GAMMA RADIATION OF PULSARS AS RESULT OF INVERSE COMPTON SCATTERING AT ACCELERATION OF ELECTRONS IN A PULSAR POLAR GAP

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A gamma radiation from pulsars due to inverse Compton scattering of coherent low-frequency radiation on relativistic electrons in a polar gap have been considered. The radio emission in the gap arises due to sub relativistic electron acceleration. The gamma radiation spectrum and luminosity estimates have been obtained and connection between gamma radiation and radio emission spectra has been found. Obtained results are in a good agreement with the discovered by Fermi LAT correlation of gamma radiation and radio emission giant pulses in the Crab pulsar.

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1. INTRODUCTION

Pulsars are rapidly rotating neutron stars with very strong magnetic fields [1–3], which have magnetosphere filled with relativistic electron-positron plasma. This plasma is produced by high energy photons in strong magnetic field above the star magnetic poles [2].

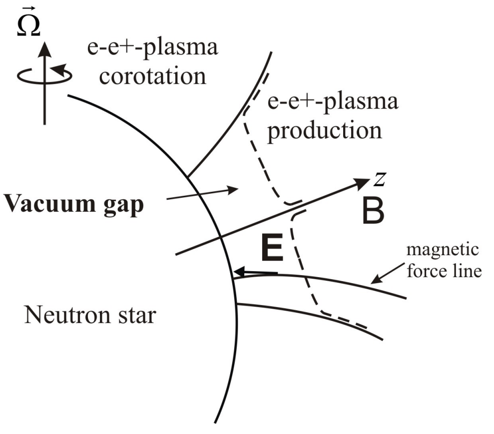

Fig. 1. *A scheme of the polar gap in pulsars*

Pulsars are the pulse sources of radio waves and some of them emit high energy gamma radiation. The pulsar gamma radiation arises in an inner gap [4] above a polar cap under magnetosphere of open magnetic field lines (Fig. 1), which plays a role of an accelerator for electrons from the star surface. In pulsar classical models [4,5] the gamma radiation are generated due to curvature radiation (CR) mechanism [6]. We showed [7] that the powerful radio band radiation in the gap changes the gamma emission mechanism from the curvature radiation to inverse Compton scattering (ICS) of low-frequency radiation. It leads to connection between pulsar gamma ray radiation and radio emission. The correlations (both in luminosities and spectra) of pulsar radio emission and gamma ray radiation was predicted in [7]. In that work we considered the polar gap as a resonator cavity accumulating powerful low-frequency radiation generated by the sparks [4] in the strong electric field of the gap. The formation of the resonator and accumulation of high energy density have some difficulties. In [8, 9] we have shown that the high energy density of low-frequency radiation may arise because of continuous energy pumping due to emission in electron acceleration process in the gap electric field. The free exit of electrons from the star surface due to low electron work function [10] leads to vanishing the electric field on the surface. This field increases from zero with distance from the star surface and emission of electrons falls within the radio spectral range. The Fermi LAT data obtained after our work [7] showed that there is a correlation in phase (Fig. 2) between radio giant pulses and gamma ray radiation [11]. The authors of [11] related this correlation with a reconnection of magnetic force lines near light cylinder [12]. In the Lyutikov model [12] of pulsar giant pulses (Fig. 3) there is a reconnection of magnetic force lines at the periphery of pulsar magnetosphere near the light cylinder where there is a region of dense hot plasma. Occasional reconnection jets produce high Lorentz factor beams propagating along magnetic force lines and emitting coherent cyclotron-Cherenkov radiation at anomalous Doppler resonance. Due to curvature radiation high

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energy beams emit also the hard gamma ray photons correlated with radio giant pulses.

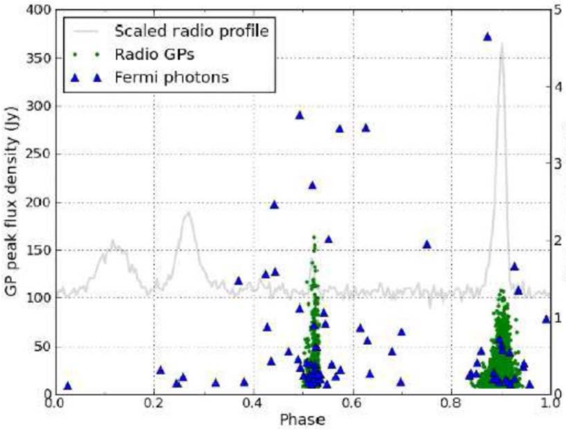

Fig. 2. *Phase correlation between gamma pulses (triangles) and radio giant pulses (circles) observed by Fermi LAT (from the paper of A.Belous et al [11])*

The observed phase correlation may be considered also as confirmation of idea of our model that there is a powerful radio emission in the gap and pulsar giant pulses are direct emissions through waveguides in the magnetospheric plasma [13, 14]. The gamma ray radiation leaves the gap through the waveguide too, therefore the phase correlation between the radio giant pulses and gamma ray pulses arises. In the Crab pulsar B0531+21 the waveguide is close to the magnetic axis.

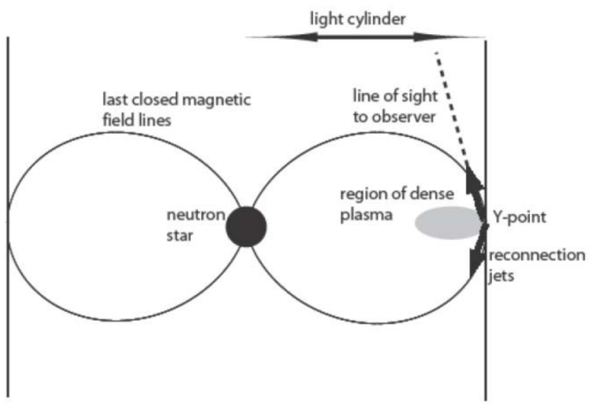

Fig. 3. *Generation of the Crab pulsar giant pulses in the Lyutikov model [12]*

Below it is shown that the total luminosity of gamma rays produced by ICS of the low-frequency radiation [7, 15] in the gap is sufficient to explain the gamma emission from pulsars if the gamma radiation goes out from the all surface of the polar cap (Fig. 1).

2. HARD GAMMA RAY RADIATION DUE TO INVERSE COMPTON SCATTERING IN THE GAP

Because of the high energy density of the low-frequency radiation there are a lot of soft photons in the gap which are scattered by the relativistic electrons. As is shown [8] that in this case the spectrum of the coherent radio emission is the power-law

$$I(\omega) \propto \omega^{-\alpha}, \tag{1}$$

where α is a spectral index, which has the values from the range $1 \leq \alpha \leq 3$. The frequencies of initial photons obey a condition $\hbar\omega\Gamma << mc^2$, so we can consider the ICS in the Thomson limit. In the electron rest frame the differential cross section of the ICS in the strong pulsar magnetic field has the form [16–18]

$$d\sigma = \frac{r_e^2}{4}\frac{\omega^2}{\omega_B^2}\left(1+\cos^2\theta\right)\left(1+\cos^2\theta'\right)d\Omega', \tag{2}$$

where r_e is the electron classical radius, $\omega_B = eB/mc$, B is the star surface magnetic field, θ and θ' are the angles between magnetic field and momenta of the initial and final photons (Fig. 4), $d\Omega' = 2\pi\sin\theta' d\theta'$. The cross section dependence on the magnetic field describes the suppression of soft photon Compton scattering in strong magnetic fields [17].

Using Eq. (4) and the Lorentz transformations for angles θ, θ' we obtain the scattering cross section for the case of the ultrarelativistic electrons

$$d\sigma = r_e^2\frac{\omega^2}{\omega_B^2}\frac{\left(1-\frac{V}{c}\cos\theta\right)^2}{\left(1-\frac{V}{c}\cos\theta'\right)^2}d\Omega'. \tag{3}$$

From Eq. (5) it is seen that the scattered radiation is quite anisotropic due to relativistic aberration and is concentrated within a narrow cone along the open magnetic field lines.

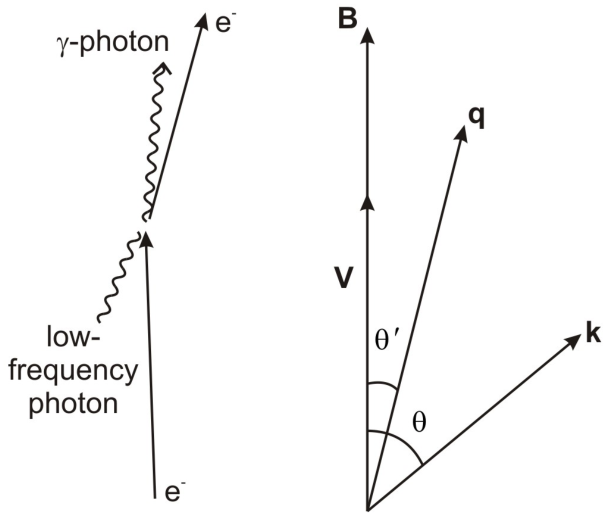

Fig. 4. *ICS (left) and its kinematics (right)*

With help of Eq. (3) we write the scattering probability as [19]

$$w(\mathbf{q}, \mathbf{k}, \Gamma)\, d^3q = c\left(1-\frac{V}{c}\cos\theta\right)d\sigma,$$

where $\mathbf{q}$ is the scattered photon wave vector, and

$$w(\mathbf{q},\mathbf{k},\Gamma) = c^4 \frac{r_e^2}{\omega_B^2}\left(1-\frac{V}{c}\cos\theta\right) \times \delta\left(\omega_\gamma - \omega\frac{1-\frac{V}{c}\cos\theta}{1-\frac{V}{c}\cos\theta'}\right), \quad (4)$$

ω_γ is a frequency of gamma ray photon. The spectrum $I(\omega_\gamma)\,d\omega_\gamma$of the radiation is given by

$$I(\omega_\gamma) = \frac{\hbar\omega_\gamma^3}{4\pi^2c^3}\int w(\mathbf{q},\mathbf{k},\Gamma) f_e(\Gamma,z)\, n(\mathbf{k}) \times d\Omega' d\Gamma d\Sigma dz, \quad (5)$$

where $f_e(\Gamma,z)$ and $n(\mathbf{k})$ are the distribution functions of electrons and low-frequency photons, which are normalized as

$$\int_1^\infty f_e(\Gamma,z) d\Gamma = n_e, \quad \int \hbar\omega \cdot n(\mathbf{k}) \frac{2d^3k}{(2\pi)^3} = U,$$

$n_e \approx n_{GJ} = \Omega B/2\pi ce$ is the average electron concentration in the gap (n_{GJ} is the Goldreich-Julian particle density [20]), Ω is the pulsar rotation frequency, and $U$is the total energy density of the radio emission in the gap. Since the low-frequency radiation spectrum is power-law we have for the distribution of the low-frequency photons

$$n(\mathbf{k}) = \frac{\pi^2c^3}{\hbar}(\alpha-1)\, U\omega_{min}^{\alpha-1}\omega^{-(3+\alpha)}, \quad (6)$$

and $\omega_{min} \sim 10^7\mathrm{s}^{-1}$ is a minimal frequency of low-frequency radiation in the gap. The electron distribution function is given by

$$f_e(\Gamma,z) = n_e\delta(\Gamma - \Gamma(z)). \quad (7)$$

Then the scattered radiation spectral distribution takes a form [7]

$$I(\omega_\gamma) = \frac{3}{8}\frac{2^{2\alpha}}{\alpha+2}\frac{c\sigma_T n_e U \Sigma_{PC}}{\omega_B^2}\omega_{min}^{\alpha-1} \times \omega_\gamma^{2-\alpha}\int_0^h \Gamma^{2\alpha-2}(z)\, dz, \quad (8)$$

with σ_T being the Thomson cross section. We see from Eq. (8) that in case of power-law radio emission spectrum (1) the gamma ray spectrum is also a power-law with the index connected with the radio spectral index $\alpha$by the relation [7]

$$\alpha_\gamma = \alpha - 2. \quad (9)$$

This relation appears due to dependence of the scattering cross section on the initial photon frequency (see Eq. (2)). According to the Fermi LAT observation data [21] several gamma ray pulsars such as PSR B0531+21 (Crab) and PSR B0833-45 (Vela) obey to this index relation (9).

Integrating the spectral distribution (8) over frequencies of scattered photons we obtain the estimation of the total gamma ray luminosity

$$I_\gamma = \int I(\omega_\gamma)\, d\omega_\gamma \approx cgn_e\sigma_T U\bar{\Gamma}^4\Sigma_{PC}h, \quad (10)$$

where $\bar{\Gamma} \sim 10^8$ is the electron maximal Lorentz factor in the gap and

$$g = \frac{24}{5}\frac{\alpha-1}{\omega_B^2}\omega_{min}^{\alpha-1}\int_{\omega_{min}}^{\omega_{cf}} \omega^{2-\alpha} d\omega. \quad (11)$$

The ICS predominates over the curvature radiation and becomes a dominant mechanism of energy losses when the condition satisfies

$$U > U_{min} = \frac{2e^2}{3R_c^2 g\sigma_T},$$

where is a curvature radius of magnetic force line. Below we suppose that this condition satisfies.

Substituting $U \approx I_R/c\Sigma_{PC}$ to Eq. (10), we obtain a relation between radio and gamma ray luminosities [7]

$$I_\gamma \approx g\sigma_T n_e h\bar{\Gamma}^4 I_R. \quad (12)$$

The total radio emission intensity in the gap is determined by contribution of all electrons of the polar cap in the radiation formation region. The power emitted by a single electron moving with acceleration $w = eE/m\Gamma^3$ is $2e^4E^2/3m^2c^3$ [6,22], where E is the accelerating field in the gap [23,24]. Taking into account the contributions from all emitting electrons and the coherence [25] of emission we have for the total radio luminosity estimate

$$I_R \approx \frac{\lambda_{max}^2\Omega^3R^3B^2}{c^2}, \quad (13)$$

where $R \sim 10^6\,\mathrm{cm}$ is the star radius and $\lambda_{max} \sim 10^2\,\mathrm{cm}$ is a wavelength, corresponding to the maximum in the pulsar radio emission spectrum. With help of Eq. (12) we have for the gamma ray luminosity

$$I_\gamma \approx \frac{\lambda_{max}^2\Omega^3R^3B^2}{c^2} g\sigma_T n_e h\bar{\Gamma}^4. \quad (14)$$

In dependence on the pulsar parameters, this estimate gives 10^{33} erg/s $\leq I\gamma \leq 10^{35}$ erg/s, that agrees with the Fermi LAT data on luminosities of gamma ray pulsars [21]. For the pulsar B0531+21 which is close to orthogonal rotator estimates (13) and (14) should be multiplied by a factor $\cos^2\chi$, where $\chi \approx 87^o$ is an angle between magnetic and rotation axis of the pulsar B0531+21 then the Eq. (14) gives a correct estimate $I\gamma \sim 10^{35}$ erg/s for the Crab pulsar gamma ray luminosity too.

Earlier [7] we considered the gamma ray radiation exit only through the waveguide near the magnetic axis. But the observations by Fermi LAT show that the gamma ray radiation is observed from larger part of open magnetic force line region. Therefore in estimates (10) and (14) we suppose that the area of hard gamma ray formation region is of order of the polar cap area.

3. CONCLUSIONS

Due to inverse Compton scattering of the power radio emission on the ultrarelativistic electrons in the gap the gamma-radiation is formed [7]. Giant pulses of radio waves correspond to the free exit of radiation through the waveguide near the magnetic axis [13, 14, 26]. According [11] one can conclude that the gamma radiation direction diagram has also the maximum along the magnetic axis. Through the same break the gamma-radiation goes out from the gap, which explains the angular correlation of the gamma-radiation with the giant pulses, including the case of absence of their simultaneity. The obtained estimates of pulsar gamma ray luminosities and spectra agree with Fermi LAT data if we take into account the gamma radiation from the all surface of the polar cap.

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ГАММА-ИЗЛУЧЕНИЕ ПУЛЬСАРОВ КАК РЕЗУЛЬТАТ КОМПТОНОВСКОГО РАССЕЯНИЯ ПРИ УСКОРЕНИИ ЭЛЕКТРОНОВ В ПОЛЯРНОМ ЗАЗОРЕ

А.Б. Фланчик, В.М. Конторович

Рассмотрено формирование гамма-излучения пульсаров при обратном комптоновском рассеянии когерентного низкочастотного излучения релятивистских электронов в полярном зазоре. Радиоизлучение в зазоре возникает при ускорении субрелятивистских электронов. Получены спектр и оценки мощности гамма-излучения, а также найдена связь между радиоизлучением и гамма-излучением. Полученные результаты находятся в хорошем согласии с открытой с помощью Fermi LAT корреляцией гамма-излучения и гигантских импульсов радиоизлучения пульсара в Крабовидной туманности.

ГАММА-ВИПРОМІНЮВАННЯ ПУЛЬСАРІВ ЯК РЕЗУЛЬТАТ КОМПТОНІВСЬКОГО РОЗСІЮВАННЯ ПРИ ПРИСКОРЕННІ ЕЛЕКТРОНІВ У ПОЛЯРНОМУ ЗАЗОРІ

О.Б. Фланчик, В.М. Конторович

Розглянуто формування гамма-випромінювання пульсарів завдяки зворотному комптонівському розсіюванню когерентного низькочастотного випромінювання релятивістських електронів у полярному зазорі. Радіовипромінювання у зазорі виникає при прискоренні субрелятивістських електронів. Отримано спектр і оцінки потужності гамма-випромінювання, а також знайдено зв'язок між радіовипромінюванням та гамма-випромінюванням. Отримані результати узгоджуються з відкритою за допомогою Fermi LAT кореляцією гамма-випромінювання і гігантських імпульсів радіовипромінювання пульсару у Крабовидної туманності.