Ultra High Energy Cosmic Rays: The disappointing model

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We develop a model inspired by the Auger mass composition for Ultra High Energy Cosmic Rays (UHECR). The crucial experimental fact for the model is given by the strong proton dominance in energy range (1 - 3) EeV in agreement with the HiRes data. At higher energies the Auger data show progressively heavier mass composition reaching the Iron-dominated one at $E \sim 35$ EeV. Assuming extragalactic origin of this EeV proton component, we argue that it disappears at higher energies due to low maximum-energy of acceleration for the protons $E_{\text{acc}} \sim (4 - 10)$ EeV. For rigidity acceleration mechanism the maximum energy for nuclei is $Z$ times higher, where $Z$ is a nucleus charge number, and thus maximum energy for Iron nuclei does not exceed (100 - 300) EeV. This energy is close to the maximum energies observed by Auger. The cutoff of the spectrum is provided by photodisintegration of the nuclei strengthened by acceleration cutoff. This model has disappointing consequences for future observations in UHECR: (i) Since the energies per nucleon are less than (2 - 5) EeV, the photopion processes in extragalactic space are absent together with GZK cutoff and production of cosmogenic neutrinos; (ii) Correlation with the nearby sources even at highest energies is absent, because of the nuclei deflection in galactic magnetic fields.

1. Introduction

There is a dramatic conflict between the recent observational data of two largest UHECR detectors: HiRes [1] and Auger [2]. The HiRes data confirm well the signatures of proton propagation through CMB, GZK cutoff [3] and pair-production dip [4] - [8], together with proton-dominated mass composition [9]. The Auger data strongly favour the nuclei composition progressively heavier in the energy region (4 - 40) EeV and indicate the strong spectrum steepening at the highest energies not much consistent with the predicted shape of the GZK cutoff.

We shall discuss first the HiRes data. To study the signatures of proton propagation through cosmic microwave background radiation (CMB) we assume that generation spectrum of protons is proportional to $E^{-\gamma_g}$ and sources are homogeneously distributed over the universe. Propagating through CMB protons obtain the spectral feature in the form of the pair-production dip due to $p + \gamma_{\text{CMB}} \rightarrow p + e^+ + e^-$ scattering and the GZK cutoff due to photopion production $p + \gamma_{\text{CMB}} \rightarrow N + \pi$. It is convenient to study the theoretical energy spectra in the form of the modification factor $\eta(E)$ given as a ratio of energy spectrum $J_p(E)$ calculated with all energy losses taken into account, and unmodified spectrum $J_p^{\text{unm}}$, where only adiabatic energy losses (red shift) are included.

$$\eta(E) = \frac{J_p(E)}{J_p^{\text{unm}}(E)}.$$  

Modification factor is less model-dependent quantity than the spectrum. In particular, it depends weakly on generation index $\gamma_g$, because both numerator and denominator in Eq. (1) include $E^{-\gamma_g}$. The dip and beginning of the GZK cutoff in terms of the modification factor do not depend on distances between sources, different modes of proton propagation (from rectilinear to diffusion), local overdensity and deficit of the sources etc (see [5]). The modification factor is presented in comparison with HiRes spectrum in the left panel of Fig. [1]. If to switch off all interactions except the adiabatic, one obtains the horizontal line $\eta = 1$ shown in the plot. If to include additionally pair-production, one obtains the dip shown in the figure by curve $\eta_{ee}$. The photopion energy losses result in the steepening of the spectrum (GZK...
Figure 1. **Left panel:** Pair-production dip and GZK cutoff in terms of modification factor in comparison with the HiRes observational data. Curves $\eta_{\text{tot}}$ and $\eta_{\text{ee}}$ show the total spectrum and spectrum with adiabatic energy losses and pair-production, respectively. **Right panel:** $E_{1/2}$ as numerical characteristic of the GZK cutoff in the integral HiRes spectrum (see text).

cutoff), which starts at energy $E \sim 50$ EeV. The theoretical dip in Fig. 1 has two flattenings. The low-energy flattening at $E \sim 1$ EeV provides transition to galactic cosmic rays, since the steep galactic component ($\propto E^{-3.1}$) unavoidably intersects the flat extragalactic spectrum at $E \lesssim 1$ EeV. The high-energy flattening explains the ankle observed at $E \sim 1 \times 10^{19}$ eV. Comparison with HiRes data shows that both signatures of proton interaction with CMB are well confirmed: the dip is seen with very good $\chi^2$, while steepening of the spectrum which starts at $E \sim 50$ EeV agrees within limited statistics with the theoretical shape of the GZK cutoff. The nature of this steepening as the GZK cutoff is further confirmed by the right panel of Fig. 1 valid for the integral spectrum.

In the integral spectrum the GZK cutoff is characterized by energy $E_{1/2}$, where calculated spectrum $J(> E)$ becomes half of the power-law extrapolation spectrum $KE^{-\gamma}$ from low energies. As calculations show, this energy is $E_{1/2} = 10^{19.72}$ eV for a wide range of generation indices from 2.1 to 2.8. HiRes collaboration found $E_{1/2} = 10^{19.73 \pm 0.07}$ eV in a good agreement with the theoretical prediction. In the right panel of Fig. 1 we reproduce the HiRes graph from which $E_{1/2}$ was determined. The plotted value is given by ratio of measured flux $J(> E)$ and its power-law approximation $KE^{-\gamma}$. Extrapolation of this ratio to the higher energies is given by unity, while intersection of measured ratio with horizontal line 1/2 gives $E_{1/2}$.

With some caution one may conclude that HiRes has detected the signatures of proton interaction with CMB in the form of pair-production dip and the GZK cutoff. The final proof of this conclusion must come from direct measurement of the mass composition of primaries, and HiRes data on fluorescent measurements of elongation rate and distribution over $X_{\text{max}}$, the atmospheric height of the shower maximum, confirm the dominance of proton composition, indeed. In Fig. 2 we plot the data of HiRes on $X_{\text{max}}$ as a function of energy (elongation rate) and RMS($X_{\text{max}}$), the width of distribution over $X_{\text{max}}$. One can see that both quantities agree with proton-dominated composition.

Auger data on spectra and mass composition are quite different. In contrast to HiRes, Auger data show nuclei mass composition starting with $E \sim 4$ EeV, which becomes progressively more heavier with increasing energy (see Fig. 3). The energy spectrum has a sharp steepening at
$E \sim (30 - 40)$ EeV, but energy shape of this steepening is quite different from one predicted for GZK cutoff. The width of $X_{\text{max}}$ distribution is a very powerful tool for determination of mass composition, free of many uncertainties involved in method of measuring the absolute value of $X_{\text{max}}$. The narrow width found in Auger experiment is difficult to falsify, but on the other hand the whole picture obtained by HiRes looks self-consistent. In particular, the confirmation of pair-production dip in four experiments, including Auger \cite{5,8}, is a strong experimental argument in favour of proton-dominated composition.

However, in this paper we address the question what consequences follow from the mass composition and energy spectrum measured only by Auger detector, and what is most natural model for explanation of these data.

2. The model

We consider here a physical model which directly follows from the Auger observations. Some additional model ingredients are accepted as assumptions, which will be justified in the end of this section.

The experimental fact, basic for our model, is the observed proton composition in energy range $(1 - 3)$ EeV, which is common for both Auger and HiRes (see Fig. 3, especially left panel for Auger data and Fig. 2 for HiRes data). We combine this observation with assumption that these protons are extragalactic. The third, and the last ingredient of our model, is assumption of rigidity-dependent acceleration in the sources, formulated in terms of maximum acceleration energy as $E_{\text{acc}} = ZE_0$, where $E_0$ is an universal energy to be determined from the data and $Z$ is atomic charge number. These three assumptions complete the definition of the model.

We determine first the maximum acceleration energy for protons $E_{\text{acc}}^{\text{max}} = E_0$. For this we calculate the extragalactic diffuse proton flux assuming the power-law generation spectrum $Q_g(E) \propto E^{-\gamma_g}$ with $E_{\text{max}} = E_0$ and normalizing the calculated flux by the Auger flux at $(1 - 3)$ EeV. For $\gamma_g$ in a range 2.0 - 2.8 we find the maximum value of $E_0$ allowed by Auger mass composition and spectrum (increasing $E_0$ beyond this limit one has a contradiction with mass composition and spectrum in Fig. 3).

The results are presented in Fig. 4. In calculations we use a homogeneous distribution of...
the sources without cosmological evolution (evolution parameter \( m = 0 \)) and with maximal redshift \( z_{\text{max}} = 4 \). As a criterion of contradiction we choose an excess of calculated proton flux at energy \((4 - 5)\) EeV, where Auger data show the dominance of nuclei. The contradiction has a different character for different values of \( \gamma_g \). For the steep spectra \( \gamma_g \approx 2.6 - 2.7 \) the Auger spectrum shape and flux are well described by \( E_{\text{p}}^{\max} \sim 10^{20} - 10^{21} \) eV and contradiction occurs only due to mass composition. The extreme case is given by \( \gamma_g = 2.8 \) and is displayed in the left panel of Fig. 4. All curves with \( E_{\text{p}}^{\max} \geq 10 \) EeV are below the data points at \( E > 5 \) EeV and these curves are excluded only by prediction of pure proton composition at \( E \sim (4 - 5) \) EeV, i.e. due to contradiction in mass composition with Auger in very narrow energy range. For the flat generation spectra the contradiction is very pronounced: the predicted total proton flux exceeds the observed one. It can be seen in Fig. 4 for extreme case \( \gamma_g = 2.0 \) when for \( E_{\text{p}}^{\max} = 5 \) EeV the calculated proton flux exceeds the observed one at \( E \approx 2 \) EeV. We conclude that with some redundancy \( E_{\text{p}}^{\max} \sim (4 - 10) \) EeV for all generation indices in the range 2.0 - 2.8. Maximum energy of acceleration for Iron is \( E_{\text{Fe}}^{\max} \sim (100 - 300) \) EeV.

In Fig. 5 we plot, as an example, the total UHECR spectrum in the 'disappointing model' using \( \gamma_g = 2.3 \), which might be the case for acceleration by relativistic shocks. The proton spectrum is calculated here in the diffusive model, more realistic for energies below 1 EeV. We assume the turbulent magnetic field with basic scales \((B_c, l_c) = (1 \) nG, 1 Mpc), the distance between sources 40 Mpc and the Kolmogorov diffusion coefficient (for notation and method of calculations see references [13]). The analysis of proton maximum energy of acceleration (see left panel of Fig. 5) gives \( E_0 = E_{\text{p}}^{\max} = 4 \) EeV, in a rough agreement with analysis for homogeneous distribution of the sources. In fact this set of parameters gives the lowest \( E_0 \) allowed by Auger data, because prediction for maximum energy for Iron nuclei is 100 EeV, while in Auger particles with almost 200 EeV are observed. However, changing the parameters, in particular increasing \( \gamma_g \), it is easy to increase \( E_0 \) to \((5 - 6)\) EeV.

The inclusion of diffusion provides flattening of proton spectrum below 1 EeV, seen in Fig. 5.
as ‘diffusive cutoff’, because flux $J(E)$ is multiplied to $E^3$. The ‘diffusive cutoff’ provides the transition from a steep galactic spectrum, most probably composed by Iron, to a flat spectrum of extragalactic protons.

The spectrum of nuclei in Fig. 5 is obtained by subtraction procedure first suggested in [14]. We subtract from the total Auger spectrum the proton spectrum as calculated above, and the resultant flux is plotted in the right panel of Fig. 5 as sum of different nucleus species. In the mixed composition model [15] with arbitrary fractions of all primary nuclei at generation it looks easy to fit the obtained nuclei spectrum.

However, the basic feature of the Auger mass composition – progressively heavier composition with increasing energy – is guaranteed by rigidity-dependent maximum energy of acceleration in our model: at energy higher than $Z E_0$ the nuclei with $Z$ disappear, while more heavier (with larger $Z$) survive. Starting from $E_p^\text{max} \sim (4 - 10)$ EeV, the higher energies are reachable only for nuclei with progressively larger $Z$. In particular, the maximum observed energy must correspond to Iron nuclei, which can reach (100 - 300) EeV. We plan to perform the detailed calculations in our next paper.

The predictions of our model are very disappointing for future detectors.

The maximum energy, (100 - 300) EeV for Iron nuclei, implies only (2 - 5) EeV per nucleon. Therefore, practically no photopion processes are induced by UHECR and no fluxes of cosmogenic neutrinos are produced.

Correlation with UHECR sources are absent because nuclei are deflected in galactic magnetic field. The absence of the correlation is strengthened in our model by dependence of the maximum energy on $Z$.

The signatures of ‘disappointing model’, which can be found by Auger detector, are mass-energy relation, seen as elongation rate $X_{\text{max}}(E)$, and transition from galactic to extragalactic cosmic rays below the characteristic energy $E_c \sim 1$ EeV.

There are some uncertainties in the calculations above. Most important ones are related to estimates of $E_p^\text{max}$. The model collapses if this energy increases to e.g. (50 - 100) EeV.

Due to uncertainties in Auger data the mass composition at (1 - 3) EeV can include some admixture of nuclei, and proton flux is lower. This effect decreases $E_p^\text{max}$, and thus is helpful.

Another effect which slightly decreases $E_p^\text{max}$ is cosmological evolution of the sources, and it was the reason we did not include it in calculations shown in Fig. 4.
Figure 5. Left panel: Comparison of calculated proton spectra with the combined Auger spectrum for $\gamma_g = 2.3$ and diffusive proton propagation (see text for details). The cutoff at $E_{p\text{max}} = 4$ EeV is needed not to contradict the data at $E > 3$ EeV. Right panel: Total UHECR spectrum in ‘disappointing model’ in comparison with the combined Auger spectrum. Spectrum of protons is taken from the left panel. The spectrum of nuclei is obtained by subtraction procedure as described in text.

EeV protons detected by Auger can be secondary, i.e. produced by photo-dissociation of the primary nuclei. In [18] it is demonstrated that flux of secondary protons in EeV range is always smaller than flux of parent primary nuclei, and in [19] considerably smaller than the sum of primary and secondary nuclei.

$E_{p\text{max}}$ is calculated for homogeneous distribution of the sources, when all modes of propagation result according to propagation theorem [20] in the same universal spectrum. In case of diffusive propagation, for large enough distance between sources, $E_{p\text{max}}$ decreases with all results remaining intact.

3. Conclusions

The model we suggested here is aimed to explanation of observational data of the Auger detector only. The observational feature crucial for the model is the proton composition in energy range (1 - 3) EeV. There are two main assumptions of the model: observed protons are extragalactic and they are accelerated by rigidity dependent mechanism with $E_{\text{max}} = Z E_0$, where $E_0$ is the same for all nuclei. The upper limit on $E_0$ (maximum acceleration energy for protons) is obtained calculating the proton spectrum at higher energies using the generation index $\gamma_g$ and normalizing flux at (1 - 3) EeV by Auger data. Cutoff of the proton spectrum at $E_0$ must provide absence of contradiction with Auger flux and mass composition at higher energies. The calculations are performed for homogeneous distribution of sources without assumption of their cosmological evolution, with maximum redshift $z_{\text{max}} = 4$ and for the wide range of $\gamma_g$ from 2.0 to 2.8. The obtained upper limit on $E_0$ is (4 - 10) EeV. The maximum predicted energy corresponds to Iron and equals to (100 - 300) EeV. The maximum energy per nucleon is only (2 - 5) EeV, and photopion processes on CMB radiation are practically absent. Therefore, the GZK cutoff and production of cosmogenic neutrinos are absent, too. The cutoff of the spectrum is provided by photodisintegration and is strengthened by acceleration cutoff.

The rigidity-dependent $E_{\text{max}}$ provides energy-dependent mass composition: at energy higher than $Z E_0$ the nuclei with $Z$ disappear, while more heavier (with larger $Z$) survive. It agrees qualitatively with Auger observations. This feature dis-
favours the correlation with the UHECR sources at the highest energies: at 100 EeV the Iron nuclei dominate and their deflection in galactic magnetic fields prevents the correlation with the sources.

There are two signatures of the model, which Auger can observe. The realistic one is transition from galactic to extragalactic cosmic rays. This transition occurs due to intersection of flat extragalactic proton spectrum with steep spectrum of galactic iron nuclei. The flat spectrum of protons below 1 EeV appears due to diffusion of protons in extragalactic magnetic field \[16,17\]. The transition below 1 EeV combined with nuclei composition above (3 - 5) EeV is a strong signature of the discussed model.

The second signature is energy-dependent mass composition, heavier with increasing the energy, indication to which is already seen in the Auger data.

Is there any alternative explanation of EeV protons in the Auger data?

The EeV protons could have a galactic origin, though it contradicts the Standard Model for Galactic Cosmic Rays (see e.g. \[21\]), where maximum acceleration energy, \(1 \times 10^{17}\) eV is reached by Iron nuclei. However, one may assume an additional high-energy-proton component of galactic cosmic rays extended to (2 - 3) EeV. The usual argument with anisotropy can be by-passed considering a case suggested in \[24\]. GRB could occur in our galaxy \(10^9 - 10^7\) yr ago producing high energy protons by inner shocks acceleration. The protons propagate in the mode of non-stationary diffusion, so that most of particles have already escaped from the galaxy and now only the tail of retarded particles with reduced anisotropy is observed. In this model the transition from galactic to extragalactic cosmic rays occurs at ankle, which is clearly seen in Auger data. This case differs from “standard” ankle model, where transition occurs from galactic Iron to extragalactic protons. This model needs more detailed investigation.

In conclusion, we face at present most serious disagreement in observational data of two biggest experiments in UHECR.

HiRes observes signatures of proton propagation through CMB in the form of the pair-production dip and GZK cutoff and these observations are well confirmed by direct measurements of proton-dominated mass composition. These observations predict the detectable UHE neutrino flux. In particular, the minimum neutrino flux predicted in proton-dominated composition \[24\] is detectable by JEM-EUSO. This detector can also observe the nearby UHECR sources using the protons with energies up to 100 EeV and above.

Auger clearly observes high-energy steepening of the spectrum, but its position and shape are rather different from prediction of the GZK cutoff. The mass composition at \(E > 4\) EeV shows the dominance of nuclei becoming progressively heavier with increasing energy and probably reaching the pure Iron composition at \(E \approx 35\) EeV. The Auger data allows most conservative explanation in terms of low maximum-energy of acceleration, based on observation of EeV protons. It seriously ameliorates a problem of acceleration in astrophysical sources, diminishing the maximum energy down to (100 - 300) EeV for Iron nuclei. This conservative and disappointing scenario can be confirmed by transition from galactic to extragalactic cosmic rays below 1 EeV, by absence of cosmogenic neutrinos with the minimum flux in the proton-dominated case and by agreement with elongation rate calculated in this model.

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