Nature of the γ radiation with ~ 1 TeV observed from the Crab and Vela pulsars

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Spectra of ultrahard γ radiation are calculated. The radiation is generated near the light cylinder in an inverse Compton scattering of relativistic electrons by thermal-radiation photons from a neutron star. It is predicted that γ bursts will be correlated with bursts in the soft x-ray region with $E_x \sim 1$ keV.

Statistically significant photon fluxes with energies $> 10^{11}$ eV have been observed from only a few sources.[1,2] Among them there are two radiopulsars: the Crab and Vela pulsars. The generation of photons at such energies in pulsars with a magnetic field $\sim 10^{12}$ G at their surface should occur fairly far from the neutron star. Only in this case would the conversion of a γ ray into an e^+e^- pair in the magnetic field not prevent the emission of the radiation from the source. For the rapidly rotating Crab and Vela pulsars, the region of a free emission of γ rays begins near the light cylinder. The radius of the light cylinder is c/Ω, where Ω is the pulsar rotation frequency.

It is becoming progressively clearer that an effective acceleration of charged particles should also occur near the light cylinder. The reason is that the existing models, in which the acceleration occurs in regions of the magnetosphere which are interior regions with respect to the light cylinder,[3-5] cannot explain the energy released in relativistic particles for the Crab and Vela pulsars. For these pulsars, this energy is comparable to the loss of rotational energy determined from the slowing of the rotation.

A theoretical analysis shows that the energy source for particle acceleration near the light cylinder is an electromagnetic field. Beskin *et al.*[6] have pointed out an important circumstance: for pulsars of the Crab and Vela type, the energy flux in the azimuthal magnetic field, which is generated during the rotation of the pulsar, is several orders of magnitude higher than the kinetic-energy flux of the plasma. The energy loss associated with the escape from the magnetosphere of the azimuthal magnetic field which is continuously being generated is[6]

$$L = \frac{1}{4}\frac{H^2R^6\Omega^4}{c^3}, \tag{1}$$

where H is the magnetic field at the surface of the pulsar, and R is the radius of the pulsar. Expression (1) was written for the case in which the rotation axis is parallel to the magnetic moment. It turns out that even in this case an effective acceleration occurs near the light cylinder.[7] This acceleration occurs in a thin sheet which forms at the Alfvén surface, where the plasma flow velocity is equal to the local Alfvén velocity. The current sheet closes the circuit for a current flowing out of the polar cap of the

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pulsar and does this onto a field line which separates regions of closed and unclosed field lines.[6] The current coming from the polar cap, generated in the course of the rotation, is related to the azimuthal magnetic field by Maxwell's equation curl $\mathbf{H}_\varphi = (4\pi/c)\mathbf{j}$. When the circuit for the current becomes closed in the current sheet, azimuthal magnetic field is annihilated, and its energy is converted into the energy of particles.

Working from the results of Ref. 7, we can derive the spectrum of particles ejected per unit time from the magnetosphere:

$$\frac{dN}{dt d\gamma} = \begin{cases} 0; & \gamma < \gamma_0 \\ 2\lambda^2 \frac{mc^3}{e^2}; & \gamma_0 \leqslant \gamma \leqslant \gamma_{max} \\ 0; & \gamma > \gamma_{max} \end{cases} \quad (2)$$

Here γ is the Lorentz factor of the particle, and λ is the ratio of the $e^+ e^-$ plasma which forms near the poles to the Goldreich density[3] $n_G = \Omega H/2\pi ec$. From Ref. 8 we have $\lambda \sim 10^3$, and the initial Lorentz factor of the plasma is $\gamma_0 \sim 10^4$. The maximum Lorentz factor of the particles is given by[7]

$$\gamma_{max} = \gamma_0 + \frac{1}{2} \frac{eHR}{\lambda mc^2} (\frac{R\Omega}{c})^2 . \quad (3)$$

One can verify that the integral $\int_0^\infty \gamma mc^2 (dN/dt d\gamma) d\gamma$ is equal to expression (1) plus an increment determined by the kinetic-energy flux of the plasma.

Spectrum (2) was derived for the case of an axisymmetric rotation of a neutron star. We will use this spectrum below to find the spectrum of γ radiation with $E_\gamma \sim 1$ TeV. We will compare this spectrum with the spectrum observed from the Crab and Vela radiopulsars. From this comparison with observations we will attempt to determine how well spectrum (2) describes the spectrum of particles accelerated near the light cylinder of real pulsars.

The γ radiation with an energy ~ 1 TeV is generated as a result of an inverse Compton scattering of relativistic electrons (and positrons) by thermal photons emitted by the neutron star. Observations show that the surface of the Vela pulsar has a temperature[9] $T = 1.0 \times 10^6$ K. The Crab pulsar, being younger, should apparently be even hotter. The density of blackbody-radiation photons near the light cylinder is $n_b = 0.244(T/\bar{\lambda})^3 (R\Omega/c)^2$. Here and below, T, E_γ, and ω (the energy of the thermal photons) are expressed in units of mc^2, and $\bar{\lambda}$ is the Compton wavelength of an electron.

The energy of the photons produced in inverse Compton scattering is, in the limit $\omega\gamma \gg 1$, essentially equal to the energy of the incident electron.[10] On this basis, we find the following integral spectrum of γ rays at the earth, using (2):

$$N(>E_\gamma) = 0{,}16 \frac{c r_e R T^2 \lambda^2}{\bar{\lambda}^3 R_*^2 \theta} (\frac{R\Omega}{c})(\ln(6T\gamma_{max}) + \frac{1}{2} \ln \frac{\gamma_{max}}{E_\gamma} \quad (4)$$

Here R_* is the distance to the source, r_e is the classical radius of an electron, and θ is

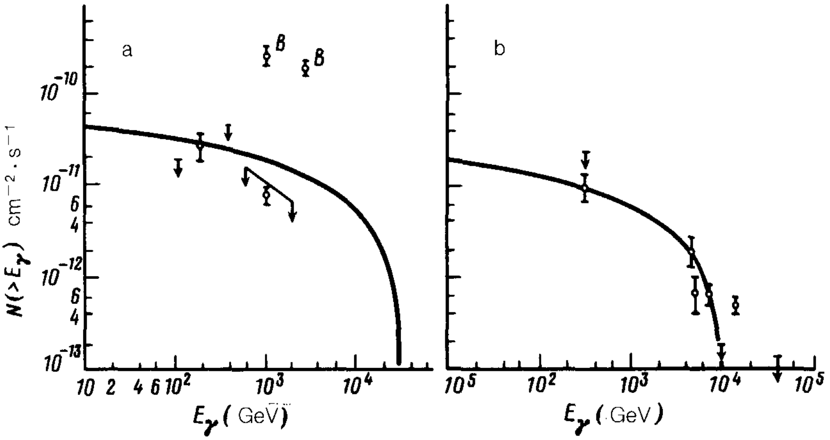

FIG. 1. Comparison of theoretical spectra with spectra of the observed γ radiation from (a) the Crab pulsar and (b) the Vela pulsar. The points labeled with a B for the Crab pulsar are flux values observed during bursts.

the vertex angle of the cone in which the radiation is generated. We found θ from the γ-ray phase brightness curve of the pulsars.

Figure 1 compares theoretical spectra (4) with observational data on the Crab and Vela pulsars. The following parameter values were used in these calculations: for the Crab pulsar, $L = 4 \times 10^{38}$ erg/s, $R_* = 2$ kpc, $\theta = 0.2$, $\lambda = 10^3$, $T = 10^6$ K, and $H = 5.8 \times 10^{12}$ G; for the Vela pulsar, $L = 7 \times 10^{36}$ erg/s, $R_* = 0.5$ kpc, $\theta = 0.6$, $\lambda = 500$, $T = 10^6$ K, and $H = 6.6 \times 10^{12}$ G. All these values are typical of these pulsars. On the whole, there is a good agreement between theory and observation. The differences which we do see could hardly be judged as being of a fundamental nature, particularly in view of the poor reliability of the experimental data, the uncertainty in the coefficient λ, and the circumstance that the angle between the rotation axis and the direction of the magnetic moment is actually not zero.

In the calculation of the γ spectrum, only the thermal radiation of the neutron star was taken into consideration. Actually, the flux of nonthermal radiation from the Crab pulsar is several orders of magnitude higher than that of the thermal radiation. If the nonthermal x radiation is not to result in the generation of excess γ radiation, it must be generated in the same place as the γ rays and by the same electrons. Only in this case would the soft photons and the relativistic electrons move in a common direction, and only in this case would their scattering not lead to the formation of hard photons.

Observations of the Crab pulsar in γ rays with $E_\gamma \sim 1$ TeV reveal sharp increases of a burst nature against the background of a periodic steady-state flux. The results of such observations are labeled with a B in Fig. 1. It can be seen from (4) that the γ intensity depends very strongly on T and λ. An increase in these properties by a factor of 4 or 5 might explain the observed increase in the flux. The coefficient γ is determined by the structure and strength of the magnetic field at distances $\sim R$ from the pulsar.[8] It is unlikely that there would be any significant variations in this coefficient. An increase in surface temperature might occur upon, for example, the release of energy associated with stress in a solid crust on the pulsar during starquakes.[11] Such effects should be accompanied by a disruption of the rotation period. For the Vela pulsar, a burst in the soft x-ray region has been observed only once, and it has not been directly associated with a disruption of the period.[12] It is possible that this factor explains the absence of observations of γ bursts from this pulsar. For the Crab pulsar, a correlation between the x-ray bursts and the γ bursts, which occur more frequently, might be observable, since an increase in the temperature to $(4\text{–}5)\times 10^6$ K would go beyond the upper limit on the range of the temperature of this pulsar,[13] 2.5×10^6 K.

[1] T. C. Weekes, Phys. Rep. **160**, 3 (1988).
[2] F. A. Agaryonyan, É. A. Mamedzhanyan, and S. I. Nikol'skiĭ, Astrofizika **31**, 195 (1989).
[3] M. Ruderman and P. G. Sutherland, Astrophys. J. **196**, 51 (1975).
[4] J. Arons, Astrophys. J. **266**, 215 (1983).
[5] K. S. Cheng, C. Ho, and M. Ruderman, Astrophys. J. **300**, 522 (1986).
[6] V. S. Beskin, A. V. Gurevich, and Ya. N. Istomin, Zh. Eksp. Teor. Fiz. **85**, 401 (1983) [Sov. Phys. JETP **58**, 235 (1983)].
[7] S. V. Bogovalov, Pis'ma Astron. Zh. **15**, 1081 (1989) [Sov. Astron. Lett. **15**, 469 (1989)].
[8] A. V. Gurevich and Ya. N. Istomin, Zh. Eksp. Teor. Fiz. **89**, 2 (1985) [Sov. Phys. JETP **62**, 1 (1985)].
[9] F. R. Harnden, Grant, Jr., P. D. Seward *et al.*, Astrophys. J. **299**, 828 (1985).
[10] V. L. Ginzburg (editor), *Cosmic-Ray Astrophysics*, Nauka, Moscow, 1982.
[11] R. Manchester and J. Taylor, *Pulsars*, Freeman, San Fransisco, 1977.
[12] A. Smith and K. A. Pounds, Nature **265**, 121 (1977).
[13] F. R. Harnden and F. D. Seward, Astrophys. J. **283**, 279 (1984).

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