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Ultra-high energy cosmic rays: energy losses and spectra

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Abstract. The energy losses and spectra of Ultra High Energy Cosmic Rays (UHECR) are calculated for protons as the primary particles. An attention is given to the energy losses due to electron-positron production in collisions with the microwave 2.73 K photons. The energy spectra are calculated for several models, which differ by production spectra and by source distribution, namely: *(i)* Uniform distribution of the sources with steep generation spectra with indicies 2.4 - 2.7, with cosmological evolution and without it. In this case it is possible to fit the shape of the observed spectrum up to $8 \cdot 10^{19}$ eV ; *(ii)* Uniform distribution of the sources with flat generation spectrum dE/E^2. This case is relevant to GRBs and results are in disagreement with observed spectrum. *(iii)* The case of local enhancement within region of size 10 - 30 Mpc with overdensity given by factor 3 - 100. The overdensity larger than 30 is needed to eliminate GZK cutoff.

1 Introduction

The energy losses of UHE protons in extragalactic space are caused by interaction with microwave radiation. The contribution of IR and optical radiation is small (for a detailed review of energy losses and the resulting spectrum see (Berezinskii et al, 1990)). The main contribution to energy losses is given by expansion of the Universe, electron-positron pair production and pion production. The latter process results in steepening of the proton spectrum referred to as the Greisen-Zatsepin-Kuzmin (GZK) cutoff (Greisen, 1966; Zatsepin and Kuzmin, 1966). The GZK cutoff is not seen in the observational data (for a recent review see (Nagano and Watson, 2000). The most conservative approach to explanation of observations is astrophysical one: the protons are accelerated in astrophysical sources (normal galaxies, compact objects in normal galaxies, e.g. GRB engines, AGN etc) and propagate towards us. This approach comprises three aspects: acceleration to UHE, total energy release of a source and absence of the GZK cutoff. This most conservative approach is considered as (almost) excluded, with certain caveats, however. The models in which the GZK cutoff problem is absent or ameliorated include nearby *one-source model* (see Wdowczyk and Wolfendale, 1980; Berezinsky et al , 1990; and most recent work (Ahn et al, 2000); the *Local Supercluster model*, in which the density of UHECR sources is locally enhanced (Berezinskii et al, 1990; Berezinsky and Grigorieva,1979), for a recent work see (Blanton and Olinto, 2001); and finally widely discussed *GRB model* which, according to calculations Waxman (2000), gives a reasonable agreement with observations. In this paper we shall analyze the two former models.

2 Energy losses

We are presenting here the accurate calculations for pair production, $p + \gamma_{bb} \rightarrow p + e^+ + e^-$, and for pion production $p + \gamma_{bb} \rightarrow p + \text{pions}$, where γ_{bb} is a microwave photon (bb is for black-body radiation). The basic elements of calculations are as follows. Pair production loss has been previously discussed in many papers. All authors directly or indirectly followed the standard approach of Blumenthal (1970), where the first Born approximation of Bethe-Heitler cross-section with proton mass $m_p \rightarrow \infty$ was used. In contrast to Blumenthal (1970), we use the first Born approximation approach of Berg and Linder (1961), which takes into account the finite proton mass. We also use the exact non-relativistic threshold formulae (see e.g. Berestetskii et al (1980)). This allowed us to calculate the average energy transfer from the incident photon to the final proton in the initial proton rest system, $x = E_{p'}/E_p$, by performing the fourfold integration of the exact matrix element. The numerical calculations, especially at high energies, are difficult in this case because of forward-backward spikes in electron-positron angular distributions. To overcome this problem, we have managed to perform two integrations analytically. The accuracy

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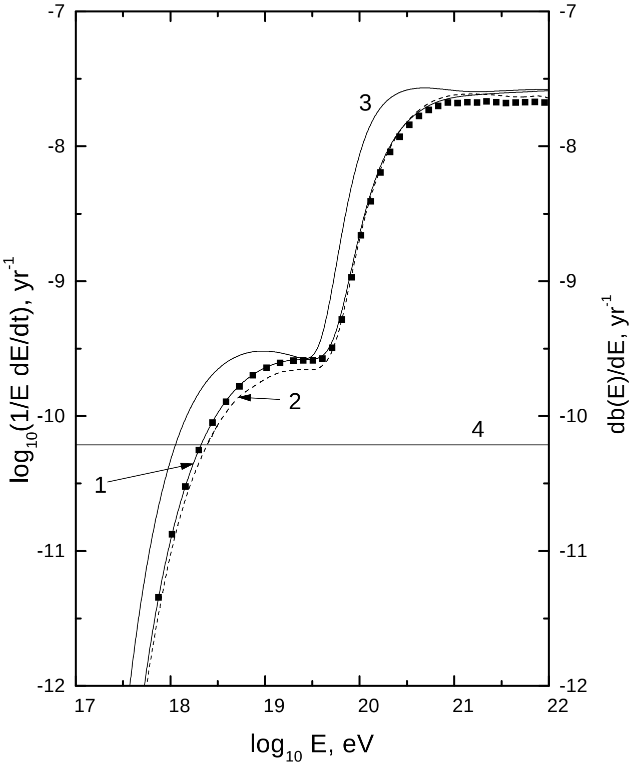

Fig. 1. Figure 1.*UHECR proton energy losses $E^{-1}dE/dt$ (present work: curve 1, Berezinsky and Grigorieva (1988): curve 2, Stanev et al (2000): black squares. The cirve 3 is the derivative $db(E)/dE$, where $b = dE/dt$.The line 4 gives the energy losses due to redshift ($H_0 = 65km/secMpc$).*

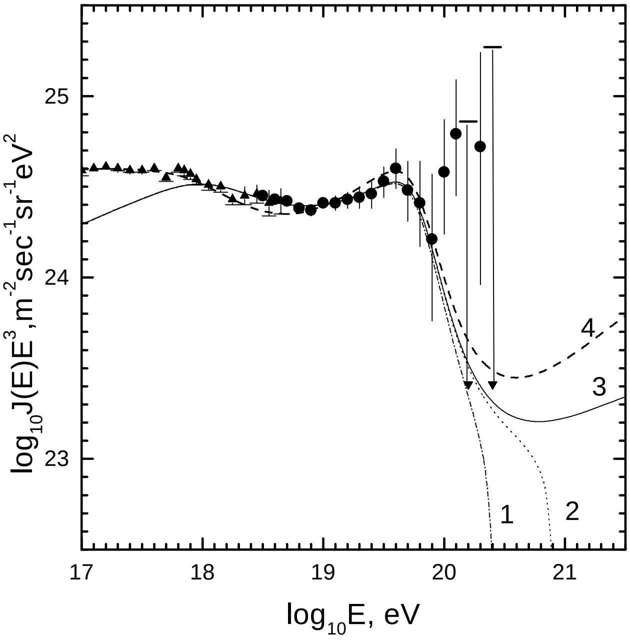

Fig. 2. Figure 2. *UHECR spectrum as obseved in AKENO (triangles) and AGASA (black dots) experiments. The lines show predicted differential spectra for the uniform distribution of the sources with or without evolution. The case without evolution (1,2 and 3 for maximum generation energy $E_{max} = 3 \cdot 10^{20}$ eV, $1 \cdot 10^{21}$ eV and ∞, respectively. The dash line gives the spectrum for the case of evolution ($m = 4$ and $\gamma_g = 2.45$).*

of high-energy calculations is checked by comparison of total cross-sections with those obtained by direct integration in the Bethe-Heitler case. Calculating photoproduction energy loss we followed the method of papers (Berezinsky and Gazizov,1993; Gazizov, 1996). Total cross-sections were taken according to Gabathuler (1974). At low c.m. energy E_c we considered the binary reactions $p + \gamma \to \pi + N$, including the resonance $p + \gamma \to \Delta$, $\quad p + \gamma \to \pi^- + \Delta^{++}$, $p + \gamma \to \rho^0 + p$. Differential cross-sections of binary processes at small energies were taken from Menze et al (1977). At $E_c > 4.3$ GeV we assumed the scaling behavior of differential cross-sections. These were taken from Meyer (1974). In the intermediate energy range we used an interpolation approach allowing to describe the residual part of total cross-section. The corresponding differential cross-sections coincide with low-energy binary description and high-energy scaling distribution and have a smooth transition between these two regimes in the intermediate region. The results of our calculations are shown in Fig.1 in terms of relative energy losses per unit time $E^{-1}dE/dt$ as function of energy (curve 1). Also plotted is the derivative $db(E)/dE$, where $b = dE/dt$ (curve 3). This quantity is needed for calculation of differential energy spectrum (see Berezinsky and Grigorieva, 1988). In Fig.1 we plot for comparison the energy losses as calculated by Berezinsky and Grigorieva (1988) (dashed curve 2). The difference in energy losses due to pion production is very small, not exceeding 5% in the energy region relevant for comparison with experimental data($E \leq 10^{21}\ eV$). The difference with energy losses due to pair production is larger and reaches maximal value 15%. The results of calculations by Stanev et al (2000) are shown by black squares. These authors have performed the detailed calculations for both aforementioned processes, though their approach is somewhat different from ours, especially for photopion process. Our energy losses are practically indistinquishable from Stanev et al (2000) for pair production and low energy pion production, and differ by 15-20% for pion production at highest energies (see Fig.1.).

3 Uniform distribution of UHECR sources and GZK cutoff

Using energy losses given in Section 2, we calculated the diffuse spectra for the model when sources are distributed uniformly in the Universe. We followed the method of calculation suggested by Berezinsky and Grigorieva (1988) and use $db(E)/dE$ as calculated in Section 2. We use two assumptions for uniform distribution of the sources: *(i)* with evolution of the sources described by factor $(1 + z)^m$ in comoving frame Berezinsky et al (1990), and *(ii)* without evolution. The power-law energy spectrum with generation index γ_g was assumed. We made different assumptions about maximum energy in the generation spectrum, namely $E_{\max} = 3 \cdot 10^{20}$ eV , $E_{\max} = 1 \cdot 10^{21}$ eV, and $E_{\max} = \infty$. Varying the parameters γ_g and m we fit the AGASA and Akeno data, taken from (Nagano and Watson, 2000). The fit of UHECR data with help of evolving sources was made in the past (e.g. see Berezinsky and Grigorieva,1983; Berezinskii et al, 1990). The widely used fit for the AGASA data with $\gamma_g = 2.7$ was first found by Yoshida and Teshima (1993). Recently Scully and Stecker (2001) made calculations similar to that above for UHECR produced by GRBs. We can fit the AKENO-AGASA data in both cases, with and without evolution. The evolutionary case needs $\gamma_g = 2.45$ and $m = 4$ (see curve 4 in Fig.2 which fits well the AKENO-AGASA data in the energy range from $1 \cdot 10^{17}$ eV and up to $8 \cdot 10^{19}$ eV). The maximum redshift of evolution is not important for large $z_{max} > 3$ at such high energies and must only satisfy $m > 3$. The case without evolution, $m = 0$ can fit the data starting from higher energy $E \geq 1 \cdot 10^{18}$ eV. The fit needs $\gamma_g = 2.7$. The curves 1, 2 and 3 show the spectra with different E_{max} equal to $3 \cdot 10^{20}$ eV, $1 \cdot 10^{21}$ eV and ∞, respectively. As Fig.2 shows the models with uniform distribution of the sources are excluded by absence of GZK cutoff in the observations. They give good fit to the lower energy data. However, this fit needs large γ_g and thus very large energy output of the sources, nL, which cannot be provided by any reasonable populations of astrophysical sources.

4 Local overdensity of UHECR sources

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Local overdensity of UHECR sources makes the GZK cutoff less sharp or eliminates it Berezinsky et al (1990). Clustering of galaxies is a gravitational property, which is determined by mass and not by internal activity of an object. The galaxies of the same masses with active galactic nuclei or without them, with burst of star formation or in quiet phase are clustering in the same way. Therefore the optical catalogues give a reasonable indication to expected clustering of UHECR sources. The nearby structure that can affect the GZK cutoff is Local Supercluster (LS) of galaxies, which has a form of ellipsoid with semi-axes 20 and 30 Mpc. The overdensity of galaxies there is estimated by factor ~ 2 (see Peebles (1993) and references therein). Such overdensity does not solve the problem of GZK cutoff (Berezinsky and Grigorieva, 1979; Blanton et al, 2001). We shall calculate here UHECR spectra for different local overdensities n/n_0, where n_0 is the mean extragalactic density of UHECR sources. We use the various sizes of overdensity R, equal to 10, 20 and 30 Mpc. The results of our calculations are presented in Fig.3 for $\gamma_g = 2.7, \quad m = 0$ and three values of overdensity n/n_0 equal to 1, 2 and 10, and for the size of overdensity region 30 Mpc (the results for $R = 20$ Mpc are not much different). From Fig.3 one can see that overdensity larger than 10 is needed to reconcile the calculations with observational data. $R_{over} = 30Mpc$

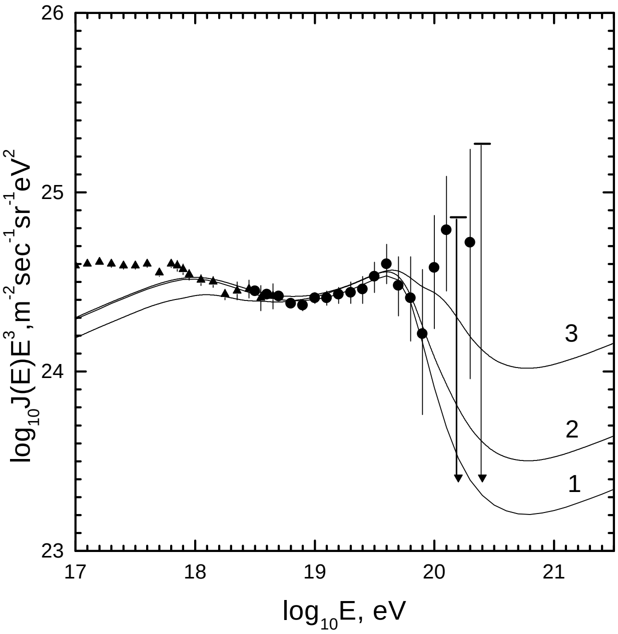

Fig. 3. *The effect of overdensity on UHECR spectra for different values of overdensity $n/n_0 = 1, 2, 10$ (curve 1, 2, 3, respectively). and for radius of overdensity region $R_{over} = 30Mpc$.*

5 UHECR from GRB

In GRBs the protons can be accelerated to Ultra High Energies (Vietri, 1995; Waxman, 1995). The strong indication that UHECR can be produced by GRB, the authors of (Vietri, 1995; Waxman, 1995) see in the equal emissivity $\mathcal{E}$ in GRBs and UHECRs. First of all let us examine critically this statement. The local GRBs emissivity, relevant for comparison with also locally produced UHECR, is estimated in Schmidt (1999) as

$$\mathcal{E}_{GRB} \approx 1.0 \cdot 10^{43} \text{ ergsMpc}^{-3}\text{yr}^{-1}. \qquad (1)$$

This is much lower than UHECR emissivity and to diminish the latter we shall take the most flat astrophysical production spectrum dE/E^2, which in fact is predicted for acceleration in GRBs. Using the space density, n, of UHECR sources and the source luminosity, L_p one readily obtains for cosmic ray emissivity:

$$nL_p \approx \frac{4\pi}{ct_0} \frac{E^3 J(E)_{\rm obs}}{E} \ln\left(\frac{E_{\max}}{E_{\min}}\right), \qquad (2)$$

where $t_0 = 1.0 \cdot 10^{10}$ yr (for $h = 0.65$) is the age of the Universe, $E_{\max}$ and $E_{\min}$, taken as $1 \cdot 10^{21}$ eV and $1 \cdot 10^9$ eV, are maximal and minimal energies in the production spectrum, respectively, and $E^3 J(E)_{\rm obs} \approx 4 \cdot 10^{24}$ eV^2 m^{-2}sec^{-1} sr^{-1} is the observed spectrum in range $1 \cdot 10^{17} - 1 \cdot 10^{19}$ eV. The energy E is taken as such, where calculated flux is equal to that of observed. To diminish the CR emissivity we take the largest possible energy $E \sim 1 \cdot 10^{19}$ eV, though at this energy the calculated spectrum is already strongly distorted by energy losses. Then we obtain for CR emissivity $nL_p \approx$

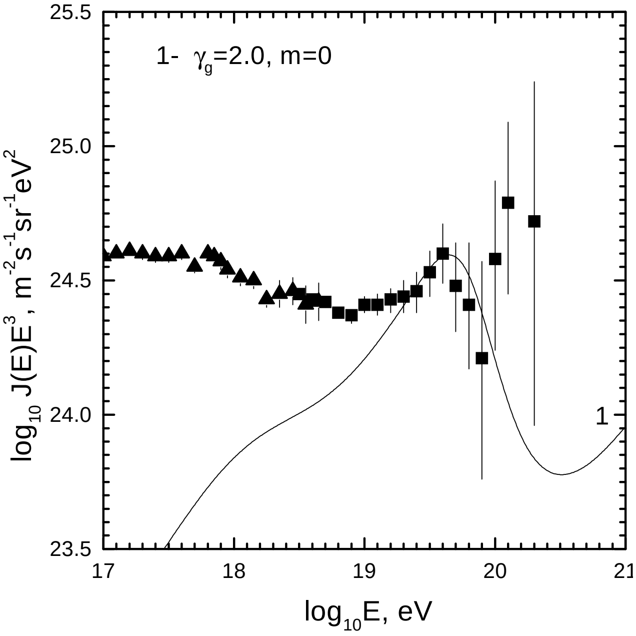

Fig. 4. *Spectra of UHECR from GRB for* $\gamma_g = 2.0$ *and* $m = 0$.

$2 \cdot 10^{45}$ ergs, i. e. two orders of magnitude larger than what GRBs can provide, according to Eq.(1).

Does the emissivity-favourable dE/E^2 spectrum fit the observations? In Fig.4 we present the calculated diffuse spectra for $\gamma_g = 2.0$ for the case without evolution ($m = 0$). One can see that this spectrum neither provide the absence of the GZK cutoff, nor give a good fit to the observed spectrum. Our conclusions coincide with that of Scully and Stecker (2001).

6 Conclusions

We made the accurate calculations of energy losses of UHE protons due to electron-positron pair production and pion production in collisions with microwave photons. The diffuse spectra of UHE protons were calculated for uniform distribution of the sources in the Universe for different maximum energies of the generation spectrum. The generation spectrum with index $\gamma_g = 2.7$ provides the good fit for energy range $1 \cdot 10^{18} - 8 \cdot 10^{19}$ eV in case of absence of evolution. For the case of evolution the good fit is given by $m = 4$ and $\gamma_g = 2.45$ in the energy range $1 \cdot 10^{17} - 8 \cdot 10^{19}$ eV. One may hope that these models combined with some others valid for energy higher than $1 \cdot 10^{20}$ eV, could explain all data, but in fact the large generation indices γ_g used for the fit, result in too high emissivity for all known populations of astrophysical sources. Local overdensity of UHECR sources, e.g. in Local Supercluster, can reconcile the weak GZK cutoff with UHECR data only if overdensity is larger than 10. The existing astronomical data favour much smaller overdensity, of order of 2. GRBs as the sources of observed UHECR give emissivity two orders of magnitude lower than needed for UHECR. In any event this model needs very flat generation spectra which fail to explain the observed spectrum and predicts the GZK cutoff.

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