RELATIVISTIC COMPLEX NUCLEI AS GENERATORS OF THE VHE $\gamma$-RAYS Emitted FROM DISCRETE GALACTIC SOURCES

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Abstract

Relative contribution of different possible $\gamma$-rays generation mechanisms are analysed as applied to Cygnus X-3 and, in a preliminary form, to Crab pulsar.

Introduction The so-called photonuclear mechanism of generation of cosmic ray $\gamma$-quanta of very-high ($>$10$^{12}$ eV) and ultra-high ($>$10$^{15}$ eV) energies was proposed in our group several years ago (Balashov et al. 1987a,b). The essence of the mechanism is that the ultrarelativistic complex nuclei in the composition of the primary corpuscular radiation disintegrate due to the great value of the Lorentz-factor $\gamma_A=\gamma_{\gamma_A}$ in their interactions with soft photons $\gamma_{\gamma}$ of interstellar or intergalactic medium, whereupon the produced excited nuclear fragments begin emitting superhard $\gamma$-rays:

\[ A + \gamma_{\gamma} \rightarrow B^* + \ldots \]

\[ \rightarrow B + \gamma \]  \hspace{1cm} (1)

Like the photo-meson generation mechanism (Zatsepin and Kuz'min 1966, Stecker 1973)

\[ p + \gamma_{\gamma} \rightarrow \pi^0 + \ldots \]

\[ \rightarrow 2\gamma \]  \hspace{1cm} (2)

the photonuclear one is of threshold character. However, the pion production threshold is an order as high as the nuclear photodisintegration threshold. Therefore, if the energy spectrum of primary fluxes of protons and nuclei is rapidly falling (say, according to the power-law $i(\Gamma_p) = \Gamma_p^{-\nu_p} \gamma_{\gamma_A}^{-\nu_{\gamma}}$), the contribution of the photonuclear mechanism (1) may dominate that of the mechanism (2) within a substantial interval of the generated $\gamma$-ray spectrum even in case of a small fraction of complex nuclei in the composition of primary corpuscular fluxes.

Various nuclear-physics aspects of the problem were discussed elsewhere (Balashov 1988, 1989). The physics of photonuclear reactions was not faced earlier with the question of multiplicity and energy distribution of the secondary $\gamma$-quanta. Some semiquantitative statistical-model calculations for the decay of giant dipole resonance in $^{56}$Fe-nucleus show (Moskalenko and Fotina 1989, Korotkikh et al. 1988) that the secondary $\gamma$-quantum energy spectrum is broad with the mean energy ~ 2-4 MeV. The mean $\gamma$-quantum multiplicity is ~ 1-3.

So, when examining the photonuclear mechanism of cosmic-ray $\gamma$-quantum generation, we raise actually a more general astrophysical question concerning a role of complex nuclei in the composition of primary fluxes from accreting stars, pulsars, etc. This is on line with the modern tendency
to revise the commonly-adopted picture concerning the primary cosmic ray composition. Here we mean, in particular, such new concepts in cosmic-ray physics as the idea of iron-dominance (Jones 1984, Blandfort and Eichler 1987) as well as a hypothesis of photonuclear mechanism of formation of the diffuse cosmic ray composition (Stamenov et al. 1987).

Results Before we paid attention entirely to the form of the energy spectrum of the VHE $\gamma$-rays. The relevant calculations allowing for the photonuclear generation mechanism were the first to demonstrate a step-like form of the Cyg X-3 spectrum in the $10^{11}$-$10^{17}$ eV range, i.e. just the same form which may be seen in the integral spectrum of $\gamma$-emission from this source. At present, we begin examining the problems concerning the absolute intensity of the $\gamma$-quantum fluxes arriving at the Earth. Following Aharonyan et al. (1987), we use their schematic Cyg X-3 model with two additional factors, namely, the nuclear component of the primary corpuscular flux (ultrarelativistic iron nuclei) and the photonuclear mechanism of $\gamma$-ray generation.

The dimensions of Cyg X-3 as a binary seem to be very approximate at present. namely, $10^{11}$-$10^{12}$ cm according to the estimates published elsewhere. We assume that the size $L$ of the region around the star filled by soft photons where the $\gamma$-quanta are generated is $\sim 10^{12}$ cm. The mean photon energy $\langle \gamma \rangle$ was estimated earlier on the basis of the VHE $\gamma$-ray spectrum form to be a few eV (Balashev et al. 1988). Now we take $\langle \gamma \rangle \approx 6$ eV, the photon energy distribution is taken to be of the Planck form. The mean free path ${\lambda}_{Fe}^{\gamma}$ of iron nuclei with respect to the photodisintegration process (1) in the soft-photon medium is $\sim 10^{11}$ cm. The relation $\lambda^{Fe}<L$ makes it necessary to include the subsequent cascade disintegration of the produced ultrarelativistic daughter nuclei B as they traverse the photon medium, just as done when studying the spectrum and the composition of diffuse cosmic rays (Stamenov et al. 1987). Basing on the calculations (Moskalenko and Potina 1989, Korotkikh et al. 1988) one can see that, on cascade disintegration in the soft-photon medium near Cyg X-3, a single ultrarelativistic iron nucleus produces, on the average, some tens of secondary $\gamma$-quanta with mean energy (in the rest frame of an ultrarelativistic excited fragment) of about 2-4 MeV. As regards the $\pi^0$-meson photoproduction process (2), the examined photon medium is "thin". Taking into account the effect of "extension" of the high-energy $\gamma$-quantum free path in a photon medium (Gould and Rephaeli 1978, Ivanenko et al. 1988), one can, for the first estimate, disregard the absorption of generated $\gamma$-quanta in the soft photon medium.

Fig. 1 shows the integral spectrum of $\gamma$-rays from Cyg X-3. The solid line is the result of our calculations made assuming the photo-meson and photonuclear generation mechanisms with the power-law index $s = 2.7$ for the energy distribution of primary protons and nuclei, the uncertainty of theoretical predictions on the mean energy and the multiplicity of secondary $\gamma$-quanta under Fe-photodisintegration being taken into account. The nuclei-to-protons number ratio in the primary
The corpuscular flux is \( \frac{I_{Fe}}{I_p} = \frac{I_{Fe}}{I_p} = 10^{-3} \) or \( \frac{I_{Fe}}{I_p} \frac{E_{Fe}}{E_p} = 10^{-40} \).

Knowing the absolute number of the \( \gamma \)-quanta arriving at the Earth from Cyg X-3, we can normalize the constants \( I_{Fe} \) and \( I_p \) and, hence, estimate the power \( P \) of this discrete source emitted in the form of ultrahigh-energy particle fluxes. Earlier, Hillas (1984) assumed that the \( \gamma \)-quanta with energies above \( 10^{16} \) eV are generated in the strong-interaction processes and obtained \( P = 2 \cdot 10^{39} \) erg/s assuming the proton flux to be monoenergetic with a \( 10^{17} \) eV energy; see also Berezinsky and Zatsepin (1987). In our model, the total power \( P \) of the power fluxes which are capable of generating the \( 10^{14} \)-\( 10^{17} \) eV \( \gamma \)-quanta is \( \sim \frac{4\pi}{\Delta} \left( \frac{T_0}{T} \right) \cdot \frac{5.0 \cdot 10^{40}}{\Delta} \) erg/s. At the solid angle \( \Delta = 4\pi \) and the period fraction \( \Delta / T_0 = 1/20 \), we obtain a not too much higher value \( P \) than those obtained in the framework of the strong-interaction model. Although these

![Figure 1: Integral spectrum of \( \gamma \)-quanta from Cyg X-3. Data are from Vladimirsky et al. (1985), Bonnet-Bidaud and Chardin (1988).](image1)

![Figure 2: Integral spectrum of \( \gamma \)-quanta from PSR 0531+21. Data are from Morello et al. (1987).](image2)

results support strongly the assumptions concerning the feasible formation of all cosmic rays in the Galaxy by individual powerful discrete sources (Wdowczyk and Wolfendale 1983), the whole question of the total power of such discrete sources as Cyg X-3 seems to remain open.

Our calculations for PSR 0531+21 pulsar in Crab Nebula and their comparison with available data (not separated at \( E_\gamma > 10^{14} \) eV onto contributions from the pulsar itself and the Nebula) are shown on Fig. 2. This is quite another type of discrete sources which differ considerably from the binaries like Cyg X-3 in their very strong magnetic field and a high number
density of electrons and positrons. Besides, one must take into consideration an essentially non-Planck distribution of soft photons near the pulsar. Nevertheless assuming the mean photon energy $\langle \omega \rangle = 30$ eV one can reproduce the specific step-like form of the $\gamma$-ray spectrum in the 1012–1016 eV range with the fitting parameter $|\mu/\mu_{E_0}|/E_0 = 8$. Note that quite a number of theoretical works (Cheng et al. 1986, Grindlay and Hoffman 1971, Lominadze et al. 1983) were devoted to analyzing $\gamma$-rays from PSR 0531+21, however none of them tried to explain the $\gamma$-quantum spectrum from this source in the TeV and PeV ranges.

To conclude, although we are now only at the very beginning in our investigation, no arguments are observed to disregard a role at relativistic complex nuclei as a possible origin of VHE cosmic rays $\gamma$-quanta.

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