Ultra High Energy Cosmic Ray Protons: Signatures and Observations

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The status of the Greisen-Zatsepin-Kuzmin (GZK) cutoff and pair-production dip in Ultra High Energy Cosmic Rays (UHECR) is discussed. They are the features in the spectrum of protons propagating through CMB radiation in extragalactic space, and discovery of these features implies that primary particles are mostly extragalactic protons. The spectra measured by AGASA, Yakutsk, HiRes and Auger detectors are in good agreement with the pair-production dip, and HiRes data have strong evidences for the GZK cutoff. The Auger spectrum, as presented at the 30th ICRC 2007, agrees with the GZK cutoff, too. The AGASA data agree well with the beginning of the GZK cutoff at \( E \lesssim 8 \times 10^{19} \text{ eV} \), but show the excess of events at higher energies, the origin of which is not understood. The difference in the absolute fluxes measured by different detectors disappears after energy shift within the systematic errors of each experiment.

1. Introduction

The systematic study of Ultra High Energy Cosmic Rays (UHECR) started in late fifties after construction of Volcano Ranch (USA) and Moscow University (USSR) arrays. At present due to the data of the last generation arrays, AGASA, HiRes, and Pierre Auger observatory, we are probably very close to understanding the origin of UHECR.

The spectra of four detectors Yakutsk \[1\], AGASA \[2\], HiRes \[3\] and Auger \[4\] are displayed in Fig. 1. One can see the great difference in the fluxes, but this difference is affected by a way of presentation: The spectra are multiplied to \( E^3 \) and thus systematic errors in energy determination strongly affect the displayed values.

The nature of signal carriers of UHECR is not yet established. The most natural primary particles are extragalactic protons. Due to interaction with the CMB radiation the UHE protons from extragalactic sources are predicted to have a sharp steepening of energy spectrum, so-called GZK cutoff \[5\]. It appears due to pion production in collisions of UHE protons with CMB photons. Another signature of extragalactic protons in the primary spectrum is the dip \[6 - 10\]. It is produced due to \( p + \gamma_{\text{CMB}} \rightarrow p + e^+ + e^- \) interaction with CMB. Being relatively faint feature, the dip is however clearly seen in the spectra observed by Yakutsk, AGASA, Fly’s Eye, HiRes, and Auger arrays. This good agreement must be considered as a proof of a large fraction of protons in the spectrum. The GZK cutoff, confirmed by HiRes observations, is also an evidence of the proton...
composition.

The direct measurements of UHECR mass composition is contradicting. While HiRes data favour \[11\] the pure proton composition, Auger measurements indicate the mixed-nuclear composition \[4\].

2. Pair-production dip.

The analysis of the dip and GZK cutoff is convenient to perform in terms of the modification factor. It is defined as a ratio of the spectrum \(J_p(E)\), calculated with all energy losses taken into account, and unmodified spectrum \(J_{p\text{unm}}(E)\), where only adiabatic energy losses (red shift) are included.

\[
\eta(E) = \frac{J_p(E)}{J_{p\text{unm}}(E)}. \tag{1}
\]

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. \eqref{1} include \(E^{-\gamma_g}\). The dip and beginning of the GZK cutoff in terms of the modification factor do not depend of distances between sources, different modes of proton propagation (from rectilinear to diffusion), local overdensity and deficit of the sources etc (see \[8\]). In Fig.2 the modification factors are shown for two spectrum indices \(\gamma_g = 2.0\) and \(\gamma_g = 2.7\). They do not differ much.

The dip in Fig. 2 has two flattenings. The low-energy flattening at \(E \sim 1 \times 10^{18} \text{ eV}\) provides transition to galactic cosmic rays, since the steep galactic component \((\propto E^{-3.1})\) unavoidably intersects the flat extragalactic spectrum at \(E \lesssim 1 \times 10^{18} \text{ eV}\). The high-energy flattening explains ankle observed at \(E \sim 1 \times 10^{19} \text{ eV}\).

In the discussion of the dip above we have not included the cosmological evolution, because the evolution is described as minimum by two additional free parameters, and agreement of the dip with observations could look less convincing. The effect of evolution was included in calculations \[8\] under assumption that AGN are the sources of UHECR \[9\]. Using the evolution of UHECR sources close to that observed for AGN, the dip was found in good agreement with observations.

3. GZK cutoff

From Fig. 3 one can see that beginning of the GZK cutoff at energy up to \(E \sim 8 \times 10^{19} \text{ eV}\) is
Figure 3. Theoretical pair-production dip and GZK cutoff in comparison with the observational data for non-evolutionary models with generation index $\gamma_g = 2.6 - 2.7$. The data of HiRes and Auger detectors show steepening of the spectrum consistent with the GZK cutoff. The excess of experimental modification factor over $\eta = 1$ at $E < 1 \times 10^{18}$ eV in the AGASA and HiRes data evidences for a new component, which is given by galactic cosmic rays.

consistent with all data including that of AGASA (the events in three highest energy bins are the problem of UHE experimental cosmic ray physics and maybe these events are initiated with small probability by lower energy particles). The data of Auger \([4]\) and especially HiRes \([3]\) agree with presence of GZK cutoff. However, low statistics and a possibility of imitation of the observed steepening by some other effect, e.g. by “acceleration cutoff”, precludes one from making the final conclusion. For the Auger data we use in Fig. 3 the data presented at 30th ICRC \([3]\), the data of the last publication \([13]\) have worse agreement with the predicted cutoff spectrum.

Recently HiRes collaboration obtained \([3]\) numerical confirmation that steepening seen in Fig. 3 is the GZK cutoff indeed. In the integral spectrum the GZK cutoff is characterized by energy $E_{1/2}$, where calculated spectrum $J(> E)$ becomes half of power-law extrapolation spectrum $KE^{-\gamma}$ from low energies. As calculations \([6]\) 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 Fig. 4 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 $E_{1/2}$.

4. Calibration of detectors with help of dip and GZK cutoff

The fluxes measured by Yakutsk, AGASA, HiRes and Auger detectors do not agree in the absolute fluxes (see Fig. 1). This discrepancy to the large extent is caused by comparison of the values $E^3J(E)$ and thus accuracy of energy determination affects strongly the observed contradiction. In the works [8,12] the energy calibration performed with help of the dip results in good agreement between the absolute fluxes of all detectors. Here we use another approach for calibration based on both features, dip and GZK cutoff [14]. Since energies as measured by HiRes fit well the both features and especially the GZK numerical characteristic $E_{1/2}$, we assume that HiRes energy scale is correct and the energies of all other detectors must be shifted by factor $\lambda$ to reach the best agreement in fluxes. This procedure gives values of $\lambda$ equal to 1.2, 0.75, 0.83, and 0.625 for Auger, AGASA, Akeno and Yakutsk, respectively. This calibration provides good $\chi^2$ for the dip shape, though does not correspond to the minimum $\chi^2$. However, it describes better the dip and beginning of GZK cutoff taken together. The fluxes after this energy calibration are shown in Fig. 3(right panel). Note, in particular the good agreement of Auger and HiRes fluxes, for which the Auger energy scale is increased by 20% allowed by Auger systematic energy error.

5. Mass composition

In this paper we consider the signatures of UHE protons. Their observational confirmations indicate the dominance of the proton component in the primary flux. This conclusion must be also supported by the direct measurement of the mass composition.

The mass composition measured in two biggest experiments, HiRes and Auger, is contradicting. While Hires data [11] favour at $E \gtrsim 1 \times 10^{18}$ eV the proton-dominated composition, Auger observatory claims the mixed-nuclei composition at the same energies [15].

How the spectral data, in particular dip and GZK cutoff, can be explained if the primary flux is dominated by nuclei?
The dip can be produced by transition from the steep galactic component at low energies to the flat extragalactic component at higher energies. This two-component model was first proposed by Hill and Schramm [16] in 1985. It was developed in detail in the mixed composition model by Allard et al [17]. The two spectra, galactic and extragalactic, are equal at the point of transition $E_{tr} \approx 3 \times 10^{18}$ eV. The both components have mixed nuclei composition. They describe most precisely the observed Auger composition, except the highest energy point. Energy spectrum in the region of the dip is mostly taken ad hoc. Assuming that the two-component dip fits precisely the observed spectrum, one must answer the question why spectrum in this ad hoc model is precisely the same as in the pair-production dip.

6. The sources

The sources of UHECR must satisfy at least two basic conditions: acceleration to energy $E \sim 10^{20} - 10^{21}$ eV and emissivity in cosmic rays $\mathcal{L} \gtrsim 10^{46}$ erg Mpc$^{-3}$ yr$^{-1}$, where in terms of space density of the sources $n_s$ and their luminosity $L_{cr}$ the emissivity is $\mathcal{L} = n_s L_{cr}$. These two conditions are satisfied by AGN and GRBs.

The sources of GRBs are assumed to be hypernovae, where particles are accelerated by the shocks in jet or in external shock (see [18] for description and references). The protons can reach energies up to $E_{\text{max}} \sim 1 \times 10^{21}$ eV, but there is a problem with the total energy output [8]. The interesting possibility considered in [19] is that hypernovae produce both galactic and extragalactic cosmic rays. Galactic cosmic rays are produced by a single hypernova in Milky Way exploded $2 \times 10^5$ yr ago. The particles with energies $E > 10^{18}$ eV escaped from Milky Way and the observed flux at these energies are produced by extragalactic hypernova.

AGN are one of the best candidates for UHECR sources, as far as acceleration and energetics is concerned. The dip, calculated with cosmological evolution of AGN, as observed in X-rays, agrees well with measured spectra [8].

The plausible candidates for sources of UHECR are Fanaroff-Riley type 1 (FR1) radiogalaxies. They are AGN with short jets where acceleration most probably occurs. FR1 with jets directed to observer compose the population of BL Lacs. There are indications to correlations of BL Lacs with UHECR in AGASA [20] and HiRes [21].

Figure 5. The spectra and fluxes measured by Yakutsk, AGASA, HiRes and Auger before (left panel) and after (right panel) energy calibration. The figure is taken from [14].
data, but these correlations are absent in Auger observations.

7. Conclusions

Extragalactic UHE protons propagating through CMB acquire two features in the energy spectrum: pair-production dip and GZK cutoff. The pair-production dip is a faint spectral feature located at energies $1 - 40$ EeV. The large statistics of observations provide the accurate measurement of the dip energy spectrum. Its shape agrees very well with the theoretical prediction. The part of the GZK feature, up to $80$ EeV, is seen in all experimental data including that of AGASA. The HiRes spectrum agrees with the predicted GZK spectrum up to $100$ EeV within the limited statistics of observations. The measured characteristic of the GZK cutoff in the integral spectrum of HiRes, $E_{1/2} = 53$ EeV, coincides with the theoretical prediction. Spectrum measured by Auger detector, as it was presented at 30th ICRC, does not contradict the calculated spectrum, too.

The good agreement of these two spectral features with theoretical prediction implies that primary particles are mostly extragalactic protons. The direct measurements of the mass composition by $X_{\text{max}}$ method is contradicting. HiRes data favour the proton-dominated composition, Auger data – the mixed-nuclei composition.

The absolute fluxes in terms of $E^3 J(E)$ measured by HiRes, Auger, AGASA and Yakutsk detectors differ much from each other. Difference in energy scale in the experiments is responsible for this discrepancy. Assuming that energy scale of the HiRes detector is correct and shifting energies in other experiments by factors $\lambda$, different for each experiment, the agreement of all data is obtained.

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