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ЕРЕВАНСКИЙ ФИЗИЧЕСКИЙ ИНСТИТУТ

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THE ULTRAHIGH ENERGY ELECTRON SPECTRUM
FORMATION IN GALAXY

ЦНИИАтоминформ

ЕРЕВАН-1985

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ФОРМИРОВАНИЕ СПЕКТРА ЭЛЕКТРОНОВ
СВЕРХВЫСОКИХ ЭНЕРГИИ В ГАЛАКТИКЕ

Рассмотрено формирование спектра электронов сверхвысоких энергий в галактическом диске и в гало. Обнаружено различное поведение спектра электронов в рамках моделей захвата в гало или в диске в области энергий $E \gg 10^5$ ГэВ, обусловленное учетом релятивистских поправок в энергетических потерях электронов при обратном комптоновском рассеянии. Проведено сравнение с имеющимися экспериментальными данными.

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1. Introduction

Discovery of primary ultrahigh energy gamma-rays ($E_\gamma > 10^6$ GeV), testifies the existence of ultrahigh energy cosmic ray (UECR) sources in the Galaxy /1,2/. If the gamma-rays are of secondary origin, i.e. they are the product of interaction of UECR with ambient medium, then ultrahigh energy electrons should also be inevitable produced. Actually, if gamma-rays are of an "electron" origin, they can be produced due to the Compton scattering of directly accelerated electrons on the ambient low frequency radiation. (At conditions of high density of low frequency radiation and magnetic fields in possible sources of CR, the other production processes are less efficient). On the other hand, if the gamma-rays are of a "proton" origin, i.e. are produced from the π^0 -decays, then the genetically associated electrons (from the π^\pm -decays) are produced nearly at the same number and with the same spectrum. Besides, the interaction between the ultrahigh energy gamma-rays with blackbody radiation (BR) 2,7k, results copious e^\pm -pair production in the interstellar medium (IM). For

example, the luminosity of firmly established source of ultra-high energy gamma-rays (UEGR) CygX-3 is $L_x(E_x \geq 10^6 \text{ GeV}) \geq 10^{37} \text{ erg/s}$ /3,4/. The high energy electrons (HEE) luminosity must be at least of the same order, since the small free path of UEGR ($\lambda \sim 10 \text{ kps}$) leads to the "hold-up" of gamma-rays in the Galaxy and hence to electron production at the same energies.

2. Electrons Spectrum Formation in IM

The energy distribution of the electron in the IM with the injection spectrum $N_0(E)$ due to energy loss and escape from the Galxy is transformed as:

$$N(E) = |B(E)|^{-1} \int N_0(E') \times \exp \left\{ - \int_{E'}^E |B(E'')|^{-1} [T^{-1}(E'') + Z^{-1}(E'')] dE'' \right\} dE', \quad (1)$$

where $B(E)$ is the total energy loss rate, $Z^{-1}(E)$ is the escape time and $T(E)$ is the electrons life time due to catastrophic loss.

In the energy range $E > 10 \text{ GeV}$ the energy loss due to ionization and bremsstrahlung are negligible (see eq./6/). In this range the loss due to interactions with magnetic field (synchrotron loss), with low frequency photon field (Compton loss) and the escape from the Galxy are dominating ones. Starting from $E > 10^2 \text{ GeV}$ synchrotron and Compton loss dominate over the escape ones, and hence the equilibrium electron spectrum has

the form

$$N(E) \sim E^{-2} \int N_0(E) dE, \quad (2)$$

since the synchrotron and Compton loss increase as E^2 . In the case of power law injection spectrum $N_0(E) \sim E^{-\alpha}$, the equilibrium spectrum is also power law one, but with the index $\alpha + 1$:

$$N(E) \sim E^{-(\alpha+1)}. \quad (3)$$

However, in the energy region under consideration, essential deviation from $dE/dt \sim E^2$ law is possible. Actually, the energy loss consists of the synchrotron and Compton ones

$$dE/dt = (dE/dt)_{\text{SYNC}} + (dE/dt)_{\text{COMPT}}. \quad (4)$$

The synchrotron losses are /7/:

$$(dE/dt)_{\text{SYNC}} = - \frac{32}{9} \pi r_0^2 c \gamma^2 W_H, \quad (5)$$

where r_0 is the electron classical radius, c is the light speed, $W_H = H^2/8\pi$ is the energy density of the magnetic field. Eq. (4) is correct up to $E \leq 10^{10}/H \text{ GeV}$, i.e. it is always correct at any reasonable values of electrons energy in IM ($H = 10^{-5} - 10^{-6} \text{ Gauss}$). The things are different for Compton loss. In Thomson limit, when the condition $b = 4 \cdot E/(mc^2)^2 \ll 1$ (ω is the ambient photon energy) is fulfilled, the losses are defined by Eq.(5), where instead of the magnetic field density the photon energy density W_F is to be substituted. When $b \gg 1$, then due to decreasing b -dependence of Klein-Nishina cross-

section, the energy loss dependence on E becomes a logarithmic one (see e.g./8,9/):

$$(dE/dt)_{\text{COMP}} = -\frac{\pi z_0^2}{\omega^2} W_F (mc^2)^2 c (\ln b - 11/6). \quad (6)$$

In general case the Compton loss are determined by /9/:

$$(dE/dt)_{\text{COMP}} = -\frac{2\pi z_0^2}{\omega^2 b} W_F (mc^2)^2 c \left[\left(6 + \frac{b}{2} + \frac{6}{b}\right) \ln(1+b) - 2\text{Li}\left(\frac{1}{1+b}\right) - \ln^2(1+b) - \frac{(11/12)b^3 + 8b^2 + 13b + 6}{(1+b^2)} \right], \quad (7)$$

where Li is dilogarithmic function. In the case $H \ll (8\pi W_F)^{1/2}$ and $b \gg 1$, the equilibrium spectrum of electrons becomes harder than the injection spectrum:

$$N(E) \sim E^{-(\alpha+1)} / \ln E. \quad (8)$$

In the IM energy loss due to Compton scattering are mainly caused by interactions of relativistic electrons with BR and starlight photons ($\omega \sim 1\text{eV}$), for which the condition $b \gg 1$ is fulfilled at $E > 10^5 \text{GeV}$ and $E > 50 \text{GeV}$ respectively. Hence, the determination of equilibrium electron spectrum in i.m. at ultrahigh energies requires the correct account of Compton loss.

Fig.1 shows the energy loss dependence in the cases, when the electrons are captured in the galactic disk (a) and halo (b). The following parameters were used in calculations: a) in the disk - the infrared and optical photons energy density $W_0 \approx 1\text{eV/cm}^3$, magnetic field $H = 3 \cdot 10^{-6}$ Gauss; b) in halo - $W_0 \approx 0,1 \text{eV/cm}^3$, magnetic field $H = 3 \cdot 10^{-7}$ Gauss. As it follows from the picture, the energy loss dependence deviation from the E^2 law at ultrahigh energies is essential both for disk

and halo. In the latter case this is clearly revealed at energies $E 10^4 - 10^5 \text{GeV}$, owing to the small value of magnetic field ($H^2/8\pi \ll W_{\text{BR}} \approx 0,25 \text{eV/cm}^3$). This feature, obviously, should reflect the equilibrium electrons spectrum shape.

3. Calculation results

The curves defining the equilibrium electron spectrum, calculated for the cases of disk and halo are plotted in fig.2. The CR life time for disk and halo is $1,15 \cdot 10^{16} \text{s}$ and $3 \cdot 10^{14} \text{s}$ respectively. The injection spectrum is $N_0(e) = E^{-2,7}$, according to /10/. As it is shown in ref./10/, the best fit of experimental data in the energy range $E > 10^2 \text{GeV}$ is attained at these parameters. In fig.3 both the calculated equilibrium spectrum of electrons captured in disk and existing experimental results /10,11/ are shown. In the energy range $E > 10^2 \text{GeV}$ the energy losses caused by the particles escape from the capture region, as it has already been noted, have no influence on the equilibrium electron spectrum, which is defined only by the injection spectrum and parameters, describing the capture region (the magnetic field, radiation density and mean energy). If the losses are proportional to E^2 , we are to expect power law spectrum with the index $\alpha = 3,7$ in the energy range $E > 10^2 \text{GeV}$. However, as it follows from fig.3, such dependence takes place only in the energy range $E > 10^5 \text{GeV}$, where the synchrotron loss proportional to E^2 dominate (see fig.1). The theoretical spectrum from ref. /10/ is also plotted in fig.3. It should be noted once more, that the relativistic corrections for inverse Compton loss were not accounted in ref./10/. From the compari-

son of the two curves, calculated at the same initial assumptions on the injection spectrum and the capture region parameters, it follows, that relativistic corrections are essential starting from $E \sim 10^2 \text{ GeV}$. The account of these corrections leads to a better accordance with the existing experimental data. The differences in the spectra behaviour, as it was expected, become more essential in the case of halo, where the magnetic field energy density is much less than the BR density.

Note, that the correct calculation of equilibrium spectrum of electrons in the energy range $E \sim 10^6 \text{ GeV}$ needs the account of e^+e^- -pair production due to the interactions of secondary gamma-rays with $E \sim 10^6 \text{ GeV}$ from the Compton scattering with BR. However, in the zero approximation, this process is negligible, since at $E \sim 10^6 \text{ GeV}$ the Compton scattering is depressed by the synchrotron loss (see fig.1).

4. Summary

It follows from the irregularity of the energy loss discussed above, that the electron spectrum at ultrahigh energies must have sharp features. Hence, the experimental study of electron spectrum in this energy range gives large possibilities to obtain information on the parameters, describing the capture region. In fig.2 essential differences between expected electron spectra for disk and halo models is observed. A possibility to obtain information on the electron spectrum at $E \sim 10^6 \text{ GeV}$ may be connected with the detection of synchrotron radiation in the X-ray region (of an order of 50 KeV and 10KeV

for disk and halo respectively), produced by these electrons. A principle possibility for ultrahigh energy electrons detection by identification of Earth Atmospheric Showers (EAS) of electromagnetic origin with anomalous small muon content, unfortunately, is excluded. Indeed, on Tien-Shan EAS array a particle flux, initiating EAS with small muon content at $E \geq 6 \cdot 10^5 \text{ GeV}$, $I = 8,3 \pm 2,9 \cdot 10^{-13} \text{ cm}^{-2} \text{ s}^{-1}$ is observed /12/. At the same time, as it follows from fig.3, the expected electron flux at same energies cannot exceed $10^{-16} \text{ cm}^{-2} \text{ s}^{-1}$ (otherwise, a contradiction with experimental data at low energies will take place). It means that: i) the flux obtained by Tien-Shan group has photon origin; ii) the registration of ultrahigh energy electrons by EAS analysis seems to be nonrealizable, since EAS induced by electrons and photons are similar.

Much more realizable is the method of registration of synchrotron X-ray radiation, emitted by electrons in geomagnetic field, suggested in ref./13/.

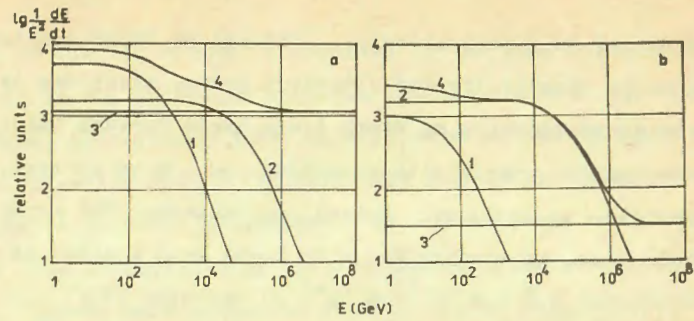


Fig.1. Energy loss of electrons in disk (a) and halo (b).
Curves 1 and 2 are the losses due to Compton scattering on optical photons and BR, respectively, curve 3 is the synchrotron loss, curve 4 is the total energy loss.

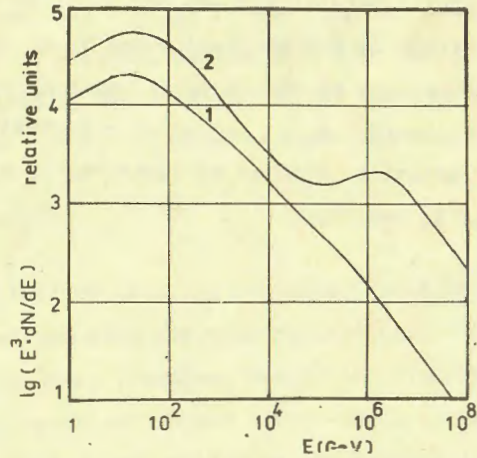


Fig.2. The equilibrium spectra of electrons for disk (a) and halo (b) models.

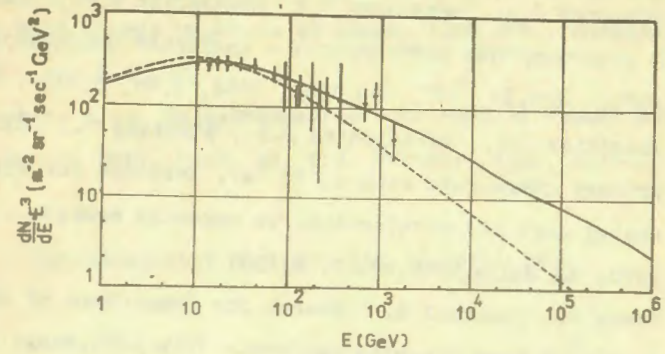


Fig.3 Differential energy spectra of electrons. Solid curve is the equilibrium spectrum for disk model; dashed curve is the spectrum from ref. /10/.

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