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A MODEL OF PULSED GAMMA-RADIATION FROM THE X-RAY BINARY HERCULES X-1/HZ HERCULIS

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МОДЕЛЬ ПУЛЬСИРУЮЩЕГО ГАММА-ИЗЛУЧЕНИЯ В ДВОЙНОЙ СИСТЕМЕ HER X-1/HZ HER

Предлагается модель пульсирующего гамма-излучения ОВЭ и СВЭ от рентгеновских двойных, в которой предполагается, что это излучение возникает в результате бомбардировки облака-мишени, выбрасываемого из звезды-компаньона, пучком релятивистских частиц, стационарно ускоряемых пульсаром. В рамках этой модели естественным образом объясняются все особенности гамма-излучения рентгеновской двойной Her X-1/HZ Her: а) смещение частоты гамма-пульсаций относительно частоты рентгеновских пульсаций; б) эпизодичность излучения с характерной длительностью $\Delta t \lesssim 1$ час; в) отсутствие корреляций между гамма-вспышками и фазой ϕ орбитального вращения; г) возможность наблюдения гамма-вспышки в фазе полного затмения рентгеновского излучения. Обсуждаются ожидаемые формы спектров гамма-излучения в широком диапазоне 100МэВ$\le E \le$1ПэВ, а также возможности экспериментальной проверки предлагаемой модели, основанные, в частности, на предсказании одновременных наблюдений аномально пульсирующего излучения в оптическом-ультрафиолетовом диапазоне $h\nu \sim (1-10)$эВ, а также в гамма-диапазоне 1МэВ$\le E \le$100МэВ.

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1. Introduction

Investigations of the last decade revealed that X-ray binaries presumably are powerful sources of γ-radiation of very high (E>100GeV), and ultra high (E>100TeV) energies (hereinafter VHE and UHE, respectively). The X-ray pulsar Hercules X-1 is one of the best studied sources of this class. The γ-radiation from this source has some distinctions confirmed by several independent observations:

a) An episodic character of the radiation. The observations testify that the γ-radiation from this source has a burst-like character. In the first observation of this source at TeV energies the burst lasted $\Delta t \simeq 3$ min [1]. In other observations (in VHE region) burst duration varied from $\Delta t \sim 10$ min to $\Delta t \lesssim 1$ hour [2-4]. Gamma events of the same timescale $\Delta t < 1$ hour have been observed at $E \gtrsim 100$ TeV by the Fly's Eye [5] and Cygnus [6] installations.

b) The frequency shift of γ-radiation pulsations relative to that of X-rays. As a rule, a difference between the pulsed γ-ray and X-ray frequencies from observation to observation is detected. The value of the shift $\Delta\nu = \nu_\gamma - \nu_o$ (where ν_o is the spin frequency of the pulsar, which is supposed to coincide with the pulsed X-ray frequency) predominantly has the positive sign (blue-shift), though at least one red-shifted event has been observed [3,4]. The characteristic shift scale is $\frac{|\Delta\nu|}{\nu_o}$ ~0.1%.

c) The absence of orbital phase modulation. γ-ray events have been observed practically at any orbital phase within $0<\phi<1$. Particularly exciting is the report [7] on observation of the γ-ray episode in the orbital phase $\phi\simeq0.95$, i.e. in an hour after the onset of the complete eclipse of the X-ray source at $\phi_{ecl}=0.93$.

The parameters of the binary Hercules X-1/HZ Herculis consisting of a pulsar and a companion normal star, have been studied with a rather high accuracy, which significantly limits the frame of the models of pulsed γ-radiation. In particular it seems problematic to explain all these features of γ-radiation by the existing models suggesting that γ-rays are produced due to bombardment of the companion star by particles accelerated in the compact object.

In this paper we propose a model of pulsed γ-radiation from Hercules X-1/HZ Herculis, the basic assumption of which is, that the companion star episodically ejects rather massive clouds of matter, which, moving along certain trajectories, may intersect the propagation cone of the beam of relativistic particles continuously accelerated by the pulsar. As a result of that "beam-cloud collision" γ-radiation can be produced for which all the characteristics mentioned above have a quite natural explanation.

2. The Model

The key assumption of the model is the hypothesis, that for some reason the normal companion star in the binary system, HZ Herculis, ejects relatively dense ($n\gtrsim10^{15}cm^{-3}$) clouds with characteristic masses $M_c\sim10^{22}-10^{23}g$ and initial velocities $v_0\sim3\cdot10^7 cm/s$ (the required parameters are discussed in Sec.4). It is assumed that the compact object (pulsar) continuously accelerates particles (protons and/or nuclei) up to $E>10^{15}eV$. Under certain conditions the cloud trajectory in the binary system may intersect with the propagation cone of the accelerated particles. The charged particles entering the cloud become chaotic due to the tangled magnetic fields in the cloud, and produce γ-rays at interactions with the ambient matter. Duration of the γ-ray emission is determined mainly by the lifetime of the cloud under intense heating by the beam. The characteristic lifetime (time of expansion) of the cloud is $\Delta t\lesssim1$ hour (see Sec.4), which is in agreement with the characteristic timescale of the observed γ-ray events.

In the frame of the proposed model the observed shift of pulsed γ-radiation frequency relative to the X-ray one (in the rest frame of the pulsar) finds a natural explanation. Namely, the frequency shift of scale $|\Delta\nu|/\nu_o\sim0.1\%$ can be easily interpreted as a consequence of the double Doppler effect (reemission of pulsed signal from a moving target). Depending on the orbital phase ϕ and on the initial conditions of cloud ejection, both positive and negative shifts relative to the pulsed X-ray frequency are possible.

Since γ-radiation arises at collision of the beam of accelerated particles with clouds, ejected spontaneously from the normal star, then it is obvious that there is no reason for any correlation between the orbital phase and the γ-ray production. Moreover, at a cloud trajectory high enough one may expect γ-rays even in the deep eclipse of the X-ray source, which just had occurred in the event of June 16, 1985 [7].

The characteristic parameters of the cloud must satisfy certain conditions. Namely, the cloud should be dense ($n \gtrsim 10^{15} cm^{-3}$) and compact ($R \lesssim 10^{10} cm^{-3}$) in order not to distort essentially the pulsed γ-radiation with period $P_0=1.24s$. At the same time, the size of the cloud should not be less than $R_{min} \simeq 3\cdot 10^9 cm$, otherwise energy requirements to the beam become extraordinarily high. The value of the magnetic field in the cloud should be $B \sim 10^2-10^3$ Gauss, for an effective opening (chaotization) of the relativistic proton beam inside the cloud.

3. Motion of the Cloud in the Rest Frame of the Binary

As is known, in the binary system Hercules X-1/HZ Herculis the stars (a pulsar and a class A giant) have circular orbits in the plane of observer.

Consider the parameters of the trajectory of a test particle ejected from the normal star which fills up its Roche lobe. The equation of motion in the system of coordinates rotating with an angular velocity $\Omega=2\pi/P_0$ around the axis passing through the centre of masses of the binary, perpendicular to the orbital plane (i.e., in the rest frame of the binary), is written as:

$$\frac{d^2\vec{r}}{dt^2} = \frac{\vec{F}}{m} + \vec{\Omega}(\Delta\vec{r} \times \vec{\Omega}) - 2(\vec{\Omega} \times \frac{d\vec{r}}{dt}). \qquad (1)$$

Here $\vec{F}$ is the sum of gravitational forces acting on the test particle with mass m; $\Delta\vec{r}=\vec{r}-\vec{r}_{c.m.}$, where $\vec{r}$ and $\vec{r}_{c.m.}$ are the radius-vectors of the test particle and of the centre-of-mass of the system, respectively.

The second term in the right hand side of Eq.(1) is the centrifugal acceleration, and the third term is the Coriolis acceleration terms, respectively, arising in the rest frame of the binary. In Eq.(1) we neglect the pressure force of the accelerated particle beam on the cloud, which is acceptable for the cloud masses and sizes under consideration (see Sec.4, Eq.(20)).

Now consider the dimensionless variables $\tau=t\Omega$, and $\vec{s}=\vec{s}/a$, where $a=6.3\cdot 10^{13}cm$ is the distance between the centres of the stars. In the Cartesian coordinates (x,y,z) with the origin coinciding with the pulsar, the x ($\equiv s_x$) axis in the direction from the pulsar to the centre of the normal star, and the z ($\equiv s_z$) axis in the direction of the angular velocity vector $\vec{\Omega}$, the Eq.(1) may be written as:

$$\frac{d^2x}{d\tau^2} = 2\frac{dx}{d\tau} - \frac{x}{(1+q)s_p^3} + \frac{q(1-x)}{(1+q)s_n^3} + x - \frac{q}{1+q}, \qquad (2)$$

$$\frac{d^2y}{d\tau^2} = -2\frac{dy}{d\tau} - \frac{y}{(1+q)s_p^3} - \frac{qy}{(1+q)s_n^3} + y, \qquad (3)$$

$$\frac{d^2z}{d\tau^2} = - \frac{z}{(1+q)s_p^3} - \frac{qz}{(1+q)s_n^3}. \qquad (4)$$

Here $q=M_n/M_p$ is the ratio of the mass of the normal star HZ Herculis ($M_n=2.2M_\odot$) to the mass of the neutron star ($M_p=1.3M_\odot$); $s_p=\sqrt{x^2+y^2+z^2}$ and $s_n=\sqrt{(1-x)^2+y^2+z^2}$ are dimensionless distances from the test particle to the pulsar and the normal star, respectively. Going over from Eq.(1) to Eqs.(2)-(4), we use the well-known relation $\Omega^2 a^3 = G(M_n + M_p)$, where G is the constant of gravitation.

To cross the propagation cone of the beam, in the general case the ejected cloud should be able to leave the surface of the normal star and travel a distance of the order of the characteristic lengthscale of the binary. Then, the ejection velocity of the cloud should be at least comparable with the escape velocity from the surface of the normal star, which in case of HZ Herculis is about 500km/s (except for the ejections from regions near the inner Lagrange point L_1). Note for comparison, that the orbital speeds of the pulsar and the normal star are equal to 170km/s and 100km/s, respectively. The characteristic velocity scale of the clouds sufficiently removed from the surface of HZ Herculis is about $v \sim 300$km/s, though in those particular cases when the cloud passes close enough to the pulsar, at $r \lesssim 10^{11}$cm, due to attraction by the pulsar, it may be accelerated up to $v \gtrsim 10^3$km/s

Giving the initial coordinates and the initial velocity $\vec{v}_0$ on the surface of the normal star, the trajectory parameters, i.e. the x,y,z coordinates of the radius-vector $\vec{s}$ and the velocity $\vec{v}(\tau) = (d\vec{s}/d\tau)a\Omega$ at $\tau > 0$ are numerically found. In Fig.1a the trajectories of test particles escaping from the inner Lagrange point L_1 ($x_L = 0.445$, $y_L = 0$) in the orbital plane (x,y) are presented. The trajectories are limited by the lifetime of the cloud with temperature $T_0 \lesssim 10^4$K, $t \lesssim 10$ hours (see Sec.4).

In a more general case, when the outbursts take place from an arbitrary point on the surface of the normal star, and with arbitrary velocities $\vec{v}_0$, the particles move in all the three

directions (x,y,z). The projections of the corresponding trajectories for $t < 3\cdot 10^4$s in the (x,y) and (x,z) planes are presented in Fig.1b. The frequency shift at reemission (proton-to-γ-ray transformation) of the pulsed signal in the moving cloud (double Doppler effect) is defined by:

$$\Delta\nu = \nu_0 \cdot \frac{u}{c} \cdot \frac{\cos(\vec{k}\,\hat{}\,\vec{u}) - \cos(\vec{p}\,\hat{}\,\vec{u})}{1 - (u/c)\cos(\vec{k}\,\hat{}\,\vec{u})}, \qquad (5)$$

where $u \equiv |\vec{u}|$ is the cloud's velocity relative to the pulsar at the instant of collision with the relativistic proton beam; $(\vec{k}\,\hat{}\,\vec{u})$ and $(\vec{p}\,\hat{}\,\vec{u})$ are the angles between the vector $\vec{u}$ and the direction of the γ-ray $(\vec{k})$ and the proton beam $(\vec{p})$, respectively. Note that the direction of the vector $\vec{p}$ coincides with that of the vector $\vec{r} = \vec{s}a$ from the pulsar to the cloud, and the wave vector $\vec{k}$ directed to the observer, is in the orbital plane, i.e. $k_z = 0$, and k_x/k and k_y/k are determined by the orbital phase ϕ. Taking into account that $\vec{u} = \vec{v} + \vec{\Omega}\times\vec{r}$, in the non-relativistic limit $u/c \ll 1$ we obtain

$$\frac{\Delta\nu}{\nu_0} = \frac{u_x}{c}\left(\cos\theta - \frac{x}{s}\right) + \frac{u_y}{c}\sin\theta - \frac{y}{s} - \frac{u_z}{c}\cdot\frac{z}{s}, \qquad (6)$$

where $s = |\vec{s}|$; $\theta = 2\pi(1-\phi)$ is the angle between the x axis and direction to the observer in the phase ϕ. Figs.2a,b present $\Delta\nu/\nu_0$ as a function of t in different phases ϕ, for the trajectories marked by "1" in Figs.1a and b, respectively. It should be noted that in some cases the pulse frequency shift $\Delta\nu/\nu_0$ may noticeably change during γ-ray production for $\Delta t \lesssim 1$ hour.

4. Conditions for Pulsed γ-Ray Production

In this section we will discuss the requirements both to the beam of accelerated protons and to the parameters of the cloud-target for an efficient γ-ray production.

4.1. Cloud Parameters

The characteristic density of particles in the cloud, n, must be sufficiently high to provide inelastic pp interaction time $t_{pp}=(nc\sigma_{pp})^{-1}$, not exceeding the period of pulsed radiation, $P_0=1.24s$, otherwise the signal would broaden, leading to smoothening of the pulsed component of γ-radiation. It should be noted that in the proposed model for production of γ-rays in the direction to the observer an essential chaotization of the relativistic proton beam must take place. So, we will not consider the case of optically thin (with respect to pp interactions) targets. Hence, on assumption of a hydrogen medium in the cloud, we find:

$$n \geq (\sigma_{pp} c P_0)^{-1} = 6.7 \cdot 10^{14} cm^{-3}. \tag{7}$$

In order to conserve the pulsed component of γ-rays, it is also necessary that the linear size of the production region, l, be smaller than $l_{max}=cP_0$, i.e. the characteristic radius of the cloud, R=l/2, is found to be:

$$R \leq R_{max} = 2 \cdot 10^{10} \text{ cm} . \tag{8}$$

At the same time, the cloud's size cannot be much less than

$R_{min} \sim 3 \cdot 10^9$ cm, otherwise serious difficulties connected with enormous requirements to the accelerated particle beam arise (see below).

Now estimate the upper limit on the number density in the cloud, which follows from the condition of cloud's transparency to γ-rays. At $E>100MeV$ the free path of γ-rays in a hydrogen medium is $\lambda_{\pm} \simeq 80$ g/cm^2, hence,

$$n \leq \frac{\lambda_{\pm}}{gRm_p} = 1.6 \cdot 10^{16} g^{-1} \left(\frac{R}{3 \cdot 10^9 cm}\right)^{-1} cm^{-3}, \tag{9}$$

where g is some factor allowing for a possible extended cloud geometry, $0.1 \leq g \leq 1$. This restriction may be somewhat softened due to possible electromagnetic cascade initiated in matter. For an efficient cascade development in matter, the energy loss of secondary electrons ($e^{\pm}$) due to bremsstrahlung must exceed the synchrotron energy loss which may occur at

$$B \leq B_1 = 5 \left(\frac{E_e}{10^{14} eV}\right)^{-1/2} \left(\frac{n}{3 \cdot 10^{15} cm^{-3}}\right)^{1/2} \text{ Gauss} . \tag{10}$$

As γ-rays with $E_{\gamma} \geq 100TeV$ have been observed from Hercules X-1 [5,6], then the cascade can be efficient only when the magnetic field in the cloud $B<10$ Gauss. At the same time, the magnetic field should be large enough to chaotize the relativistic proton beam to provide γ-radiation in the direction to the observer (the cloud must emit γ-rays within a large solid angle). It may take place, if the gyroradius does not exceed the size of the cloud, so

$$B \geq 300 \left(\frac{E_p}{10^{15} eV}\right) \left(\frac{R}{10^{10} cm}\right)^{-1} \text{ Gauss} . \tag{11}$$

The obtained restriction (11) on the magnetic field excludes the possibility of satisfying the condition (10), at least for radiation at $E_\gamma \gtrsim 100$TeV. Thus, cascade development in matter hardly could soften the restriction (9) noticeably.

With account of the obtained restrictions to the size and number density, the mass of gas in the cloud should vary within $M_c \sim 10^{22}-10^{23}$g. For velocities $v_0 \sim 3\cdot 10^7$cm/s, the corresponding kinetic energy of the ejected cloud is from about $5\cdot 10^{36}$ to $5\cdot 10^{37}$erg. Note that ejection of even 10^3 such clouds a year corresponds to the mass loss rate of the normal star of $\dot{m} \lesssim 10^{-7} M_\odot$/year, which is comparable with the accretion rates of the pulsar (see, e.g., Ref.[8]). Probably only some of ejected clouds will have trajectories favourable for interaction with the accelerated particle beam, and hence, for an efficient production of γ-rays. The pulsed γ-radiation burst duration is determined by the lifetime of the cloud, more exactly, by the time interval during which the parameters of the cloud satisfy the requirements (7)-(9) and (11). There are several characteristic timescales in the proposed model:

a) The time necessary for the cloud to travel the characteristic lengthscale of the system of $\sim 3\cdot 10^{11}$cm (the radius of the star $R_n \simeq 2.6\cdot 10^{11}$cm; the distance between the stars, $a = 6.3\cdot 10^{11}$cm), $t_f \sim R_n/v_0 \simeq 10^4$s at $v \sim 3\cdot 10^7$cm/s.

b) The lifetime of the cloud with size $3\cdot 10^9\text{cm} < R < 2\cdot 10^{10}$cm, and initial temperature, $T_0 \lesssim 10^4$K. The minimum time is determined by the cloud expansion (in vacuum), $\Delta R \sim R$, with the sound speed, $v_s = \sqrt{kT_0/m_p}$:

$$t_c^{(min)} \geq 1.1\cdot 10^4 \left(\frac{R}{10^{10}\,\text{cm}}\right)\left(\frac{T_0}{10^4\,\text{K}}\right)^{-1/2}, \text{ s} . \qquad (12)$$

Note that due to the magnetic field frozen in plasma, the velocity of expansion may be lower than the sound speed. In Eq.(12) we utilize normalization to the cloud temperature $T_0 \lesssim 10^4$K, which seems reasonable, because the cloud is ejected from the surface of HZ Herculis with characteristic temperature of $T_n \simeq 7\cdot 10^3$K. But in cases when the cloud is under beam, the cloud temperature increases rapidly up to $T \gg T_0$. This very temperature determines the real timescale of γ-ray emission of the cloud.

c) The lifetime of cloud under beam. The characteristic temperature of the cloud heated by the beam is determined from the thermal balance: the heating rate = the radiative cooling rate. The characteristic energy of proton beam injected into the cloud is $\Delta\dot{W}_p = \dot{W}_p(\Delta\Omega/\Omega_0)$, where $\dot{W}_p$ is the total power of the beam propagating within the solid angle Ω; $\Delta\Omega \simeq \pi(R/r)^2$ is the solid angle at which a cloud with radius R is seen at a distance r to the neutron star. For the index of differential spectrum of accelerated protons, $\Gamma \simeq 2$, only ~5% of $\dot{W}_p$ goes for heating of the cloud (mainly due to ionization losses of low energy protons, $E_p \lesssim 2$-3GeV). To provide the observed γ-ray fluxes, the energy density of the beam must be $\dot{W}_p/\Omega_0 \sim 10^{40}$erg/s·sr (see below). The minimal cloud temperature occurs at maximal cooling rate which is achieved at black-body emission:

$$T \gtrsim T_{BB} = \frac{\Delta\dot{W}_h}{4\pi R^2 \sigma_{S-B}} = 7\cdot 10^4\,\text{K}\left(\frac{\dot{W}_p/\Omega_0}{10^{40}\,\text{erg/s}\cdot\text{sr}}\right)^{1/4}\left(\frac{r}{3\cdot 10^{11}\,\text{cm}}\right)^{-1/2} . \qquad (13)$$

Substituting this value into Eq.(12), we have:

$$\Delta t = \frac{R}{v_s} \le 4\cdot 10^3 \left[\frac{R}{10^{10}\,cm}\right] \left[\frac{\dot{W}_p/\Omega_0}{10^{40}\,erg/s\cdot sr}\right]^{-1/8} \left[\frac{r}{3\cdot 10^{11}\,cm}\right]^{1/4} s \ . \quad (14)$$

As Δt depends linearly on the cloud size R, and with account of the fact that R varies within $(3\cdot 10^9 - 2\cdot 10^{10})$ cm,*[1] we come to a conclusion that the characteristic timescale of γ-ray emission should be $20\mathrm{min} \le \Delta t \le 2$ hours. The duration of emission may be less, if the opening angle of the beam (directivity diagram) is very narrow, $\Delta\psi \le 1^\circ$. In this case the accelerated particle beam propagates actually in a limited region between the two coaxial cone surfaces (shaded area in Fig.1a) with a common vertex at $r=0$ (pulsar) and with angles $(\alpha-\Delta\psi)$ and $(\alpha+\Delta\psi)$ at the common vertex. Here α is the angle between the rotation and the magnetic field axes of the pulsar. Then the γ-radiation duration would be determined by the time of the cloud's being under the beam. Since at characteristic distances to the pulsar, $r \sim 3\cdot 10^{11}$ cm, the thickness of the beam propagation region $\Delta l \le 10^{10}$ cm, then at velocities of $v \ge 3\cdot 10^7$ cm/s, the time of the cloud's bombardment by the beam $\Delta t = (2R+\Delta l)/v \le 10$min.

4.2 The Beam Parameters

The characteristic energy injected by the relativistic protons into the cloud can be estimated from the observed episodic γ-ray flux, $F_\gamma(>1\mathrm{TeV}) \ge 10^{-10}\,\mathrm{cm^{-2}s^{-1}}$. The experimental data available at present do not carry information on γ-ray

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*In case of a prolonged cloud, the minimal, i.e. the transverse size of the cloud stands for R, which, in principle, may be less than $3\cdot 10^9$ cm.

spectrum. It should be noted, that the observed fluxes at $E \ge 1$TeV and $E > 100$TeV (though detected in different bursts) testify to very hard photon spectra. To be definite, we will assume power-law spectra of photons extended up to $E \sim 10^{15}$eV. Then, for differential power-law index of the γ-ray spectrum emitted isotropically, we obtain the production rate of γ-rays:

$$\dot{N}'_\gamma(E) = 2.8\cdot 10^{35} \left[\frac{F_0}{10^{-10}\,cm^{-2}s^{-1}}\right] \left[\frac{d}{5kpc}\right]^2 \left[\frac{E}{TeV}\right]^{-2}, \ \mathrm{TeV^{-1}s^{-1}}. \quad (15)$$

where $F_0 \equiv F_\gamma(>1\mathrm{TeV})$ is the typical γ-ray flux observed at $E \ge 1$TeV. The corresponding luminosity within $10^{12} < E < 10^{15}$eV is $L_\gamma(>1\mathrm{TeV}) \simeq 3\cdot 10^{36}$ erg/s. The maximum γ-ray production rate, $\dot{N}_\gamma(E)$, is reached in the case when the relativistic proton escape time from the cloud is much larger than their cooling time in the cloud, $t_{pp} = 1/\sigma_{pp} nc$. Then, the relevant production rate, $\dot{N}_\gamma(E)$, depends mainly on the relativistic proton injection rate $\Delta\dot{N}_p(E)$:

$$\dot{N}_\gamma(E) = \frac{\langle nx^\gamma\rangle \cdot \Delta\dot{N}_p(E)}{(\Gamma-1)\cdot f}, \quad (16)$$

where f is the inelasticity coefficient at pp interactions ($\simeq 0.5$); the so-called γ-moment of inclusive γ-ray spectrum, $\langle nx^\gamma\rangle$, varies from 0.2 to 0.1 when the proton differential spectrum index, $\Gamma=\gamma+1$, varies from $\Gamma=2.0$ to $\Gamma=2.2$ [9]. Hence, we can easily find $\Delta\dot{N}_p$, and the corresponding power of injection of relativistic protons into the cloud is:

$$\Delta\dot{W}_p = 1.8\cdot 10^{37} \left[\frac{F_0}{10^{-10}\,cm^{-2}s^{-1}}\right] \left[\frac{d}{5kpc}\right]^2 \frac{erg}{s}, \quad (17)$$

where we suppose that the power-law spectrum of protons is extended up to 10^{16}eV.

Notice, that the power $\Delta\dot{W}_p$ is only a small part of the power of continuous proton acceleration by the pulsar, $\dot{W}_p$. Indeed, if $\dot{W}_p$ is distributed within some solid angle Ω_0, then at distances $r>10^{11}$cm from the pulsar the cloud covers the solid angle of

$$\Delta\Omega = \pi\left(\frac{R}{r}\right)^2 = 3.5\cdot 10^{-3}\left(\frac{R}{10^{10}cm}\right)^2\left(\frac{r}{3\cdot 10^{11}cm}\right)^{-2} sr . \qquad (18)$$

Hence,

$$\dot{W}_p = \Delta\dot{W}_p \frac{\Omega_0}{\Delta\Omega} = \qquad (19)$$

$$=5\cdot 10^{39}\left(\frac{\Omega_0}{1sr}\right)\left(\frac{r}{3\cdot 10^{11}cm}\right)^2\left(\frac{R}{10^{10}cm}\right)^{-2}\left(\frac{F_0}{10^{-10}cm^{-2}s^{-1}}\right)\left(\frac{d}{5kpc}\right)^2\frac{erg}{s}.$$

It is worth noting that even for $\Delta\psi\simeq 5^o$ and $\alpha=45^o$, the solid angle $\Omega_0=1.5$sr. So, one may conclude from Eq.(19) that $\dot{W}_p\sim 10^{40}$erg/s. In principle, this power may be lower by an order of magnitude, if the cloud radiates non-isotropically, e.g. within some solid angle $\sim\pi$, as well as if the distance d to the source corresponds to the lower value of the supposed interval d=2-6kpc (see, e.g., Ref.[8]). Also note, that the cloud size cannot be less than $R_{min}\sim 3\cdot 10^9$cm, otherwise $\dot{W}_p$ would be too high, $\gg 10^{40}$erg/s.

As is shown above, the powerful proton beam heats the cloud up to $T\lesssim 10^5$K, which determines the characteristic scale of the life time of cloud. Besides, the beam may affect the motion of the cloud, if the pressure force on the cloud exceeds that of attraction (gravitation) to the pulsar. As in the proposed

model it is assumed that the proton beam becomes chaotic in the tangled magnetic field of the cloud, an essential part of the beam momentum is transferred to the cloud, $\Delta p/p_{beam}\lesssim 1$. As the pressure force $|\vec{F}_{beam}|=|d\vec{p}/dt|\simeq\Delta\dot{W}_p/c=\dot{W}_p\Delta\Omega/\Omega_0 c$, we obtain:

$$\frac{F_{beam}}{F_g} \le 0.2 \left(\frac{R}{10^{10}cm}\right)^2\left(\frac{\dot{W}_p/\Omega_0}{10^{40}erg/s\cdot sr}\right)\left(\frac{M_c}{3\cdot 10^{22}g}\right)^{-1} . \qquad (0)$$

Thus, for clouds with $M_c\ge 10^{22}$g the beam pressure does not essentially affect the cloud trajectory, but for low masses (and at $R\sim 10^{10}$cm) it may dominate. In this case the cloud may sharply change its trajectory under the beam pressure and be thrown out of the system.

In its turn, the cloud ejected from the normal star may affect the motion of the pulsar in those particular cases, when the cloud passes near the pulsar, so that it is captured by the accretion disc. In result, the orbital moment of the cloud is transferred to the pulsar, leading to a noticeable change in its speed of rotation. The estimates show that at ejection velocities $v_0\ge 3\cdot 10^7$cm/s and masses $M_c\ge 10^{22}$g, the amplitude of such jumps may be $|\Delta P|/P_0\ge 10^{-6}$. Realization of such possibility requires additional research work. Note, that jumps of the period of Hercules X-1 (deceleration) at the level $|\Delta P|/P_0\sim 3\cdot 10^{-6}$ are observed (see, e.g. Ref.[10]).

5. γ-Ray Production

Even in case of acceleration of electrons by the pulsar the reaching of these electrons with $E \gtrsim 1TeV$ the cloud seems problematic because of drastic energy losses in the low-frequency radiation and magnetic field in the binary. γ-ray production by UHE protons and nuclei seems likelier. At ultrahigh energies the protons and nuclei interact with optical radiation via photomeson and photonuclear mechanisms. However, due to hard energy requirements to the accelerated particle beam, in this paper we restrict ourselves to consideration of more efficient production mechanisms connected with the interaction of accelerated protons with ambient matter.

In case of power-law protons the γ-ray spectrum repeats that of primary particles (see Eq.(16)). Fig.3 presents integral γ-ray spectra, $F_\gamma(>E)$, for different values of the power-law index Γ, normalized to the flux $F_0 \equiv F_\gamma(>1TeV)=10^{-10}\,cm^{-2}s^{-1}$. The results of observations of the Hercules X-1 above 1TeV are presented in the same figure. Since till now there are no reports on simultaneous detection of γ-ray fluxes at $E>1TeV$ and $E>100TeV$ during the same episode, it is difficult to draw final conclusions concerning the γ-ray spectrum. Here we can only note that even on assumption of a very hard proton spectrum (e.g., $\Gamma=2$), we should expect during UHE γ-ray events also VHE γ-rays on the level $F_\gamma>3\cdot 10^{-9}\,cm^{-2}s^{-1}$, which, however, exceeds the most intense γ-ray flux reported at TeV energies [1].

One of possible reasons which might bring to such hard γ-ray spectra, may be due to a monoenergetic beam of accelerated particles with $E_0 \sim 10^{16}-10^{17}eV$, as supposed by Hillas for Cyg X-3 [11]. Below we will discuss another possible mechanism of formation of a flat γ-ray spectrum which follows naturally from the model proposed. Namely, the flattening of γ-rays at TeV energies may be due to partial absorption of γ-rays interacting with optical photons of thermal radiation. This process is discriminative for different energy bands. Really, at field photon characteristic energies $\varepsilon_0 \doteq 3kT \simeq 10-20eV$ the cross section of the process $\gamma\gamma \to e^+e^-$ has a maximum at $E_* \sim 3(m_e c^2)^2/\varepsilon_0 \simeq (0.5-1)\cdot 10^{11}eV$. At lower energy range the free path of γ-rays sharply (exponentially) increases, as γ-rays, due to the threshold of the process, interact only with the Wien tail of field photons. At high energies, $E_\gamma \gg E_*$, the free path also increases, being related with the decrease of the cross section as: $\sigma_{\gamma\gamma} \propto E_*/E_\gamma$. The free paths $l_{\gamma\gamma}$ of γ-rays at different energies calculated for cloud temperatures $T=5\cdot 10^4K$ and $T=10^5K$, using the results of Refs.[12,13], are presented in Table 1.

Table 1

E (eV)		10^{10}	10^{11}	10^{12}	10^{13}	10^{14}
$l_{\gamma\gamma}$ (cm)	$T=5\cdot 10^4K$	$1.5\cdot 10^{11}$	$3.8\cdot 10^9$	$9.1\cdot 10^9$	$4.6\cdot 10^{10}$	$3.2\cdot 10^{11}$
	$T=10^5K$	$2.5\cdot 10^9$	$4.8\cdot 10^8$	$1.8\cdot 10^9$	10^{10}	$7.0\cdot 10^{10}$

As is seen from the table, a significant absorption of TeV γ-rays takes place for the cloud size $R \sim 10^{10}$ cm. As a result, already at $T=5\cdot 10^4K$ the flux of escaping radiation decreases by a factor of $\exp(-l_{\gamma\gamma}/R)$. At the same time, the source remains transparent for γ-rays with $E \gtrsim 100TeV$. As a result of this, in the energy range $1TeV<E<100TeV$, the spectrum escaping from the cloud becomes flatter than the production spectrum. Moreover, at higher cloud temperatures, $T \simeq 10^5K$, the free path of TeV

γ-rays becomes remarkably shorter than the minimal permissible size of cloud, $R_{min} \simeq 3 \cdot 10^9$ cm, which will result in a catastrophic suppression of the TeV band of the spectrum, while the γ-rays with $E > 100$TeV escape from the cloud freely, as before. Thus, change in the temperature of the cloud heated by the beam in a narrow range, $T \simeq (0.5-1) \cdot 10^5$K, brings to an essential change in the escaping γ-ray spectrum. That is why, in accordance with Eq.(13), depending on r at which interaction of the proton beam with the cloud takes place, one may expect quite different ratios of γ-ray fluxes above 1TeV and 100TeV.

Note that in case of development of an electron-photon cascade in the field of thermal radiation, one may expect a significant weakening of this effect, since cascade leads to an essential increase in the γ-ray free path. However, for an efficient development of cascade, Compton energy loss of electrons (in Klein-Nishina limit) must exceed synchrotron energy losses. This is possible if the energy density of thermal radiation at least by an order of magnitude exceeds that of the magnetic field. From this condition we find the critical value of magnetic field:

$$B \leq 700 \left(\frac{T}{10^5 K}\right) \text{Gauss} \qquad (21)$$

The obtained value of the field falls within the range of the magnetic fields necessary for an effective opening of proton beam in the cloud (see Eq.(11). For a self-consistent calculation of escaping radiation, more information on the magnetic field in the cloud is required. The results of calculation revealing a large variety of relevant γ-ray spectra within the model proposed, will be published elsewhere.

6. Discussion

In the last few years the results of observations of VHE and UHE γ-ray episodes from the X-ray binary Hercules X-1 are systematically reported. Different specialists treat these data differently, which is connected with both certain doubts in the confidence of these data and extraordinary γ-ray characteristics of γ-radiation of this source, namely:

a) The shift of the pulsed γ-ray period with respect to the X-ray period;

b) Observation of pulsed γ-rays in the phase of deep eclipse of the X-ray source;

c) No correlation between the time of γ-ray emission and the orbital phase (P_{orb}=1.7 days);

d) Episodic character of γ-radiation with typical duration $\Delta t \leq 1$ hour. All these peculiarities do not conform to the existing models of γ-ray production in X-ray binaries, and hence, they create the negative attitude of many theorists.

Being far from drawing final conclusions on confidence of the reported γ-ray events from Hercules X-1, we propose a model in the frame of which all these features find natural interpretation.

The basic idea of the model is that γ-rays are produced at interaction of relativistic proton beam, continuously accelerated by the pulsar, with the cloud which for some reason is ejected from the normal star. In this case the shift of pulsed γ-radiation period is due to the double Doppler effect (in the source-moving-target-observer system), when the pulsed signal of accelerated protons is transformed at interaction with moving cloud into a pulsed γ-ray signal. The observed variation of both the value and the sign of these shifts ar owing to different trajectories of the clouds in the binary system (depending on the initial coordinates and velocities) and to different orbital phases at the moment of interaction of the beam with the cloud. The scale of the observed frequency shift amplitudes, $|\Delta\nu|/\nu_0 \sim 0.1\%$, corresponds to the scale of cloud velocity, $v \sim 300 km/s$, which agrees with the velocities needed for the cloud to leave the normal star. In this paper we suggest ejection of the clouds (with $M_c \leq 10^{23} g$) not discussing the possible reasons of such process. Note that the outflow of large amounts of matter from stars is a common phenomenon, and in case of young stars these processes take place in much larger scales (see, e.g., Ref.[14]).

It is obvious that in the model proposed γ-ray production may occur at any orbital phase ϕ. Moreover, under definite initial conditions the cloud trajectories allowing to observe γ-ray events in the phase of deep pulsar eclipse , $\phi \sim 0$, are possible. An attempt to explain the γ-ray episode in the phase of complete X-ray eclipse was made by Gorham and Learned [15]. According to their model, γ-rays in the eclipse of the pulsar are due to deviation of the proton beam in magnetic fields of certain configuration (between the pulsar and normal star). However, this model cannot explain γ-radiation observed at orbital phases far from the eclipse. Besides, this model may be realized under rigid requirements to the energetics of the beam and to the configuration of the magnetic field. The timescale of γ-ray burst duration, $\Delta t \lesssim 1 hour$, is a natural consequence of the proposed scenario. A dense cloud of mass $M_c \sim 10^{22}-10^{23} g$ ejected from the normal star is rapidly heated up to $T \simeq (0.5-1)\cdot 10^5 K$ by the beam (depending on the distance r to the pulsar; see Eq.(13)). Until the number density of the cloud remains above $n \gtrsim 10^{15} cm^{-3}$, γ-radiation repeats the time profil

of the pulsed proton beam with some shift in the frequency . Duration of this stage is defined by the time of expansion of the beam-heated cloud (see Eq.(14)). Obviously, efficient γ-ray production may also continue in an expanded cloud with lower density, but the pulsed component in γ-rays will vanish. The possibility of verifying this model, connected with this effect, seems rather attractive. However, observation of this (non-pulsed) stage is much more difficult and requires detectors with high sensitivity. Moreover, such possibility may be limited by the time during which the cloud remains under the beam (in case of small opening angle of the beam).

A natural consequence of the model proposed is production of pulsed thermal radiation in optical and UV bands with the same time characteristics as γ-radiation, namely, the frequency shift of pulsations and the absence of orbital modulation. Both the spectral characteristics and duration of this radiation strongly depend on the temperature of the heated cloud. For instance, at $T \lesssim 10^4 K$, the duration of the pulsed optical radiation should be several hours (in accordance with Eq.(12)), which is in compliance with the timescale of optical bursts observed from Hercules X-1/HZ Herculis. These bursts as a rule have a shifted frequency with $|\Delta\nu|/\nu_0 \sim 0.1\%$ [16], similar to the γ-ray events. It is obvious that pulsed optical events must be also accompanied with γ-radiation. But because of relatively weak injection of proton beam energy into the cloud (which occurs at large distances r, to keep $T \lesssim 10^4 K$; see Eq.(13)), the γ-ray intensity appears to be lower than the sensitivity of existing γ-ray detectors. That is why we predict detection of γ-ray events from Hercules X-1 with low intensity but longer duration, with improvement of the sensitivity of γ-ray detectors.

In cases when the cloud passes near the pulsar, $r \lesssim 10^{11}$ cm, the beam energy injected into the cloud is enough for an intense γ-ray production. This leads to an episodic γ-radiation with $\Delta t \lesssim 1$ hour and flux $F_\gamma(>1TeV) \geq 10^{-10} cm^{-2} s^{-1}$. The cloud temperature is expected within $T \simeq (0.5-1) \cdot 10^5 K$, so these strong γ-ray events must be accompanied by thermal radiation having Relay-Jeans spectrum in optical band, (1-2)eV. The maximum of the thermal radiation should fall into the UV band, $h\nu \sim 10eV$. The total luminosity of thermal radiation of the cloud can reach $L_{UV} \lesssim 10^{36}$ erg/s, the energy release in the optical range $1eV \lesssim h\nu \lesssim 2eV$ being $L_{opt} \lesssim 10^{33}$ erg/s. It should be noted that in case of a strongly heated (up to $T \gg 10^4 K$) cloud the observation of optical and UV radiation will provide estimation of both the cloud temperature and the size, which play an essential role in formation of the γ-ray spectrum escaping from the cloud.

Although at temperatures $T \lesssim 5 \cdot 10^4 K$ the TeV γ-rays are partially absorbed in a cloud with size $R \lesssim 10^{10}$ cm, however, it does not essentially distort the initial γ-ray spectrum, since $\tau_{\gamma\gamma} \lesssim 1$ (see Table 1). In this case, even for very hard proton spectra (e.g., $\Gamma=2$) at typical value of the TeV γ-ray fluxes, $F_\gamma(>1TeV) \simeq 10^{-10} cm^{-2} s^{-1}$, one would expect fluxes above 100TeV on the level $\leq 10^{-12} cm^{-2} s^{-1}$. Detection of these fluxes seems problematic even for large particle arrays, e.g. CASA (see Fig.3). It will be hard to observe these events also in the energy range $E \sim 100MeV$. Indeed, even for the GRO's EGRET detector with effective area $\simeq 2000 cm^2$ [17], for detection of even 30 events during $\Delta t \lesssim 1$ hour the flux above 100MeV must exceed $5 \cdot 10^{-6} cm^{-2} s^{-1}$. As is seen from Fig.3, for $F_\gamma(>1TeV) \simeq 10^{-10} cm^{-2} s^{-1}$ such values of fluxes above 100MeV are possible only at the power-law index $\Gamma \geq 2.3$. Thus, at cloud temperatures $T \lesssim 5 \cdot 10^4 K$ the most convenient range for detection

of γ-ray events is $E \sim 1TeV$.

Situation may be quite different when the cloud passes near the pulsar, $r \sim 10^{11}$ cm, and is heated up to $T \simeq 10^5 K$. Then, due to large optical depth ($\tau_{\gamma\gamma} \sim 5$ for $r \sim 10^{10}$ cm), a catastrophic suppression of TeV γ-rays takes place (by a factor of ≥ 100), while UHE γ-ray absorption remains unessential. Hence the spectra of the strongest bursts may have an unusual form with a dip in the interval $10GeV \lesssim E \lesssim 10TeV$. As a result, detection of powerful bursts of UHE γ-rays by particle arrays (which is possible for fluxes $F_\gamma(>100TeV) > 10^{-11} cm^{-2} s^{-1}$; see Fig.3) may not be accompanied by observation of TeV γ-rays. At the same time, the cloud is transparent for γ-rays with $E < 10GeV$ and the expected fluxes at $E \sim 100MeV$ are on the level $\sim 10^{-5} cm^{-2} s^{-1}$ even for $\Gamma=2$. These 100MeV γ-ray transients associated with 100TeV γ-ray events from Hercules X-1 can be detected by EGRET.

In strong bursts anew component of γ-rays connected with synchrotron radiation of secondary electrons (produced in interactions of γ-rays with the ambient thermal photons in the cloud) arises. For the value of the magnetic field in the cloud, $B \sim (10^2 - 10^3)$ Gauss, a wide spectrum of synchrotron radiation with the main energy release within 1-100MeV is formed. The detailed analysis of the spectrum of this component is presented elsewhere. Here we'll only note that the expected fluxes with hard spectrum, $\dot{N}_\gamma(E) \propto E^{-1.5}$, appears high enough to detect γ-ray transients by means of GRO γ-ray detectors.

In conclusion, we would like to emphasize that the features of episodic γ-radiation from Hercules X-1 possibly are common for other X-ray binaries, such as Vela X-1, Cen X-3, 4U0115+63, etc. [18]. We hope the proposed model will bear complex testing using new data expected in the near future.

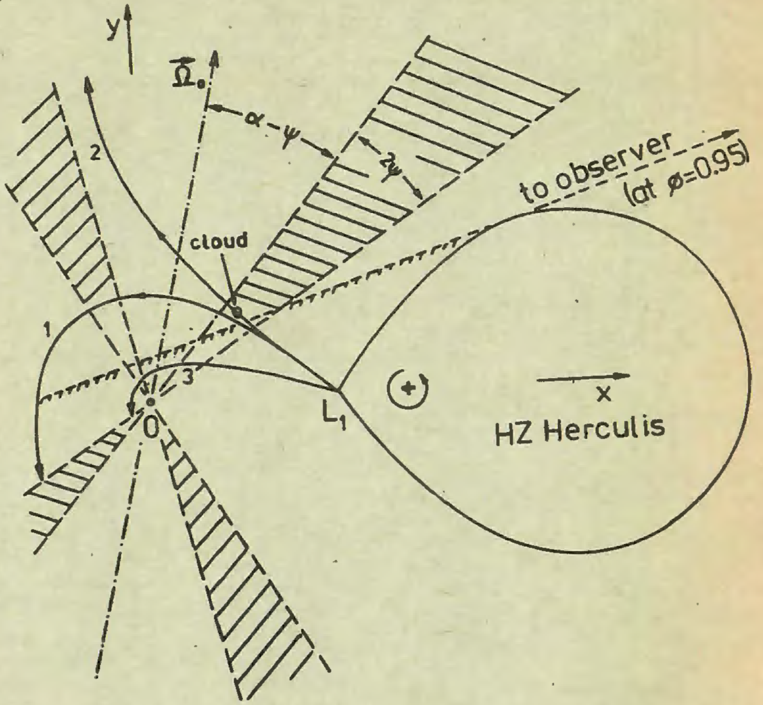
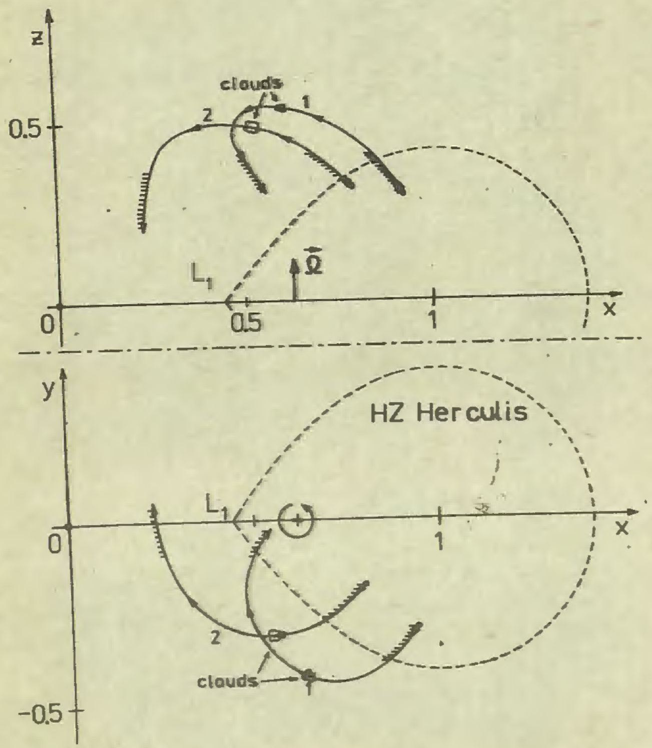

y
$\vec{\Omega}_e$
α−ψ
2ψ
to observer
(at ø=0.95)
cloud
1
2
3
0
L_1
x
HZ Herculis

Fig.1a


z
0.5
clouds
1
2
L_1
$\vec{\Omega}$
0
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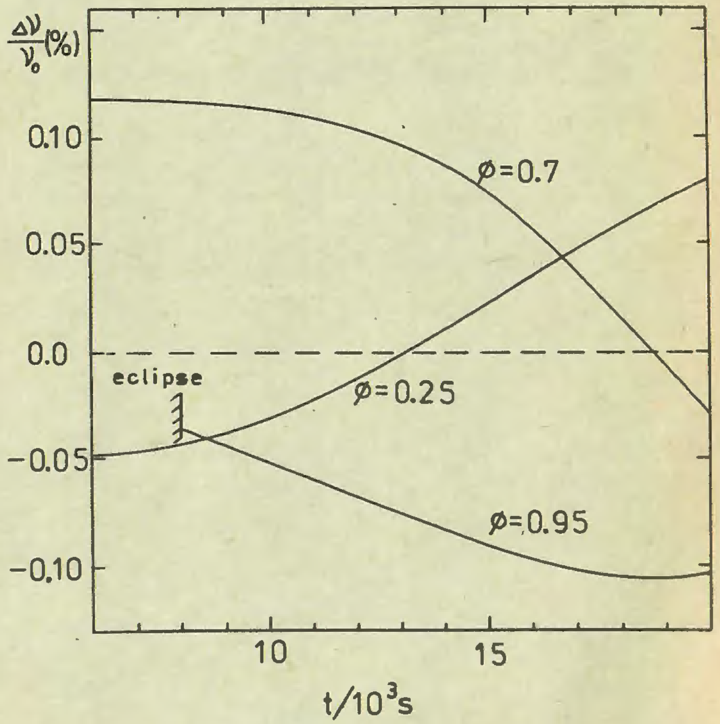
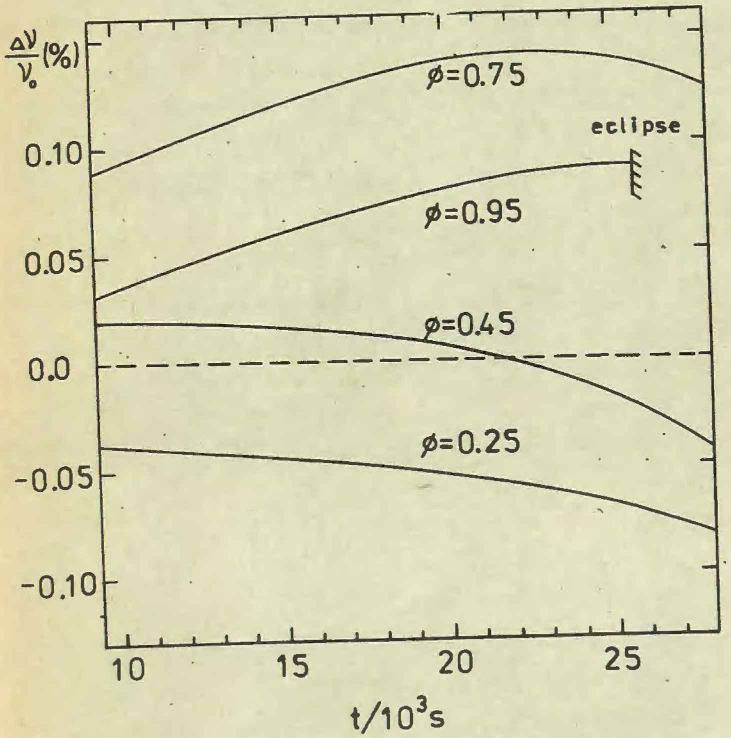
1
x
y
HZ Herculis
0
1
x
2
clouds
1
-0.5

Fig.1b



$\frac{\Delta\nu}{\nu_0}$(%)
0.10
0.05
0.0
-0.05
-0.10
eclipse
ø=0.7
ø=0.25
ø=0.95
10
15
t/10³s

Fig.2a



$\frac{\Delta\nu}{\nu_0}$(%)
0.10
0.05
0.0
-0.05
-0.10
ø=0.75
eclipse
ø=0.95
ø=0.45
ø=0.25
10
15
20
25
t/10³s

Fig.2b

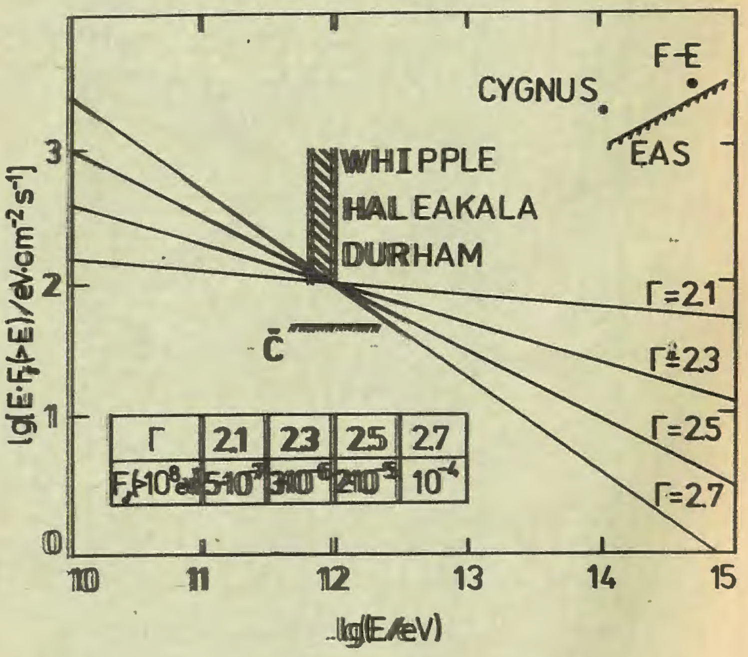


Fig.3

Figure Captions

Fig.1a,b. Trajectories of test particles (clouds) in the rest-frame of the binary at different ejection velocities $\vec{v}_0$ from the surface of the companion star HZ Herculis. The pulsar is placed at the zero point $x=y=z=0$.

a) The particular case of cloud ejection from the Lagrange point L_1 in the orbital plane (x,y). The trajectories 1,2 and 3 are for initial velocities v_0=300km/s, 400km/s, and 100km/s, respectively. The pulsar angular velocity vector $\vec{\Omega}$ as well as the space (shaded area) wherein the accelerated proton beam (with the full opening angle of the beam being equal to 2ψ, and α representing the angle between the pulsar's magnetic axis and $\vec{\Omega}$) is propagating, are presented schematically.

b) The general case of ejection from arbitrary points of the surface of HZ Herculis with initial velocities v_0=300km/s, and 350km/s for the curves 1 and 2, respectively. The shaded sections of trajectories correspond to the eclipse of the clouds behind HZ Herculis for the binary in the orbital phase ϕ=0.95.

Fig.2a,b. The frequency shift $\Delta\nu=\nu_\gamma-\nu_0$ of gamma-ray pulsations, ν_γ, relative to the X-ray frequency $\nu_0=\Omega/2\pi$ in different orbital phases ϕ for the trajectories marked "1" in Figs.1a,b, respectively (t is the time of flight). The eclipse of clouds (for the binary the orbital phase ϕ=0.95) are also shown in both figures.

Fig.3 Integral spectra of gamma-rays normalized to the flux $F_{\gamma}(>1TeV)=10^{-10}cm^{-2}s^{-1}$, expected from pp-interactions for different Γ of the differential spectra of accelerated protons (without possible distortion of the spectra due to interactions of γ-rays with the ambient thermal photons). The expected fluxes above 100MeV (in units of $cm^{-2}s^{-1}$) are presented in the table. The dashed column indicates the interval of the observed TeV γ-ray fluxes. The observational data from CYGNUS and Fly's Eye installations are presented by full circles. The sensitivities of forthcoming γ-ray detectors (Č-telescopes and EAS arrays) for γ-ray episodes with Δt~1hour are also plotted.

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МОДЕЛЬ ПУЛЬСИРУЮЩЕГО ГАММА-ИЗЛУЧЕНИЯ В ДВОЙНОЙ СИСТЕМЕ HER X-1/HZ HER

(на английском языке, перевод Г. А. Папяна)

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