Pis'ma v ZhETF, vol.70, iss.8, pp.487-492 © 1999 October 25

GENERATION OF $10^{15}-10^{17}$ eV PHOTONS BY ULTRA-HIGH ENERGY COSMIC RAYS IN THE GALACTIC MAGNETIC FILED

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Submitted 18 June 1999
Resubmitted 17 September 1999

We show that the dip expected in the diffuse photon spectrum above the threshold of e^+e^--pair production, i.e., at energies $10^{15}-10^{17}$ eV, may be absent due to the synchrotron radiation by the electron component of the extragalactic Ultra-High Energy Cosmic Rays (UHECR) in the Galactic magnetic filed. The mechanism we propose requires small ($< 2\cdot 10^{-12}$ G) extragalactic magnetic fields and large fraction of photons in the UHECR. For a typical photon flux expected in top-down scenarios of UHECR, the predicted flux in the region of the dip is close to the existing experimental limit. The sensitivity of our mechanism to the extragalactic magnetic field may be used to improve existing bounds on the latter by two orders of magnitude.

PACS: 98.70.Sa

1. Introduction. The spectrum of diffuse photons is expected to have a dip of more than two orders of magnitude at energies $10^{15}-10^{17}$ eV [1]. This dip is similar in nature to the well-known Greisen – Zatsepin – Kuzmin (GZK) cutoff [2] and is caused by electron pair production on the cosmic microwave background, $\gamma\gamma_b \to e^+e^-$. The cross section of the latter process reaches its maximum of $0.3\sigma_T \sim 0.2$ barn near the threshold at $3\cdot 10^{14}$ eV and decreases at higher energies (see, e.g., ref. [3]). The attenuation length of photons in the region of the dip is of order 100 kpc, so the dip in the spectrum is a universal feature of models in which high energy photons have extragalactic origin. Indeed, the existence of the dip is confirmed by simulations in various models of Ultra-High Energy Cosmic Rays (UHECR), for a review see, e.g., refs.[3, 4]. For instance, in the region of the dip the top-down models typically give the photon flux[2] of order 10^{-3} eV$\cdot$cm$^{-2}\cdot$s$^{-1}\cdot$sr^{-1}, while at ultra-high energies, $E \gtrsim 10^{20}$ eV, the predicted flux is more than two orders of magnitude larger and reaches (a few) $\times\, 10^{-1}$ eV$\cdot$cm$^{-2}\cdot$s$^{-1}\cdot$sr^{-1}.

The spectrum of diffuse photons at energies above $\sim 10^{11}$ eV is known rather poorly. Detection of the photons at the lower and upper boundaries of the dip were reported by the Tien-Shan air shower array and Yakutsk experiment. They claimed that a γ-ray intensity is at the level ~ 100 eV$\cdot$cm$^{-2}\cdot$s$^{-1}\cdot$sr^{-1} at $E \geq 4\cdot 10^{14}$ eV [5], and 1 eV$\cdot$cm$^{-2}\cdot$s$^{-1}\cdot$sr^{-1} at $E \geq 10^{17}$ eV [6]. In the region of the dip the bounds have been obtained by EAS-TOP [7] and CASA-MIA [8]. At $E \sim 10^{16}$ eV the bound is of order ~ 0.5 eV$\cdot$cm$^{-2}\cdot$s$^{-1}\cdot$sr^{-1}, about two orders of magnitude higher than has been predicted by top-down models. At ultra-high energies the photon flux can be as large as ~ 1 eV$\cdot$cm$^{-2}\cdot$s$^{-1}\cdot$sr^{-1} if the observed UHECR events are interpreted as photons (recent results from AGASA [9] suggest this possibility [10]).

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[2] Here and below we mean the energy flux $F(E)$ which is expressed in terms of the differential spectrum $j(E)$ by means of the relation $F(E) = E^2 j(E)$ and is measured in the units of eV$\cdot$cm$^{-2}\cdot$s$^{-1}\cdot$sr^{-1}.

While experimentally the existence of the dip in the photon spectrum is an open question, theoretically it is not solid either. Calculations of the spectrum cited above do not take into account the possibility that high energy photons can be generated in our Galaxy by UHE electrons via synchrotron radiation in the Galactic magnetic field. As we argue below, the account for synchrotron emission may substantially change the photon spectrum at $E \sim 10^{15} - 10^{17}$ eV filling the dip and bringing the expected photon flux close to the existing experimental limit.

The synchrotron mechanism requires large flux of UHE electrons to hit the Galactic magnetic field. It has been recently pointed out in ref. [11] that this condition is naturally satisfied in the halo models of UHECR (these models explain UHECR by decays of heavy relic particles clustered in the Galactic halo [12]). Due to the fragmentation process, the decay products of the superheavy particles contain a large fraction of UHE electrons.

In this paper we show that UHE electrons which are necessary for the synchrotron mechanism to work can be of extragalactic origin, provided extragalactic magnetic fields are small. We will see that, in fact, the large flux of UHE electrons is inherent in top-down models of UHE CR, so that the generation of high energy photons by the synchrotron mechanism is a generic prediction of top-down scenarios and is not specific to halo models of UHECR .

The key observation is that UHE photons propagate in the extragalactic space via cascade process being converted to electrons and back with a small energy loss. As a result, the flux of UHE photons is necessarily accompanied by the flux of UHE electrons. At energies of order $10^{22} - 10^{23}$ eV and in the absence of extragalactic magnetic fields the electron flux is at least as large, or even much larger, than the photon one[3]. While UHE photons reach the Earth and contribute to the observable flux of UHECR, UHE electrons emit synchrotron radiation in the Galactic magnetic field and transfer their energy to high energy photons. As we will see below, the energy of produced photons lies in the region of the dip, while their flux is similar to that of UHE electrons (and, thus, of UHE photons). Hence, in the absence of extragalactic magnetic fields the flux of UHE photons at the level of ~ 1 $\mathrm{eV{\cdot}cm^{-2}{\cdot}s^{-1}{\cdot}sr^{-1}}$ implies the flux of synchrotron photons at the same level which fills the dip in the photon spectrum. Since the large flux of UHE photons is one of the signatures of the top-down mechanisms of UHECR, in the absence of extragalactic magnetic fields these models generically predict no dip in the spectrum of diffuse photons.

The mechanism we propose is sensitive to magnetic fields on distances up to 50 Mpc from our Galaxy. If no dip in the photon spectrum is observed and halo models are ruled out, the extragalactic magnetic field on this distances must be smaller than $2 \cdot 10^{-12}$ G. This is two orders of magnitude better than the existing bounds [13]. Inversely, if the dip is found and, at the same time, UHECR have a large fraction of photons, the extragalactic magnetic field must be larger than $2 \cdot 10^{-12}$ G.

The paper is organized as follows. In Sect.2 we estimate the flux of UHE electrons given the flux of UHE photons and zero extragalactic magnetic field. In Sect.3 we calculate the spectrum of synchrotron radiation in the galactic magnetic field for injected electrons of given energy. In Sect.4 we estimate the effect of extragalactic magnetic fields. Sect.5 contains our conclusions.

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[3] In the presence of the extragalactic magnetic field the electrons rapidly loose energy via synchrotron radiation and the argument may not work (see Sect.4 for details).

2. The flux of UHE electrons. Our aim in this section is to show that in the energy range $10^{22}-10^{23}$ eV the flux of UHE photons is necessarily accompanied by a comparable or larger flux of UHE electrons, provided the extragalactic magnetic fields are absent. The argument is based on the observation that at these energies the photon propagation is a cascade process (see, e.g., [4]), i.e., propagating photon is converted to an electron and back with small energy loss. As this process is random, one should expect certain ratio of photons and electrons far from the source.

The main reactions driving the cascade are e^+e^--pair production (PP) on the radio background, $\gamma\gamma_b \to e^+e^-$, double pair production (DPP), $\gamma\gamma_b \to e^+e^-e^+e^-$, and the inverse Compton scattering (ICS), $e\gamma_b \to e\gamma$ [3]. In the energy range of interest double pair production dominates, so one should expect to find more electrons than photons.

A simple estimate can be obtained if one neglects secondary particles and energy losses. In this (rather crude) approximation PP and DPP lead to the conversion of photon to electron with the rates a_{PP} and a_{DPP}, respectively, while ICS converts electron back to photon with the rate b. The set of equations which describes propagation of photons and electrons reads

$$dn_\gamma/dR = -an_\gamma + bn_e, \qquad dn_e/dR = an_\gamma - bn_e,$$

where R is the distance from the source, $n_\gamma(R)$ and $n_e(R)$ are fractions of photons and electrons at the distance R, respectively, and $a \equiv a_{PP} + a_{DPP}$. The solution to this system is

$$n_e/n_\gamma = [ae^{R(a+b)} - C]/[be^{R(a+b)} + C]\,, \tag{1}$$

where C is an integration constant whose value is determined by the ratio n_e/n_γ at $R = 0$. Far from the source the value of this constant is irrelevant.

The observed fluxes $F_{e,\gamma}$ are given by integrals over the space of $n_{e,\gamma}$ multiplied by the particle injection rate. To estimate F_e/F_γ we note that the integrals are dominated by large distances where the ratio n_e/n_γ is constant, $n_e/n_\gamma \sim a/b$. Therefore,

$$F_e/F_\gamma \sim a/b. \tag{2}$$

Both a and b depend on energy. At $E \sim 10^{22}$ eV one has $a \sim 2\cdot10^{-2}$ Mpc^{-1}, $b \sim$ $\sim 8\cdot10^{-3}$ Mpc^{-1} [3], and thus

$$F_e/F_\gamma \sim 2 \qquad \text{at} \quad E = 10^{22}\ \text{eV}. \tag{3}$$

At higher energies the rate a is dominated by DPP process and tends to a constant, $a \to 8\cdot10^{-3}$ Mpc^{-1}, while the rate b rapidly falls off [3]. At $E \sim 10^{23}$ eV eq.(2) gives

$$F_e/F_\gamma \sim 10 \qquad \text{at} \quad E = 10^{23}\ \text{eV}. \tag{4}$$

In a more accurate estimate one should take into account energy losses by leading particles and possible energy sharing in the leading e^+e^--pair in DPP. In this approximation the result depends on the energy distribution of initial particles, as well as on the energy dependence of the rates a_{PP}, a_{DPP} and b. We have performed such estimate by dividing energy interval $10^{21}-10^{24}$ eV into 10 energy bands and solving numerically the system of 20 coupled equations analogous to eqs.(??). We have found that the corrections to eqs.(3) and (4) are small and do not change our conclusions, unless the extragalactic magnetic filed is non-zero (the latter case is considered in Sect.4).

3. Synchrotron radiation in the galactic magnetic field. Consider now the synchrotron radiation of UHE electrons in the Galactic magnetic field. An ultra-relativistic particle of energy E moving in the magnetic field B emits radiation at the characteristic frequency [14]

$$\omega_c = \frac{3\sqrt{\alpha}B}{2m_e^3}E^2 = 6.7\cdot 10^{14}\left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^2\left(\frac{B}{10^{-6}\,\mathrm{G}}\right)\,\mathrm{eV}. \tag{5}$$

The width of the frequency band is roughly $\delta\omega \sim \omega_c$. As a result of this process, the particle looses energy at the rate

$$dE/dx = -2\alpha^2B^2E^2/3m^4. \tag{6}$$

Both equations are written for the case of particle momentum normal to the direction of the magnetic field. Generalization to other cases is straightforward.

Eq.(5) implies that in the Galactic magnetic field, $B \sim 10^{-6}$ G, electrons with energy $E \sim 10^{20}$ eV radiate at the characteristic frequency $\omega_c \sim 10^{15}$ eV. This process is the source of high energy photons in the Galactic halo models of UHECR [11]. Since the Galactic magnetic field far from the Galactic center is smaller, the extragalactic electrons which we consider in this paper should have higher energy in order to produce synchrotron radiation in the same frequency range.

For the quantitative analysis of the synchrotron emission by the extragalactic electrons consider an UHE electron moving in a varying magnetic field $B(x)$ perpendicular to its velocity. Integration of eq.(6) gives

$$\frac{1}{E(x)} - \frac{1}{E_0} = \frac{2\alpha^2}{3m_e^4}\int_{-\infty}^{x} B^2(x)dx, \tag{7}$$

where E_0 is the initial energy of the electron.

For definiteness, let us take the exponentially decaying magnetic field,

$$B(x) = B_0\exp(x/x_0) \tag{8}$$

(note that we consider a particle propagating from $x = -\infty$). This behavior is expected in some recent Galactic magnetic field models [15] for the field in the direction normal to the Galactic disk. The scale x_0 is of order 4 kpc. Making use of eqs.(7) and (8) one finds the relation between E and B at a given point of particle trajectory,

$$(1/E) - (1/E_0) = \alpha^2x_0B^2/3m_e^4.$$

This equation, together with eq.(5), determines the dominant radiation frequency as a function of particle energy,

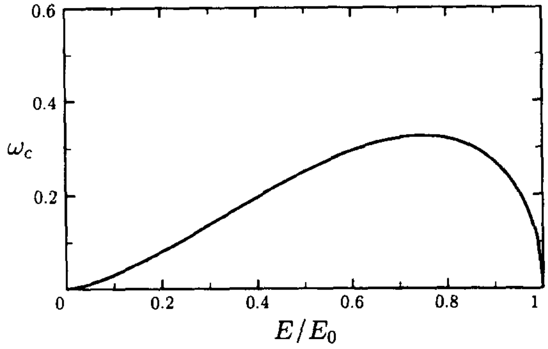
$$\omega_c(E) = \frac{9E_0^{3/2}}{2m_e\sqrt{3\alpha x_0}}f(E/E_0), \quad \text{where} \quad f(y) = y^{3/2}\sqrt{1-y}.$$

This function is shown in Figure. As can be seen from the picture, most part of the electron energy is emitted at frequencies close to

$$\omega_{max} = \omega_c(3E_0/4) = \frac{27E_0^{3/2}}{32m_e\sqrt{\alpha x_0}} = 0.8\cdot 10^{15}\left(\frac{E_0}{10^{22}\,\mathrm{eV}}\right)^{3/2}\left(\frac{x_0}{4\,\mathrm{kpc}}\right)^{-1/2}\mathrm{eV}. \tag{9}$$

According to eqs.(5) and (9), at $E = 10^{22}$ eV the electron looses most part of its energy in the region where the magnetic field is $\sim 10^{-10}$ G, i.e., at the distance ~ 36 kpc from the galactic disk for $B_0 \sim 10^{-6}$ G.

In the case of magnetic field not perpendicular to particle velocity, the spectrum of synchrotron photons is softer. The same is true for the magnetic field which falls off slower than in eq.(8), as usually assumed for the Galactic magnetic filed in the direction parallel to the Galactic plane. Thus, one should expect angular dependence of the photon spectrum with more energetic photons coming from the direction normal to the Galactic plane, and softer spectrum from the directions in the Galactic plane. The above estimates indicate that this effect is small and its detailed study at this point seems premature.



The dependence of ω_c (arbitrary units) on particle energy for the exponential model of the Galactic magnetic field

Finally, let us estimate the flux of synchrotron photons assuming the flux of UHE photons which is typical for top-down scenarios, (a few) $\cdot\, 10^{-1}$ eV$\cdot$cm$^{-2}\cdot$s$^{-1}\cdot$sr^{-1} at energies $\sim 10^{22} - 10^{23}$ eV. Eq.(3) implies that, outside the Galactic magnetic field, there is at least as large flux of UHE electrons which transfer their energy to high energy photons in the Galactic magnetic field. Since the synchrotron spectrum has $\delta\omega \sim \omega$, the energy conservation implies that the flux of synchrotron photons is approximately the same as the flux of UHE electrons, which is larger by the factor F_e/F_γ than the flux of UHE photons.

4. Effect of extragalactic magnetic field. As it was shown above, in the absence of extragalactic magnetic fields the observed flux of $10^{15} - 10^{17}$ eV photons is proportional to the flux of UHE photons and the ratio F_e/F_γ at energies above $E \gtrsim 10^{22}$ eV. The presence of large enough extragalactic magnetic field can significantly decrease this ratio. Indeed, if $\gamma \to e$ conversion length, $a^{-1} = (a_{PP} + a_{DPP})^{-1}$, is large compared to the energy loss length of the electron due to the synchrotron radiation in the extragalactic magnetic field, the flux of UHE electrons should be much smaller than the flux of UHE photons.

Let us estimate the value of the extragalactic magnetic field at which the ratio $F_e/F_\gamma \sim 1$ at $E \gtrsim 10^{22}$ eV. For this purpose note that the solution to eq.(6) in the constant magnetic field B can be written in the form

$$l = (3m^4/2\alpha^2 B^2 E)[1 - (E/E_0)], \tag{10}$$

where l is the distance passed by the electron while its energy decreases from E_0 to E. Eq.(10) implies that electrons with energy E can only come from distances smaller than

$$l_E = 3m^4/2\alpha^2 B^2 E \sim 50\,(2\cdot 10^{-12}\mathrm{G}/B)^2\,(10^{22}\mathrm{eV}/E)\,\mathrm{Mpc}\,. \tag{11}$$

Taking into account that the length a^{-1} of $e \to \gamma$ conversion is of order 50 Mpc at $E = 10^{22}$ eV [3] one finds that the extragalactic magnetic field should be smaller than $2\cdot 10^{-12}$ G at the distances $\lesssim 50$ Mpc from our Galaxy in order that the ratio F_e/F_γ to be comparable or larger than one. If the magnetic field at distances of order 50 Mpc is much larger than $2\cdot 10^{-12}$ G (for the discussion of present limits on the extragalactic magnetic field see, e.g., ref. [16]), the ratio F_e/F_γ is much smaller than one and the flux of UHE electrons is not sufficient to fill the dip in the photon spectrum by synchrotron mechanism.

It is worth noting that the mechanism we propose is not sensitive to magnetic fields at distances larger than $\sim$ 50 Mpc because this distance is sufficient for generation of a large fraction of electrons, $F_e/F_\gamma \sim 1$. The effect of distant magnetic fields is mere decreasing of the UHE photon flux, which is not important for our argument since we normalize UHE photon flux to the observed flux of UHECR.

5. Conclusions.

With proper account for the synchrotron radiation in the Galactic magnetic field the top-down models, under certain conditions, generically predict the flux of $10^{15} - 10^{17}$ eV photons which is close to the current experimental limits. Thus, it is important to improve the sensitivity of the experiments in the energy range $10^{15} - 10^{17}$ eV. The detection of the diffuse photon flux at the level of $\sim 10^{-1}$ eV·cm^{-2}·s^{-1}·sr^{-1} would strongly suggest that UHECR are produced by a top-down mechanism. Moreover, this would imply that either the mechanism based on the halo model [11] or the one proposed here works. The two possibilities can be distinguished by measuring the angular anisotropy of UHECR [17] and of produced high energy photons [11]. On the contrary, if the photon flux in the region of the dip is smaller than $\sim 10^{-3}$ eV·cm^{-2}·s^{-1}·sr^{-1} and, at the same time, UHECR have a large fraction of photons, the extragalactic magnetic field must be larger than $2 \cdot 10^{-12}$ G.

The authors are indebted to D.S.Gorbunov, O.E.Kalashev, M.V.Libanov, V.A.Rubakov and D.V.Semikoz for useful discussions and comments. The work of S.D. is supported in part by Russian Foundation for Basic Research under grant 99-02-18410, INTAS grant 96-0457 within the research program of the International Center for Fundamental Physics in Moscow, and ISSEP fellowship.

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