PRIMARY GAMMA-RAYS WITH $E_\gamma \gg 10^{15}$ eV: EVIDENCE FOR ULTRAHIGH ENERGY PARTICLE ACCELERATION IN GALACTIC SOURCES

Aharonian F.A., Mamidjanian E.A.
Yerevan Physics Institute, Markarian St.2,
375036, Yerevan, Armenia, U.S.S.R.

Nikolsky S.I., Tukish E.I.
P.N.Lebedev Physical Institute
117924, Moscow, U.S.S.R.

ABSTRACT

The recently observed primary ultrahigh energy gamma-rays (UHEGR) testify to the cosmic ray (CR) acceleration in the Galaxy. The available data may be interpreted as gamma-ray production due to photomeson production in CR sources.

According to the existing viewpoint the ultrahigh energy CR, at least $E \leq 10^{17}$ eV, have a galactic origin (see, e.g. /1/). Recently discovered primary gamma-rays with $E_\gamma \geq 10^{15}$ eV /2-6/ should be considered as the first model-independent evidence for this hypothesis. For such a strong statement there are the following arguments:
1) The analysis of UHEGR absorption on the 2.7 K microwave background radiation shows that the free path of gamma-rays with $E_\gamma \geq 10^{15}$ eV is about 10 kpc, i.e. the observed UHEGR are produced within the Galaxy.
2) From the Tien Shan EAS array data it follows that there exist showers with anomalously small content of muons and hadrons /2/. The "diffuse" flux of the primary gamma-rays initiating such showers is estimated as J_γ ($E_\gamma \geq 6 \cdot 10^{14}$ eV)=$(8.4\pm2.9) \cdot 10^{-13} cm^{-2} s^{-1} sr^{-1}$ /7/. However the observed emission may be called a "diffuse" one only conventionally as it is, most probably, due to superposition of the unresolved discrete sources, and not to CR interactions with the interstellar medium (ISM). Indeed, assuming that CR, responsible for the observed flux of "diffuse" UHEGR, are captured in the region with lengthscale L, for the ratio of energy release in UHEGR and CR we have

$$\varkappa = \frac{\dot{W}_\gamma}{\dot{W}_{CR}}\Bigg|_{E\sim10^{15}eV} \sim \frac{J_\gamma}{J_{CR}} \cdot \frac{L}{\lambda}, \qquad (1)$$

where λ is the magnetic inhomogeneities scale in the ISM, and $J_\gamma/J_{CR} \sim 10^{-3}$ is the relative content of UHEGR in CR at $E_\gamma \geq 10^{15}$ eV /2,7/.

Substituting the characteristic values of $L \sim 1$ kpc (the Galaxy disk thickness) and $\lambda \sim 1$ pc, we obtain $\varkappa \sim 1$! This is a remarkable result since if gamma-rays have secondary origin (which seems beyond any doubt), then the extremely efficient mechanism to transform the CR energy to UHEGR must operate. In other words, the CR must pass the path of the order of their free path in the UHEGR production region.
3) Apparently, the interactions leading to UHEGR could not occur in the ISM since the grammage traversed by CR in the ISM is much less than 100 g/cm^2 - absorption free path with respect to the nuclear inter-

actions. In the energy range of interest the contributions from the proton and electron interactions in the ambient proton fields of the ISM are also quite insignificant. Hence, the UHEGR "diffuse" component should, in fact, be the superposition of contributions of unresolved discrete sources, wherein the CR energy transformation to UHEGR is more efficient.

So, from the facts of the limited UHEGR production region (≤ 10 kpc) the large value of the ratio $\varkappa$ (~ 1), and the incapability of CR to provide the observed UHEGR flux in the ISM it follows that the main portion of ultrahigh energy CR (at least in the energy range 10^{15} - 10^{17} eV) is accelerated in the Galactic sources.

Generally, the interactions of both accelerated protons and electrons in the sources may result in the secondary UHEGR production. Under conditions of high energy density of low-frequency radiation and magnetic fields in presumable CR sources the most essential UHEGR production mechanism, connected with the directly accelerated electron component, is the inverse Compton scatterings (ICS). However the gamma-ray spectrum expected at ICS is not in compliance with the observed one /8,9/. Besides, the electron acceleration up to $E \geqslant 10^{15}$ eV seems to be highly problematic due to strong energy losses in the magnetic field of the source ($-dE/dt \propto E^2$). The "proton" origin of the observed UHEGR seems more probable.

If the UHEGR are produced in interactions of accelerated protons with the ambient gas, then as was mentioned, they should traverse the grammage $\geqslant 100$ g/cm^2 prior to escape from the source. However in this case the accelerated nuclei won't be able to escape from the source due to a practically complete spallation in ~ 100 g/cm^2 of matter. On the other hand, the hypothesis of the UHEGR production in p-p collisions leads to the gamma-ray fluxes in the region $E_\gamma \geqslant 100$ MeV, exceeding observed ones from the COS B sources. In principle, the photon intensity at $E_\gamma \geqslant 100$ MeV might be "suppressed", assuming very hard spectra of CR in the sources; however such spectra would contradict CR observations. Moreover, the set of data obtained for the best known UHEGR source, Cyg X-3, reveals the spectrum flattening tendency in the range 10^{12} - 10^{14} eV (Fig.1). Obviously, it is impossible to explain such spectral feature by p-p collisions under any reasonable assumptions on CR spectra.

Here we suppose that the observed UHEGR are produced as a result of photomeson production in CR sources. If the initial protons having power-law spectrum ($J_{CR}(E)=K_0 E^{-s}$) interact with low-frequency photons with field density n_f and characteristic energy $\bar{\varepsilon}$, then the spectra of gamma-rays and neutrino from the secondary π-meson decays have the form /10/

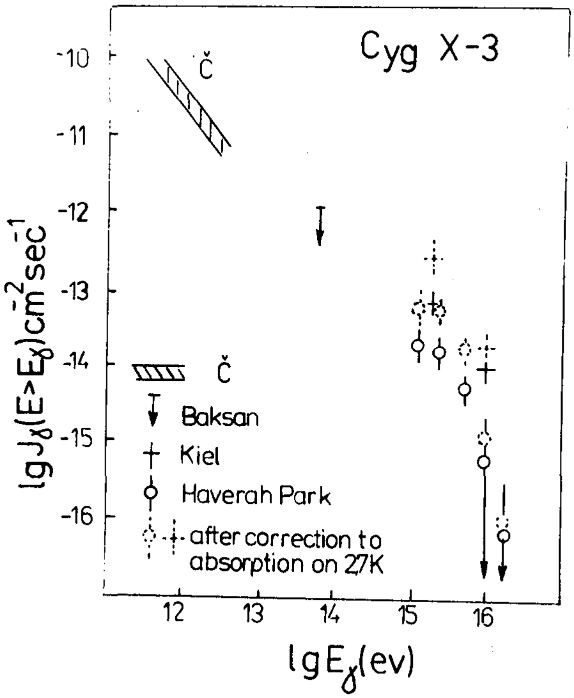
$$q_{\gamma\nu} = \begin{cases} Q_{\gamma\nu} & E_{\gamma\nu} \leq E_1 \quad , \\ Q_{\gamma\nu}\,(E_{\gamma\nu}/E_1)^{-(s+1)} & E_{\gamma\nu} > E_1 \quad ; \end{cases} \tag{2}$$

$$Q_{\gamma\nu} = 20\pi\sigma_0 n_f K_0 (E_0/2)^{-s}/\eta(s+1) \; ; \quad \sigma_0 \simeq 2\cdot 10^{-28}\,\text{cm}^2;$$

$$E_1 = \eta E_0/5 \quad ; \quad E_0 \simeq 0.35\, m_p c^2/\bar{\varepsilon} \quad .$$

The parameter η characterizes the kinematics of decays $\pi^0 \to 2\gamma$ and $\pi \to \mu\nu$: $\eta_\gamma = 0.5$ and $\eta_\nu \simeq 0.21$.

Fig. 1



If besides the low-frequency photons there is also a gas component in the production region of UHEGR, then the resulting gamma-ray spectrum will be composed of two (pp- and pγ) components. Fig.2 presents the total gamma-ray spectrum which is described by 3 peculiarities:

1) The first (low-energy) part is mainly owing to p-p interactions. In case of proton power-law distribution, the gamma-ray spectrum in the region $E_\gamma \gg m_\pi c^2$ may be approximated in the form /11/

$$q_\gamma(E_\gamma) = \varphi(s)\, \sigma_{in}^{pp}(E_\gamma/f) K_0 n_g E_\gamma^{-s} , \tag{3}$$

where n_g is the ambient gas density, σ_{in}^{pp} is the cross section of the inelastic p-p interactions at $E = E_\gamma/f$ ($f \sim 0.05$). The function $\varphi(s)$ weakly depends on s and changes within limits 0.01 - 0.05.

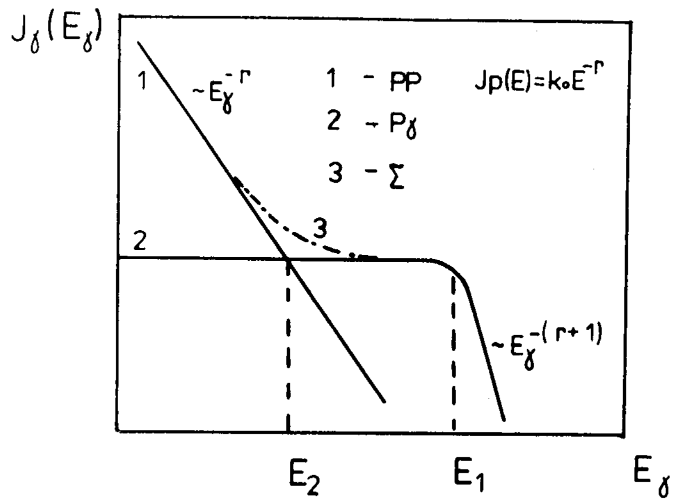
2) At $E_\gamma \sim E_2$, when the pp- and pγ - photon contributions become of the same order ($J_{pp}(E_\gamma) \sim J_{p\gamma}(E_\gamma)$), the total spectrum of gamma-rays is flattened:

$$E_2 \sim 5E_1 \left[\frac{(s+1)\varphi(s)}{40\pi} \cdot \frac{n_g}{n_f} \cdot \frac{\sigma_{in}^{pp}}{\sigma_0} \right]^{1/s} . \tag{4}$$

Obviously the flattening occurs only when $E_2 \ll E_1$. Assuming that in the source $s = 2.0$-2.1 /12/, we have $n_f > 10 n_g$. The value of E_2 is determined only by the ratio n_f/n_g and by CR spectrum index s .

3) In the region of $E_\gamma > E_1$ the gamma-ray spectrum is entirely due to pγ-component and has a power-law behaviour $\propto E_\gamma^{-(s+1)}$.

Fig. 2



Thus, knowing the peculiarities of gamma-ray spectrum in the wide range of energy, one may obtain an important information on the UHEGR sources: determining cutoff in the gamma-ray spectrum at $E_\gamma \sim E_1$ one may obtain the index of the CR spectrum in the range $E \geqslant 10E_1 \sim E_0$ ($s = s_\gamma - 1$), as well as may estimate the "temperature" of ambient photons in UHEGR production region $\bar{\varepsilon} \simeq 30\ (E_1/10^{15}\ \text{eV})^{-1}$ eV; using the observed values of E_1 and E_2, one may obtain the ratio n_f/n_g, etc. For example, in the case of Cyg X-3 we have $\bar{\varepsilon} \sim 30$ eV and $n_f/n_g \sim 10^2 \div 10^4$. It should be noted that approximately the same values of these parameters are required to explain both the cutoff in CR spectrum at $E \sim 10^{15}$ eV and the observed primary CR composition by photomeson production and nuclear photodisintegration in the ultrahigh energy CR sources /12-14/.

The future studies of UHEGR as well as the ultrahigh energy CR spectrum and composition will undoubtedly provide very important information on the ultrahigh energy CR sources. Similar programs are planned within the framework of "ANI" project on mt. Aragats.

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