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Reflection of positron radiation from star surface and shift of inter pulse position in Crab pulsar

V. M. Kontorovich[1,3]*, *S. V. Trofymenko*[2,3]†

[1]Institute of Radio Astronomy NAS of Ukraine, Art Str., 4, 61002 Kharkiv, Ukraine
[2]Akhiezer Institute for Theoretical Physics of NSC KIPT, 1 Akademicheskaya Str., Kharkiv 61108, Ukraine
[3]Karazin Kharkiv National University, Svobody Sq. 4, Kharkiv, 61022, Ukraine

The pulsed radiation from the Crab pulsar consists of the main pulse (MP) and inter pulse (IP), as well as of the extra pulse components appearing at certain frequencies. It has been studied in many frequencies and contains unique information, which is not available for the majority of the pulsars. One of the mysteries of these data, found by Moffett and Hankins twenty years ago, is the shift of the IP at high radio frequencies compared to lower ones and return to its previous position in the more high-frequency optical and X-ray range. We propose the explanation of these mysterious changes with the frequency as a reflection of radiation by relativistic positrons from the stellar surface. The magnetic field of the pulsar in the pole must be inclined to the surface of the star and affects on the discussed processes.

Key words: neutron stars; pulsars: PSR B0531+21; radiation mechanisms: non-thermal; interpulse shift

INTRODUCTION

The pulsars are natural accelerators in which charged particles are accelerated to considerably high energies within short spatial gap. Region of the pulsar magnetosphere in the vicinity of the magnetic pole of the star, consisting of the open field lines, is so called polar (inner, vacuum) gap. Inside this region electrons are accelerated by longitudinal, with respect to the magnetic field, electric field of the star.

This intense electric field, which is generated by the magnetic field of the rotating star, accelerates the electrons up to the value of the Lorentz-factor of the order of 10^7. Their curvature radiation in magnetic field of the star, dipole or different from the dipole one, generates the cascade of electron-positron pair creation which forms the magnetospheric plasma (see [4, 11, 28] and references therein). The radiation of the electrons inside the gap is considered in a large number of papers. We will concentrate on radiation of positrons moving towards the surface of the star and accelerated by the same electric field (Fig. 1). The electron gains energy when it starts to accelerate near the surface of the star, and the positron – near the lower boundary of the magnetosphere. In the regions of opposite field direction it corresponds to radiation of electrons which move back to the surface, which we will not mention further.

As we demonstrate below, the radiation from relativistic positrons, reflected from the surface, has a series of peculiarities which differ them from the direct radiation from the electrons moving away from the surface. First of all, these peculiarities are associated to the fact that the positrons radiate at the same frequency as electrons in different regions of space with respect to electrons, and at different angles due to their acceleration along the curved magnetic field lines (Fig. 1). In the inclined magnetic field this results in a shift of the inter pulse position, which is described in the present paper.

FREQUENCY SHIFT OF THE PULSE LOCATION OF THE CRAB NEBULA PULSAR

As we have described above, the pulsed radiation from the Crab pulsar dramatically changes with the frequency: at certain frequencies MP disappears and IP shifts, see [7, 24]. The author's theoretical examination of the problem see in [6]. The explanation of the observed IP shift in this frequency range requires consideration of a new process — reflection of relativistic positrons' radiation from the pulsar surface.

The necessity to take into account the reflected positron radiation is stipulated by the aforemen-

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*`vkont@rian.kharkov.ua`
†`trofymenko@kipt.kharkov.ua`

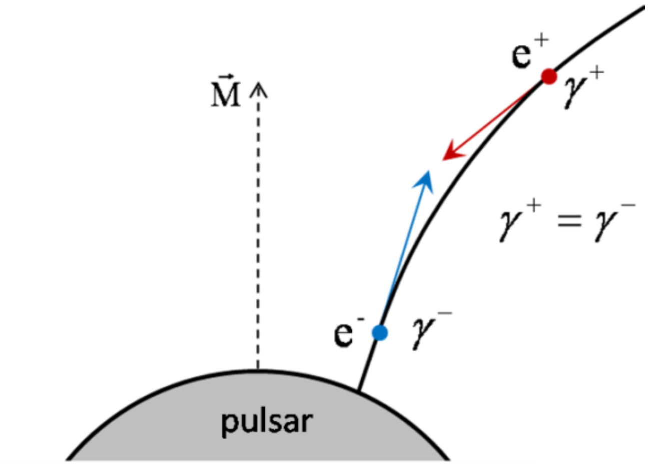

Fig. 1: Schematic image of electron and positron radiating at the same frequency corresponding to the same Lorentz-factor. Both particles move in the accelerating electric field of the gap.

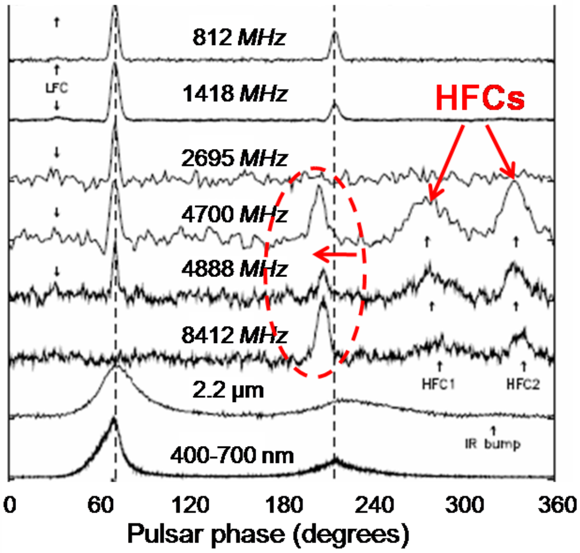

Fig. 2: Diagrams imaging data of multi-frequency observations by D. Moffet & T. Hankins [24], fragment. With gratitude to the authors.

tioned observed frequency variations of the intensity and position of the pulses from the pulsar in Crab Nebula, which do not still have proper physical explanation. Presently it is the only opportunity to explain the mysterious displacement of the inter pulse. These variations are presented in figures from [24], where the gradual 'disappearance' of the MP and low-frequency IP (Fig. 2) could be seen as well as the shift of the IP and appearance of two high-frequency (hf) pulsed components. The MP is localised near 70 degrees and IP – near 215 degrees. The areas of disappearance and shift of the pulse positions are highlighted. At the same frequencies as the shift arises the high-frequency components HFC1 and HFC2 appear. It is possible to come up with ingenious mechanisms of the appearance of additional components, more or less plausible, but the displacement of the inter pulse has been a mystery for more than 20 years. It can be naturally explained by the reflection of radio waves from the surface of the pulsar. Such reflection does not contradict to any information about the surface of neutron stars, which we possess.

THE CHANGE OF RADIATION MECHANISMS

The explanation of MP 'disappearance' was proposed by one of the authors and A. B. Flanchik [16] and consists in consideration of 'non relativistic' radiation mechanism with broad angular diagram during longitudinal acceleration of electrons in the polar gap as the mechanism of low-frequency radiation emission. When the accelerated electron reaches relativistic velocities this mechanism weakens and turns off at rather high frequencies. The break of the spectrum, discovered by Malofeev and Malov [21, 22, 23] during the analysis of the pulsar spectra catalogue, corresponds to the change of a radiation mechanism. The disappearance of the main pulse can be explained as a result of transition from the non-relativistic radiation mechanism by longitudinal acceleration to a relativistic mechanism with narrow angular distribution of radiation (angular diagram). Thus, it is necessary that the narrow beam from the main pulse does not get to the telescope, but from the inter pulse does [16]. At frequencies higher than the frequency of the spectral break the well-known relativistic curvature radiation with the narrow angular diagram begins playing important role [12, 28]. Therefore the geometrical factors associated as well with the magnetic field topology become significant. This requires a certain inclination of the 'magnetic plane' passing through both magnetic poles and the centre of the star, which may be also the plane of the magnetic torus in the interior of the star. The inclination of the magnetic plane in the case of non-relativistic dipole radiation (low frequencies, the maximum of radiation is orthogonal to the dipole axis) should be such that the main pulse was more intense than inter pulse, as is observed. Since the dipole axis is tangential to the trajectory, this means that the line of sight for inter pulses passes closer to the magnetic axis [16].

To explain our idea of reflection from the surface, we will initially exaggerate it and start with the assumption of a possible reflective nature of hf-components (Further we, however, use such assumption for explanation of the inter pulse shift). The appearance of high-frequency components can be clearly understood if we consider reflected hf-radiation from the positrons moving towards the surface of the star and being accelerated by the same electric field as the electrons moving from the surface. Return motion of positrons, arising due to penetration of the accelerating electric field in the gap inside the electron-positron plasma, was considered in connection with the heating of the star surface both by the hard gamma-quanta emission by positrons and by the positron reverse current itself in a number of publications, a detailed bibliography of which is presented in the article of Barsukov et al. [3]. However, the hf-radiation from returning positrons has not been considered yet. The idea of reflection needs, however, also an assumption that the magnetic field on the poles, corresponding to IP (and maybe to MP), emerges from the stellar surface at large angles to the surface normal, so that the reflected radiation is directed into the angles corresponding to the observed components (Fig. 3). The difference of the magnetic field from a strictly dipole one, resulting in particular in its inclination, was also discussed in the literature in relation to a number of problems, see detailed references in [3].

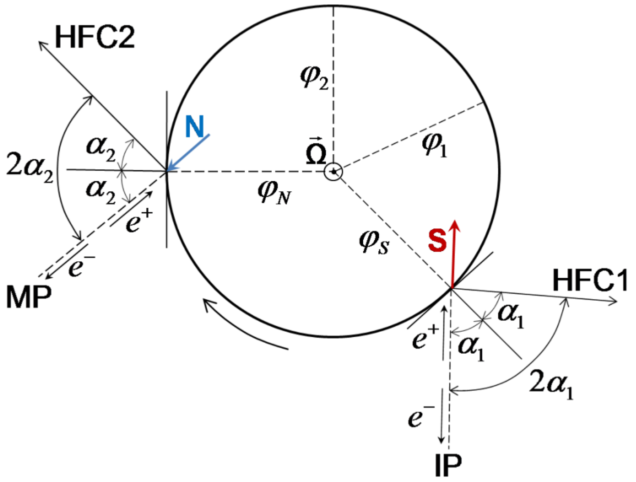

Fig. 3: Possible, but not suitable, explanation of the appearance of high-frequency components from the reflected emission by positrons in the case of large inclination angles of the magnetic field to the surface normal.

The present model, however, does not explain the shift of IP position, the explanation of which by reflection requires small value of the angle of the magnetic field emergence at the surface. Such model with large angles of the magnetic field inclination to the surface normal, explaining hf-components, however, cannot be used for explanation of the IP shift and we do not accept it further. Therefore we will use the idea of reflection of returning positron emission for the case of IP shift. Let us note that the idea of nonlinear reflection of emission by positrons taking into account the diffraction on the perturbed surface is more suitable for the description of the hf-components. This idea is discussed in [15], which is the continuation of the present work.

SHIFT OF THE INTERPULSE POSITION

In order to explain the IP shift we assume that in the 'magnetic plane' (see Fig. 5) the magnetic field at the poles, where it emerges at the surface, is deflected from the direction orthogonal to the surface to a small angle in the way presented in Fig. 4. We accept that the positron radiation is directed towards the stellar surface along the magnetic field at an angle determined by the angle of the magnetic field inclination. The doubled (due to the mirror reflection) deflection angle of the reflected radiation direction provides the required shift of IP.

The mirror reflection of radiation from the surface is assumed in this case. To explain the shift of the inter pulse positron by the mirror reflection of the positron radiation, it is necessary to introduce the inclination of the magnetic field at the poles equal to half of the angular displacement of the inter pulse. In the rough model the positrons radiate in the vicinity of the magnetic axis in the direction towards the surface. Due to the magnetic axis inclination the shift of the reflected radiation appears (see Fig. 4, φ_S is the phase of the normal to surface at the S-pole, which corresponds to the IP, φ_N is the same for the MP, $\Delta\varphi$ is the angle between the poles, which, according to Fig. 2, is 135 degrees), the very radiation which is observed at high-frequencies. Indeed, in this case the emission from positrons, which is narrowly focused due to the relativistic aberration, can be considered as directed along the magnetic field. Its mirror reflection from the surface will result in the turn of the reflected radiation direction at a double angle. Since, according to the observational data, the displacement of the IP is 7 degrees, we obtain for the slope of the field the value of 3.5 degrees in the magnetic plane. The latter itself has to be slightly inclined at a small angle to the equatorial plane (Fig. 5) that is orthogonal to the rotation axis. Due to this fact the MP may not hit the telescope diagram in agreement with observations. The 'line of knots' in Fig. 5 is the intersection of these planes, from which it is convenient to count the angles in the planes. The angles θ are the supplementary angles to the polar ones and denote the directions of the magnetic fields on the poles, the angle i is the angle between the planes, the azimuthal angles φ reader may find in the previous figure. The numbers with the primes refer to the magnetic plane and indicate the position of magnetic poles, numbers without the primes are their projections on the equatorial plane.

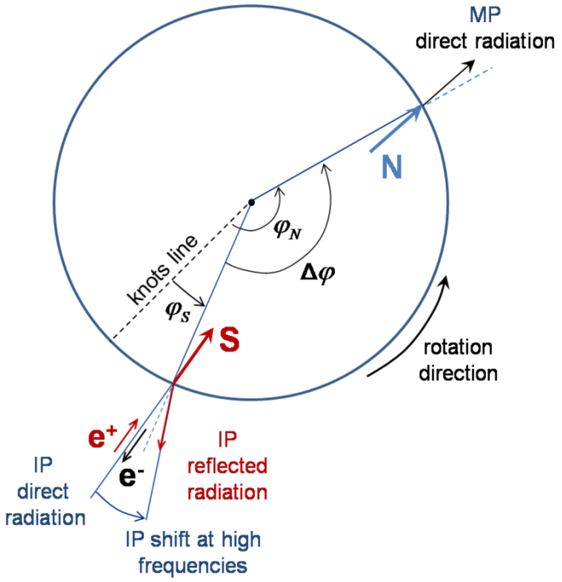

Fig. 4: To the explanation of the IP position shift as a result of positron radiation reflection. The magnetic field deflection from the normal to the surface of the star is the half of the IP angular shift.

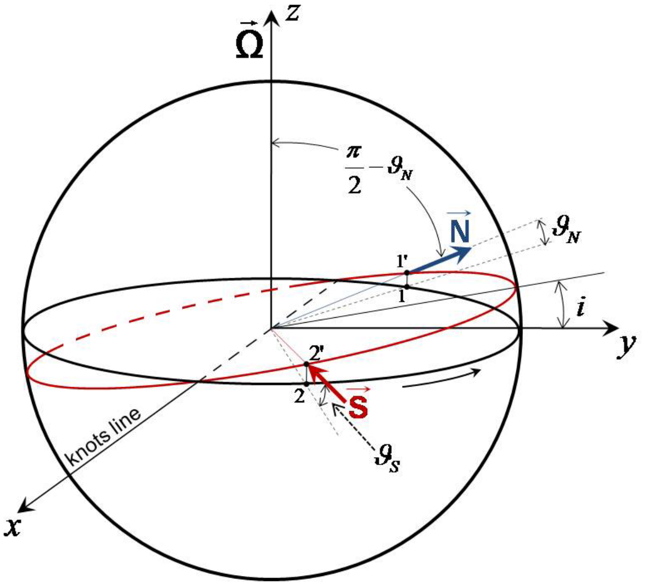

Fig. 5: Relative position of equatorial and magnetic planes.

POSSIBLE GEOMETRY OF THE MAGNETIC FIELD

In this section we will temporarily withdraw from the dipole model and show that in the toroidal one all its parameters can be restored from the observational data. In this case we consider the disappearing of the MP and IP [7, 24] as related to the mechanism of longitudinal acceleration in the gap [16]. As it is well known, a toroidal component can make a substantial contribution to the magnetic field of stars. This component can be even much more intense than the poloidal one, see [5]. Such a component can be inherent to pulsars as well. In this section we assume that the toroidal magnetic field lies in the 'magnetic plane', inclined to a small (of the order of several degrees) angle i with respect to equator. The z-axis is directed along the pulsar rotation axis. Outside the star in the vicinity of the poles we can still consider the field as close to the dipole one.

The azimuthal angle φ, supplementary to the rotation phase of the star, is counted in the equatorial plane from the 'knots line' which is parallel to the x-axis. In this case the coordinates (x, y, z) of a point on the surface of a unit sphere in the equatorial plane and the coordinates (x', y', z') of the corresponding point (the position of the initial point after rotation of the equatorial plane to the angle i around the x-axis, see Fig. 5) in the magnetic plane are defined as follows:

$$x = \cos\varphi,\ y = \sin\varphi,\ z = 0;$$

$$x' = x,\ y' = \cos i \sin\varphi,\ z' = \sin i \sin\varphi$$

Let us denote the magnetic pole corresponding to the main pulse (MP) as N, and the one corresponding to inter pulse (IP) as S. The azimuthal coordinate φ_N of MP and such coordinate φ_S of IP (at low frequencies) are connected by relation

$$\varphi_N = \varphi_S + \Delta\varphi, \tag{1}$$

where $\Delta\varphi = 135^\circ = 3\pi/4$ (for convenience of further discussion we have made a slight approximation of the values corresponding to the measured data [7, 24]: $\Delta\varphi = 145^\circ$).

Let us introduce the polar angle of a point in the magnetic plane as $\pi/2 - \theta$. Then the z-coordinates of magnetic poles are $z_{N,S} = \sin\theta_{N,S}$. On the other hand, they are equal $z_{N,S} = \sin i \sin\varphi_{N,S}$. The 'shutdown' of nonrelativistic radiation mechanism [16] is defined by the projection of magnetic field on the rotation axis B_z. The difference of frequencies at which MP and IP disappear may mean both the difference of magnetic inductions on the poles and the difference of projections at the same value of induction. We will assume the latter case. Then, according to [13, 14], the ratio of the values of B_z on the poles equals the ratio of the squares of the spectra cut-off frequencies (the value of this ratio is not precisely known and we choose it equal to 3). This leads to the expression:

$$\frac{\omega_N^2}{\omega_S^2} = \frac{(\Omega B \cos(\pi/2 - \theta_N))^2}{(\Omega B \cos(\pi/2 - \theta_S))^2} = \frac{\sin\theta_N}{\sin\theta_S} = \frac{\sin\varphi_N}{\sin\varphi_S} \approx 3 \tag{2}$$

for azimuthal coordinates of the poles, which with the use of Eq. 1 is reduced to

$$\sin\varphi_N = -3\cos(\varphi_N - \pi/4). \tag{3}$$

Therefore if we know the angle between the axes on the poles (from the magnetic dipole losses and the spectra cut off frequencies, as an example see [13]) and their azimuthal coordinates (from Eq. 1-3, that shows that the precise value of ratio in Eq. 2 is not very significant. Indeed, the change of the ratio causes vertical displacement of the curves, which in a fixed period will cause only a slight displacement of the intersection point of the curves defining our solution. The curves denote the left and right parts of Eq. 3, see Fig. 6), in principle it is possible to define the angle between magnetic and equatorial planes, and hence completely define the magnetic torus position. In this case the angle of the magnetic field emergence on the surface is defined by the phase shift of the interpulse.

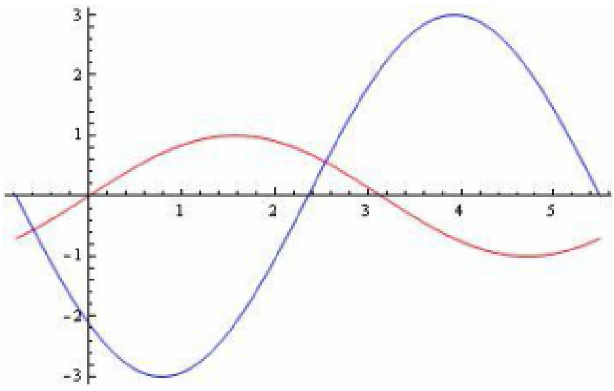

Fig. 6: Graphic solution of Eq. 3 for MP azimuthal coordinate φ_N of the North pole.

SUMMARY

Let us note that the relativistic positrons, which are accelerated towards the surface of the star by the inner gap electric field, radiate as 'half-bare' particles. The spectral-angular properties of this radiation differ from those ones of the electron curvature radiation inside the gap. Together with that and with hard radiation at positron annihilation on the surface, which is not considered here (see [19]), the interference of the positron's own Coulomb field with its curvature radiation, the so called relativistic positron 'half-bareness' effect, is significant within macroscopic radiation 'formation' length [1]. (The term 'half-bare' highlights the fact that during the positron motion along a magnetic field line in the gap the long-wave part of its Coulomb field does not have time to follow the shorter-wavelength part, which influences upon the reflected radiation characteristics.) This influences upon the characteristics of both the reflected radiation and the 'transition' one [9] generated at the moment of the positron contact with the stellar surface. The latter arises when a charged particle crosses the border of media with different dielectric constants. In the considered case the backward transition radiation interferes with the high-radio-frequency part of the curvature radiation emitted by the positrons and reflected from the surface of the star.

The more detailed discussion with the use of data about accelerating electric field in the case of dipolar magnetic field in the gap [2, 8, 26, 27] and known formulae of classical electrodynamics [1] see in [17, 18] and in the next separate paper in the present journal. For independent treatment of the HFCs, not connected with the IP shift, see [25].

Further elaboration of the approach considered here might clarify the connection between the observation data in the frequency range, in which the reflected radiation prevails, with the surface properties of the pulsar in Crab, and obtain quite direct information about them.

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APPENDIX: LIST OF DENOMINATIONS IN FIG. 3-5

Fig. 3. α_1 and α_2 are the angles of the magnetic field inclination in the equatorial plane at the poles responsible for the main pulse and the interpulse formation, at which the mirror reflected components would correspond to the observed phases φ_1 and φ_2 of hf-components; φ_S and φ_N are respectively the phases of S and N poles; Ω is the angular rotation frequency of the star; the arrows show the directions of rotation, magnetic fields and the motion of electrons and positrons. The proposed variant does not explain the interpulse shift and is not considered further .

Fig. 4. φ_S and φ_N, as well as S and N, have the same meaning as in Fig. 3, but are counted from the 'knots line' (see Fig. 5); $\Delta\varphi$ is the phase shift between the main pulse and the interpulse .

Fig. 5. Equatorial plane is the plane orthogonal to the rotation axis z; magnetic plane is the plane, in which by assumption the magnetic fields at both

poles S and N lie; 'knots line' is the line of intersection of the equatorial and the magnetic planes; ϑ_S and ϑ_N are the angular rise of the poles above the equatorial plane; $1'$ and $2'$ are the poles positions in the magnetic plane; 1 and 2 are the projections of the poles positions on the equatorial plane; x axis is directed along the 'knots line', y axis is perpendicular to it and lies in the equatorial plane; i is the angle between the equatorial and the magnetic planes; the magnetic and the rotation axes are assumed to be nearly orthogonal and the angles ϑ_S, ϑ_N and i are small.

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