscript{26} at the open field line borders. The radiation also leaks out through the magnetosphere plasma. The correlation between radio and gamma radiation, arising due to inverse Compton scattering of accelerated electrons at a powerful low-frequency radiation, can be an indirect confirmation of the powerful oscillations in the gap\textsuperscript{25}. GP may be another and more evident manifestation of the strong oscillations in the gap.

In this work we distinguish between two approaches, that we propose. One of them is to consider the passage of powerful quasi-stationary oscillations in the cavity through the random breaks in the magnetosphere. Under the assumption, the vacuum gap serves as a resonator (see Section 2 and Appendix B). With the other approach we examine (to explain the GP microstructure) the direct radiation of the individual discharge by-passing the plasma through the slot and the waveguide. This allows explain both the nanosecond pulse duration (due to relativistic aberration in the fast-rotating pulsars) and the observed circular polarization of GPs (see Section 3 and Appendix C). The last approach does not use the concept of the vacuum

\textsuperscript{4} See also discussion in Appendix A
Figure 1: The inner vacuum gap serves as a cavity-resonator for radio band electromagnetic oscillations excited by discharges in the gap. The radiation goes out through the wave-guides and percolates through the magnetosphere plasma. 1 – rotation axis, 2 – magnetic axis, 3 – waveguides, 4 – vacuum gap, 5 – polar cap, 6 – neutron star.

gap as a cavity. Similar notions and views may turn out to be useful in analyzing the properties of ordinary pulses, their substructure, subpulse drift, etc. However, these attempts will doubtless be restricted to the lack of developed concepts of the ”random” magnetosphere of open field lines and the most probable routes of the radiation transmission through such a medium. These questions are briefly discussed in Appendix A in the application to the random magnetosphere which is a stationary one on average only.

Description of the model

In our opinion, GP can represent a direct emanation of radiation from the gap (fig.1) through the breaks in the magnetosphere.

The particles accelerated in the gap undergo Compton losses, which exceed the curvature radiation losses under sufficient density of oscillation energy\(^{25}\). The energy received from the longitudinal electric field and, in the long run, from star rotation, is emanated in the form of gamma quanta (which generate the electron-positron plasma), and in the form of radio emission as in common models\(^{27-28}\).

The energy density \(U\) in the gap can be estimated according to the law of electromagnetic field energy conservation in the cavity (see Appendix B)
stimulated by external discharge currents in view of the radiation losses (the irradiation through the waveguide). Under the stationary conditions the square averages of these terms (the averages over space and time) have to be equal to each other. To estimate the scalar product of the current density and the electric field we use the Cauchy inequality. The energy density is determined as the square of the average electric field. We find the upper limit of energy density from the condition that the average current through the gap should be equal to the Goldreich-Julian current, which results in the following:

$$U \leq 4\pi (1 + \mu)^2 \left( \frac{\Sigma_{PC}}{\Sigma_w} \right)^2 (h \cdot \rho_{GJ})^2,$$

(1)

where $\Sigma_{PC}$ is the area of the polar cap, $\Sigma_w$ is the area of the waveguide cross-section, $\rho_{GJ}$ is the density charge of Goldreich-Julian, $h$ is the average height of the gap, $\mu$ is the part of the resonator locked modes that cannot go out through the waveguides. The appropriate parameter estimation leads to the energy densities comparable with those observed at GPs: $U \leq 10^{16} \text{erg}/c$. The same condition may be transformed into the energy density restriction from below if we express it in the terms of radiation intensity $I_R$:

$$8\pi U \geq \left( \frac{I_R}{c \rho_{GJ} h \cdot \Sigma_{pc}} \right)^2,$$

(2)

which allows one to estimate $U \geq 10^{12} \text{erg}/s$. One more estimate of the energy density $U$ in the gap may be made by using the momentum conservation law. The very high level of the energy density in the gap means that the pressure of radiation in it has to be very high too. It follows that the form of the boundary of the cavity with plasma must be sufficiently sharp. The boundary condition of the momentum density flux continuity gives for $U$:

$$U \leq mn_{GJ} c^2 \Gamma_{sec}^2$$

(3)

where $n_{GJ} = \rho_{GJ}/e$ is the Goldreich-Julian concentration, $\kappa \approx 10^3$ the multiplicity factor, $\Gamma_{sec}$ the Lorentz-factor of the secondary $e^\pm$-plasma above the vacuum gap. Here we assume that the contribution of gamma-ray quanta in the flux is of the same order or smaller. It implies that the position of the control section in the plasma must be at a distance of some gamma quanta mean free pass above the boundary. The estimation $\Gamma_{sec} \approx 10^3 - 10^4$ gives

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5 Cf. with the non-relativistic expression for momentum density flux $P + mnV^2$, $P$ is the pressure, $n$ is the particle concentration, $m$ is the mass of the particle.
us \( U \leq 10^{14} - 10^{15} \text{ erg/cm}^3 \) – the same as the previous ones on the rough scale. The more accurate estimation requires the solution of difficult problems of the plasma boundary structure and of the transmission (reflection) of the powerful electromagnetic waves through such a boundary. This problem is not yet solved. (In that case the linear approach to the problem is not applicable at all.)

Thus, we assume that a great amount of energy may actually be concentrated in the vacuum gap and the gap may be regarded as a cavity resonator with good quality-factor. Some additional arguments in favor of this will be mentioned in the text below. We will discuss below the implications of these assumptions relative to the GPs and will confirm a consistency (noncontradictory) and efficiency of such a hypothesis.

The energy radiated by the GPs is determined by the oscillation energy density in the gap and parameters of the break in the magnetosphere plasma. The energy emanated in the pulse duration is proportional to the volume of the break \( S \cdot \Delta z \), where \( \Delta z \) is its height proportional to radiation time \( \Delta t \).

**Discussion**

For the distribution of the oscillation energy density in frequencies \( U (\nu) \) we take the same power law with index \( \alpha_R > 1 \) as for the observed radio frequency radiation\(^6\)

\[
U (\nu) = U \cdot \left( \frac{\nu_{\text{min}}}{\nu} \right)^{\alpha_R}, \quad U = \int_{\nu_{\text{min}}}^{\nu_2} d\nu U (\nu). \tag{4}
\]

Here \( \nu_{\text{min}} \approx c/\lambda_{\text{max}} \) is determined by the longest-wave modes, and \( \nu_2 \) is the maximal possible frequency of oscillations in the cavity corresponding to the high-frequency edge of the pulsar radio spectrum. The link between the break area \( S \) and received flux density \( F (\nu) \) at the given frequency has the form

\[
U (\nu) \cdot c \cdot S = D^2 \cdot \Delta \Omega \cdot F (\nu). \tag{5}
\]

Here \( D \) is the distance from the pulsar, \( \Delta \Omega \) is the spatial angle interval in which the radiation is emanated. The azimuth angular distance \( \Delta \phi \) is passed for the time \( \Delta t = P \Delta \phi / 2\pi \) where \( P \) is the period. Thus, the solid angle

\(^6\) Pulsar in the given model emanates GPs in the frequency interval \( \nu_1 < \nu < \nu_2 \), where \( \nu_1 \approx c/\sqrt{S} \) is determined by the conditions of the wave transmission through the break (waveguide) of the given cross-section \( S \), \( \nu_{\text{min}} < \nu < \nu_1 \) is the interval of the locked modes.
ΔΩ = Δθ·Δϕ correlates with the time of radiation Δt as ΔΩ ≈ 2π·Δθ·Δt/P.

The break area S also requires the time Δt for passing through. Taking into consideration S << πR<sup>2</sup>, S = πR<sup>2</sup>ΔΩ<sub>s</sub> where R<sub>s</sub> is the effective radius where the break is realized and ΔΩ<sub>s</sub> is the corresponding spatial angle, we see that the length of the pulse Δt falls out from our relations. If Δθ<sub>s</sub> ≈ Δθ then we have

\[
\pi R^2_s = D^2 · F(\nu) / (U(\nu) · c)
\]

The average GP profile is attached to the definite phase of the polar cap θ. Hence, the average shape of the arch of the cavity is h(θ) ≈ Rs – Rs. Probably, close to the magnetic axis this description is rather acceptable. Yet, near the slot it is necessary to take account of its curvature, a decrease in amplitude of the low frequency oscillation near the border of the open field lines, along with other complicating factors.<sup>30</sup>

Now we can make the independent rough estimate<sup>29</sup> of the energy density U (from the top). Assume (only for this estimation!) that it makes the same contribution to each spectral interval of the observable density flux. If we make a sufficiently rough model to be considered in each frequency window U = Const, then for the spectral index α = 3 the area of the break falls out (see<sup>29</sup>) from formulas F(ν) = (α − 1)·S·U·λ<sup>α</sup> / (D<sup>2</sup>·ΔΩ). Here D is the distance to the pulsar, F(ν) is the flux at a frequency ν, λ is the wavelength, ΔΩ is the solid angle of radiation. Since α ≈ 3 corresponds to the spectrum of the Crab pulsar, we are able to evaluate U from the observational data for Crab: U = D<sup>2</sup>ΔΩ · λ<sup>−3</sup>F(ν) / 2 , α = 3 (for this estimation only!). This gives us U ≤ 10<sup>17</sup>erg/cm<sup>3</sup>, which is in good correlation with other estimates (see the text above and App.B).

**GP short duration**

An extremely short giant pulse duration of several nanoseconds allows us to suggest that the pulses arise in the vacuum gap<sup>12</sup> in the process of primary electron acceleration<sup>13</sup> to the gamma-factors of order of 10<sup>7</sup>. Indeed, relativistic aberration (see also the work<sup>49</sup>) in the primary electron beam reduces the cone of radiation down up to the values δϕ ∼ 10<sup>−7</sup>, and in this case the rotation with periods P ≈ 2π · 10<sup>−2</sup>s leads to the nanosecond pulse duration δt ≈ δϕ · P/2π ∼ 10<sup>−9</sup>s. This explanation is also consistent with the fact that giant pulses are observed in the rapidly rotating pulsars only.
Thus, we have to deal with the emission of an individual discharge in the vacuum gap (cf. 28).

**GP phase**

The observed localization of the GP phase can be associated with radiation through the waveguides. In pulsar B1112+50 GPs are located in the center of the average pulse. We reckon that this localization may correspond to the radiation through the ”waveguide” near the magnetic axis of the pulsar. If the GP phase corresponds to the ”edge” of the average pulse, then it most likely corresponds to the radiation through the slot. The edge can be either retarded against the average profile (B1937+21), or advanced (J1823-3021A). This corresponds to trailing or leading edges of the slots in the section of the telescope diagram. The fine structure of the GPs may reflect the discreteness of the discharges visible through the breaks.

From this point of view the correlation between the GP phase and the phase of the hard pulsar emission (X-ray and γ-ray) becomes truly evident: radiation arises in the same process of particle acceleration and goes out through the same waveguides.

Localization of GPs (near the waveguides and near the slots) signifies that the magnetosphere of the open field lines is not transparent, on average, to radiation, except for these places of GP localization. This statement also supports the idea that the inner vacuum-gap is a cavity resonator. However, sporadic GP can occur at all phases.

**Circular polarization and electromagnetic tornado**

The observed circular polarization is naturally explained by the peculiarities of the discharge in the vacuum gap. Coulomb charge repulsion in the discharge bunch furnishes the radial electric field orthogonal to the magnetic one. Owing to the drift in the crossed fields it causes the discharge jet rotation around its axis (see Appendix C) and, accordingly, the circular polarization of generated electromagnetic waves. In fact, both accidental and regular deviations from the ideal axisymmetric form of discharges results in the rotational electric field around the discharge axes and the related circular polarization of radiation. Owing to the drift the discharge channel turns into a peculiar vortex resembling the well-known tornado. However, contrary to the hydrodynamic nature of the usual tornado, the vacuum gap tornado is of purely electromagnetic origin.
Figure 2: In the discharge bunch filament the Coulomb particle repulsion leads to rotation in the crossed electric and magnetic fields around the bunch axis. This rotation transforms the bunch into an electromagnetic tornado. For electrons and positrons the rotation directions are opposite. The rotation can cause the circular polarization which is observed in GPs. 1 – magnetic field, 2 – bunch velocity, 3 – radial electric field of space charge, 4 – drift velocities.

From the equation $\text{div}E = 4\pi \rho$ for the spatial charge $\rho$ of the form

$$\rho(r) = \rho_0 r_0^4 / \left( r_0^4 + r^4 \right),$$

the Coulomb field $E_r$ radial to the vortex axis is

$$rE_r = 2\pi \rho_0 r_0^2 \arctg \left( \frac{r^2}{r_0^2} \right).$$

For the particle drift velocity (fig.2)

$$V_\phi = cE_r / H$$

at large distances from the axis there is a movement with constant circulation and solid-type rotation on the small ones.

The quasi-classical quantization is possible by using the condition

$$mrV_\phi = n \cdot \hbar,$$

which leads to the angular frequency of the bunch

$$\omega = cE_r / (mrH).$$
\[ \Omega_n = n \cdot \hbar/mr^2. \]  
(11)

The particle linear density \( N = \pi r_0^2 \cdot \rho_0/e \) and, correspondingly, the current of the vortex tube \( ceN \) are quantized. As a result, they do not contain any model parameters and are dependent on the magnetic field only:

\[ ceN = n \cdot \hbar B/m. \]  
(12)

Here \( n \) is integer or half-integer. The full Goldreich-Julian current flowing through the gap is provided by \( q \) vortex lines as

\[ q \simeq \frac{\Omega m}{\pi n \cdot \hbar} \Sigma \Omega \rho C. \]  
(13)

In the ground state it is required that \( q \approx 10^7 \) lines. For a smaller \( q \) the Rydberg states with \( n >> 1 \) are required. Discharges may arise owing to the charges running off from the microscopic edges of the polar cap surface, thereby forming bunches and low frequency radiation that feeds the cavity. The edges may be destroyed in this process followed by subsequent restoration. Rotation frequencies form the bands whose borders are determined by tornado internal and external radii. For example, the radius \( r \approx 10^{-5}\text{cm} \) matches to the frequency of \( \Omega \approx 10^{10}\text{s}^{-1} \). Such a structure might explain the frequency bands\(^{34} \) observed in the GP spectrum\(^3\).

**Power-law distributions**

In the scheme under consideration the energy emanated in the GP is proportional to the break area. The observed power-law of GPs occurrence frequency in accordance with their energy\(^{35} \) means the power dependence of a break appearance probability upon the break area. Here the analogy with the geophysical phenomena in which many examples of such distributions are known seems to be quite relevant. Many observed statistical patterns causing power-low distributions can be obtained under the elementary assumption of the small correlation time of random force with different physical definition of ”forces” and ”particles”.\(^{36} \) The consequence of such a force correlation is the dependence of the form \( N (\geq E) \propto E^{-1} \) for the cumulative frequency of the events with ”energy” \( E \) which explains many empirical dependencies\(^{36} \). Here,

\(^7\) These strips have been observed in the interpulse spectrum only. But it is possible to suppose that in the main pulse spectrum they just merge into one single spectrum. According to \(^{18} \) the strips correspond to Bernstine modes.
apparently, it is necessary to add frequency of the GP pulsar appearance where the energy is proportional to the break areas in the magnetosphere. With smaller energies $E$ the GP complies with the power-law $N(\geq E) \propto E^{-a}$ ($a = 0.9 - 1.1$). With greater energies a sharp bend in the distribution is observed. It can easily be interpreted as the result of the break superposition which leads to the steepening of the distribution ($a > 2$).

**Resume**

Now we summarize the foregoing.

In the giant pulses the energy density is comparable with that of oscillation in the inner vacuum gap cavity. It means that we obtain radiation at the GP instants directly from the cavity by-passing the magnetosphere plasma. It becomes possible if the breaks or the cracks and holes appear in magnetosphere due to random allocation of plasma-generating discharges. GP duration is not always fully attributable to its physical nature. The pulse length may be determined by the dynamics of the break appearance and disappearance in the magnetosphere. The GP power-law intensity distribution is also determined by the probability of appearing the breaks of different size and is not directly associated with GP radiation physics. The appearance of breaks is most probable in the phases that conform to the "waveguides" near the magnetic axis or near the edge of open field lines. Separate discharges may be superimposed on the radiation through the breaks. In such cases the relativistic aberration (see also 49) narrows down the angle range $\Delta \varphi$ up to $10^{-7}$ and fast rotation contracts the pulse duration $\Delta t = P \Delta \varphi / 2\pi$ up to $10^{-9}$s. Obviously, circular polarization of GP is also governed by physics of its radiation. Such a polarization can be generated by electromagnetic tornados in the gap.

To sum up consider a simple analogy with the Sun radiation observed on a cloudy day. In the breaks in the clouds we observe some kind of a "pulse". A large break lets more energy get through (an analogue of the GP intensity) but it is the characteristic of the break and not of the emitter. The "pulse" duration is determined by the break existence but not by the physics of the radiation. The steepness of the "pulse" is also determined by the movement of the clouds but not by the solar processes. The emitter’s main characteristic is the brightness temperature and spectrum as well as polarization. But fast fluctuations such as solar flares and bursts of solar radiation could make their own contribution if we can see them between the clouds.
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Appendix A. On nontransparency of the pulsar magnetosphere in the open field lines region

Electrodynamics of the boundary of the vacuum gap with plasma in the region of open field lines, which limits the cavity from above, is a fairly challenging task and has not been sufficiently developed, although it was announced in the work\(^\text{22}\). Therefore we give below the following physical considerations indicating that this boundary should have relatively high reflective properties, so that the gap could be considered as a good resonator. Now we would like to focus our attention primarily on the random environment (the electron-positron plasma) which has to pass through the wave from the vacuum gap before leaving it.

This randomness is the result of random character of the discharges on the surface of the polar cap\(^\text{23}\). Discharges generate the plasma via the birth of electron-positron pairs in a magnetic field (by gamma-ray photons emitted at breakdowns). The geometry of the open field lines and the strong magnetic field create a configuration that is close to the one-dimensional one, in which the predominant role is played by the backward scattering that results in Anderson localization\(^\text{50}\). With such scattering in a stationary random environment the reflected wave travels the path along which all the random phase shifts acquired by the wave along the straight path are fully compensated for. This leads to an exponentially small average transmission coefficient of the wave through a layer of random medium exceeding the localization length\(^\text{51}\) \(l\) and, accordingly, to an exponentially small difference between the average reflection coefficient \(\overline{R}\) and unity\(^\text{52,53}\):

\[
\overline{R} \approx 1 - \frac{\pi^{5/2}}{2} \left( \frac{L}{l} \right)^{-3/2} e^{x} \left( - \frac{L}{4l} \right),
\]

where \(L\) is the thickness of the layer. (The wave transmission occurs only on the most favorable paths that are different for different random realizations\(^\text{54}\); they are reported in the text in a simplified manner as the breaks in the magnetosphere). In order to render the use of these findings reliable it is necessary to make sure that the situation is actually quite close to one-dimensional
and that the nonstationarity of configurations (in the unchallenged stationary random process) does not destroy the desired coherence of scattering. (Nonstationarity may occur even on average\textsuperscript{43}). This question is left open now and we hope to return to this issue separately.

This does not contradict the fact that in a smoothly inhomogeneous magnetized relativistic electron-positron plasma with identical distributions of electrons and positrons the transverse electromagnetic waves have the gapless nature\textsuperscript{55–57} and, seemingly, can easily penetrate through the magnetosphere\textsuperscript{8}. However, the magnetosphere is not the smoothly inhomogeneous, especially in the area of open field lines, and this is a basic fact for the problem of reflection of electromagnetic waves. But besides this, in the transition layer between the gap and the plasma the electromagnetic waves is of a different character. Indeed, there is a strong longitudinal electric field in the transition layer, which turns the positrons, that are born in pairs, back to the star.

Therefore, there should be a layer of non-relativistic positron plasma with the Goldreich-Julian plasma frequency $\omega_{GJ} = \sqrt{\omega_c \Omega} \approx 10^{10} \text{s}^{-1}$ (here $\omega_c$ is the cyclotron frequency and $\Omega$ is the angular frequency of star rotation). Note that the upper edge of the pulsar radio spectrum, as remarked in \textsuperscript{25}, is located close to this frequency. It is important, however, to highlight one more circumstance. The back scattering is strongly suppressed in the relativistic outflowing plasma. But in the transition layer in which the reverse flow of the positrons is accelerated up to the speed of light, the backscattering of the waves is also very efficient due to the same relativistic aberration. This should lead to the opacity of the plasma and to the high reflective properties of the upper lid of the vacuum-gap resonator. It will be recalled that the existence of the cavity resonator is an assumption in this paper. We analyze the consequences of this assumption, which in fact allows us to give a consistent explanation of all the facts relating to the issue of GPs.

Appendix B. Energy density estimation

The average energy density $U$ of the low-frequency electromagnetic field in the gap can be estimated from the energy conservation law in the cavity excited by external discharge currents. The conservation law averaged over time yields the balance condition $\text{div} \mathbf{S} = -j_{\text{ex}} \mathbf{E}$, where $\mathbf{S}$ is the Poynting

\textsuperscript{8} The most frequent objection to the resonance properties of the vacuum gap. Let us note, that the waves are linearly polarized.
vector, $\mathbf{j}_{ex}$ is the density of the spark currents and $E_\sim$ is the strength of the low-frequency electric field. The bar denotes averaging over time. By the average values of $\mathbf{A}$ we imply their mean square values $\sqrt{\mathbf{A}^2}$. Integrating the balance equation over the volume of the resonator and using the Gauss’ theorem we obtain $\oint S d\Sigma = -\int dV \mathbf{j}_{ex} \cdot E_\sim$. The average value $\int dV \mathbf{j}_{ex} \cdot E_\sim$ is estimated with Cauchy-Bunyakovsky inequality $\int dV \mathbf{j}_{ex} \cdot E_\sim \leq \int dV \mathbf{j}_{ex} \cdot E_\sim$. For the average current density $\mathbf{j}_{ex}$ we take the Goldreich-Julian value $\mathbf{j}_{ex} = c\rho_{GJ}$ where the Goldreich-Julian charge density is $\rho_{GJ} = -\Omega B/(2\pi c)$. Using the theorem about the average for the integral in the right-hand side of the balance condition inequality we obtain the estimate $\int \mathbf{j}_{ex} \cdot E_\sim dV \leq c\rho_{GJ} \cdot E_\sim \cdot \Sigma_{PC} h$. Here $h$ is the height of the gap, $\Sigma_{PC}$ is the area of the polar cap. Note that the power emitted in the radio-frequency region is $I_R = \oint S d\Sigma = cU_R \Sigma_w$, where $U_R = U/(1 + \mu)$, $U = E_\sim^2/(4\pi)$ and the contribution of the closed modes is $\mu \approx (\omega_1/\omega_{min})^{\alpha_R-1} \left[ 1 - (\omega_{min}/\omega_1)^{\alpha_R-1} \right]$. Inserting these relations into the balance condition we have $\frac{1}{1+\mu} \frac{E_\sim^2 \Sigma_w}{4\pi} \leq c\rho_{GJ} \Sigma_{PC} h$ and whence we estimate the average electric field in the gap: $E_\sim \leq 4\pi \rho_{GJ} h \frac{\Sigma_{PC}}{\Sigma_w} (1 + \mu)$. Finally, raising to the square we find the upper bound for the energy density in the gap (1)

$$U = E_\sim^2 \leq 4\pi (1 + \mu)^2 (\Sigma_{PC}/\Sigma_w)^2 (h\rho_{GJ})^2,$$

whence follows under the typical values of parameters that

$$U \leq 10^{16} (1 + \mu)^2 \text{ erg/cm}^3.$$

On the other hand, we can make an independent estimate of $U$ by expressing the average field $E_\sim$ through the intensity of radio emission $I_R$. Using the balance condition in the form $\oint S d\Sigma \leq c\rho_{GJ} \cdot E_\sim \cdot \Sigma_{PC} h$ we have estimate $E_\sim$ limited from below $I_R \leq c\rho_{GJ} \Sigma_{PC} h \cdot E_\sim$ which leads to the lower bound for the energy density of oscillations in the gap (2):

$$\frac{1}{4\pi} \left( \frac{I_R}{c\rho_{GJ} \Sigma_{PC} h} \right)^2 \leq U.$$
Appendix C. Electromagnetic tornado

Let us consider an electromagnetic tornado in the vacuum gap (see 58). The equations of motion in the plane orthogonal to a magnetic field in complex variables $\xi = x + iy$ take the form $\frac{dw}{dt} - i\omega_c w = \frac{E}{mr} \xi$, $w = \frac{d\xi}{dt}$, where $E = E \cdot r$, $r = (x, y)$, is the field of a space charge, and $\omega_c = \frac{eH}{mc}$ is the cyclotron frequency. In the axial electric field $E = E(r)$ depending solely on the distance $r$ from the axis, which we believe to be a constant parameter, these equations allow solutions of the type $\xi = \xi_0(r) e^{i\Omega(r)t}$. The frequencies $\Omega$ obey the equation $\Omega^2 - \omega_c \Omega + \frac{E}{mr} = 0$, roots of which are equal to $2\Omega = \omega_c \pm \sqrt{\omega_c^2 - 4\frac{E}{mr}}$. Transition to the l-system in which the bunch moves with relativistic velocity results in replacing $\Omega \rightarrow \Omega / \Gamma$ where $\Gamma$ is the Lorentz-factor. In this derivation, the appearance of the azimuthal magnetic field in the l-system, which is induced by the longitudinal electric current should be taken into account. This field can be found from the Maxwell equations. In the pulsar conditions there is a small parameter $\frac{4E}{m\omega_c^2} << 1$ the expansion by which yields the values $\Omega_+ \approx \omega_c$ and $\Omega_- \approx c^2 \frac{1}{r}$. The first root is in agreement with the common cyclotron mode slightly modified by the electric field. The second root, being of basic interest to us, corresponds to the drift in the crossed fields. We may check it by going over to the polar coordinates through substitution $\xi = re^{i\varphi}$. The equations for the radial and azimuthal velocities $V_r = \frac{dr}{dt}, V_\varphi = r \frac{d\varphi}{dt}$ take the forms $\frac{dV_r}{dt} - \frac{V_r^2}{r} + \omega_c V_\varphi - \frac{E}{m} = 0$ and $\frac{dV_\varphi}{dt} + \frac{V_\varphi V_r}{r} - \omega_{\varphi} V_r = 0$, respectively. The stationary solution, in which the azimuthal velocity is time-independent, has to satisfy the conditions $\frac{V_\varphi^2}{r} - \omega_c V_\varphi + \frac{E}{m} = 0$ and $\left(\frac{V_\varphi}{r} - \omega_c\right) \cdot V_r = 0$. They are held at $V_r = 0$ and $V_\varphi = r \cdot \Omega_\pm$, where $\Omega_\pm$ are the frequencies found above and having the meaning of angular velocities of rotation (cf. 59). The solution $V_\varphi = r \cdot \Omega_-$ describes the electromagnetic tornado in the vacuum gap in which the repulsion field of the space charge is compensated by the Lorentz force, the radial movement is absent, and rotation is specified by the drift in the crossed fields. Due to this rotation, the circular polarization appears in the discharge radiation.

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