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Greisen – Zatsepin – Kuzmin effect: top-down and bottom-up view

M I Panasyuk

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Contents

Abstract. In 1966, Greisen and independently Zatsepin and Kuzmin published evidence for the existence of a relic (GZK) cutoff in the proton energy spectrum in ultra-high energy cosmic rays (UHECRs) above 5×10^{19} eV. Half a century of experimental ground-based UHECR research has resulted in a large amount of data on energy spectra, anisotropy, and mass composition. The first space experiment to measure UHECRs was launched in 2016. In this paper, we discuss the results and prospects of experimental UHECR research in light of the proposed theoretical model of the GZK cutoff.

Keywords: cosmic rays, extensive air showers

If experiment confirms theory, it is nice.
If not, it is interesting.
Ya B Zel'dovich

1. Introduction

The energies of cosmic ray (CR) particles span a vast range extending from $\sim 10^8$ eV to at least $\sim 10^{21}$ eV. CR atoms do not have electron shells: they are actually fully ionized atoms or 'bare nuclei'. The reason is that CR atoms interact with matter in the process of traveling across the Universe. In interacting with neutral particles, the atoms lose electron shells as a result of charge exchange. Calculations show that the average path that the atoms travel on their way from their origin to Earth is sufficient for them to lose all orbital electrons as a result of interaction with space matter. The CR mass composition is also quite broad: it varies from protons, which are dominant in CR fluxes, to super-heavy elements.

M I Panasyuk Skobeltsyn Institute of Nuclear Physics,
Lomonosov Moscow State University,
Leninskie gory 1, str. 2, 119234 Moscow, Russian Federation
E-mail: panasyuk@sinp.msu.ru

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Although CRs have been studied for more than a century, a full understanding of their nature is still missing. Determining CR sources and the acceleration and transport mechanisms is an important problem for today's astrophysics, which is now part of a broader area referred to as *astroparticle physics*. This combines interrelated research on the charged component, CR nuclei, gamma-ray astronomy, and neutrino astrophysics. Studies of ultra-high-energy cosmic rays (UHECRs) with energies above 10^{18} eV, which are the most energetic particles in the Universe, are of high priority because of the importance of the fundamental problems related to those CRs.

The most important characteristic of CRs is their energy spectrum, i.e., the dependence between the particle flux and the particle kinetic energy.

On a double-logarithmic scale, the spectrum of all CR particles can be described as a superposition of several spectra. In the first approximation, each sequential segment of the CR particle spectrum differs from the preceding one by the spectral exponent and, as has been established by now, a characteristic change in their mass composition. Figure 1 [1] shows the energy spectrum of CRs based on data from several existing experimental facilities.

The experimental change in the slope of the spectrum of all CR particles was described in the most reliable way in 1956 by Khristiansen and Kulikov [2] (the so-called Khristiansen astrophysical kink at $E \approx 3 \times 10^{15}$ eV, denoted as E_1 in Fig. 1). Owing to the measurements made by ground facilities in extended atmospheric showers (EASs), it has been determined by now that enrichment of the nuclear composition of CRs with heavy nuclei begins for $E > E_1$. This observation is in line with theoretical concepts of regular diffuse acceleration of CR particles on the shock waves that form in the bursts of supernovae in the Galaxy. This mechanism proposed by Krymskii [3] was developed later in a large number of publications (see, e.g., [4–6]). However, the maximum energy of the accelerated particles cannot be greater than $E_{\max} \sim BLZ \approx 10^{14}$ eV, where B is the strength of the interstellar magnetic field, the estimated value of which is several μG, L is a characteristic size of the acceleration region in the magnetic fields of the interstellar medium, and

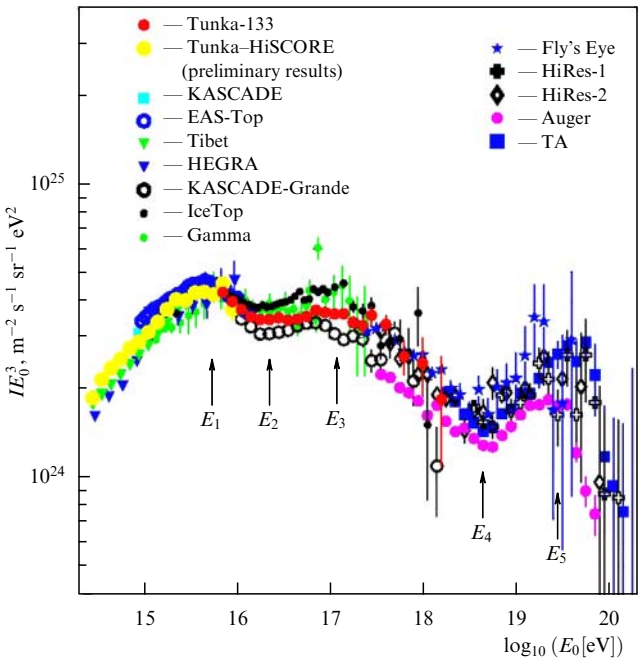

Figure 1. Differential CR energy spectrum plotted using data from various experimental facilities according to [1]. (EAS-Top is an EAS detector on top of the Gran Sasso underground laboratory; HEGRA is an abbreviation for High Energy Gamma Ray Astronomy).

Z is the particle charge. Modern models, which are based on the effect of the enhancement of the local magnetic field in shock waves from supernova explosions due to the interaction of those waves with the CRs themselves, yield the maximum energy $E_{\max} \approx 10^{17}$ eV (see, e.g., [7]).

In the $E > E_1$ energy range in Fig. 1, the spectrum is plotted using data from the Tunka-133 and TAIGA-HiSCORE (Hundred Square km Cosmic ORigin Explorer) facilities and is compared with the spectra from other experiments according to [8]. The behavior of the CR spectrum in this energy range, which is more complex than was assumed previously, is one of the main results obtained by the Tunka-133 facility. Two statistically significant features are observed in the CR spectrum. At $E_2 \approx 2 \times 10^{16}$ eV, the slope of the energy spectrum decreases by about 0.2 [10], while at energies $E_3 \approx 3 \times 10^{17}$ eV, the slope increases again by about 0.3 [9]. Figure 1 also shows the spectrum obtained using the Tunka-25 facility [11], a predecessor of Tunka-133. At $E \approx 8 \times 10^{16}$ eV (see Fig. 3 below), a kink is observed in the spectrum of 'heavy' nuclei, indicating changes in the nuclear composition of CRs.

At energies $E = E_4 > 3 \times 10^{18}$ eV, the slope of the spectrum of all particles becomes steeper again. We note that according to the data from many ground facilities (see, e.g., [12, 13]), it is in this area that a lighter CR component appears; this can be an indication of the presence of an extragalactic component at $E > 10^{18}$ eV.

The spectral characteristics of CRs at energies up to $E \approx 10^{18}$ eV, which are presented above, are compatible with data from other current ground facilities, including KASCADE-Grande (KASCADE: KArlsruhe Shower Core and Array DEtector) [14], IceCube [15], and the Yakutsk facility for studying EASs [12].

The variations in the slope of the CR energy spectrum evidences the occurrence of various effects in CRs that are related to acceleration, transport, and losses of CRs, as well as the spatial distribution of CR sources across the interstellar medium. Nevertheless, experimental data in the energy range up to 10^{18} eV (the characteristic Z-dependent change in the spectrum slope and nuclear composition) are in line with the main paradigm of the galactic origin of CRs and the decisive role of supernovae as the main CR accelerators. The first kink at $E = E_1$ corresponds to the onset of the cutoff of the flux of light nuclei and the second kink, at $E = E_3$, to the cutoff of heavy (primarily iron) nuclei. At the same time, those experimental results can be used as a basis for further developing the standard mechanisms of CR acceleration in supernova remnants and CR transport mechanisms [3–6].

The CR spectrum in the energy range $E > 10^{15}$ eV is rather steep (see Fig. 1), and the cosmic ray flux varies in a broad range, from one particle per square meter per second (at the energy $\sim 10^{10}$ eV) to one particle per square kilometer every 100 years (at the energy of several units of 10^{20} eV). It is this factor that makes experimentalists' task especially difficult: to obtain reasonable statistics, facilities have to span large areas. This requirement is of critical importance for UHECR particles with $E > 10^{18}$ eV.

The first event, the registration of an EAS with a high energy (6×10^{19} eV), was observed by John Linsley et al. in 1963 at the US-based Volcano Ranch facility (Fig. 2). This event made it clear that there are astrophysical objects in the Universe that can accelerate CRs to energies this high.

In 1966, shortly after Linsley's pioneering experiment, Zatsepin and Kuz'min [17], and independently Greisen [18], a US physicist, published studies on the possible cutoff of the proton spectrum in the cosmic microwave background (CMB) remaining after the Big Bang. For sources uniformly distributed across the Universe, their studies showed that the UHECR

Figure 2. John Linsley was the first to register a UHECR EAS with an energy of 6×10^{19} eV, the maximum energy as of the early 1960s.

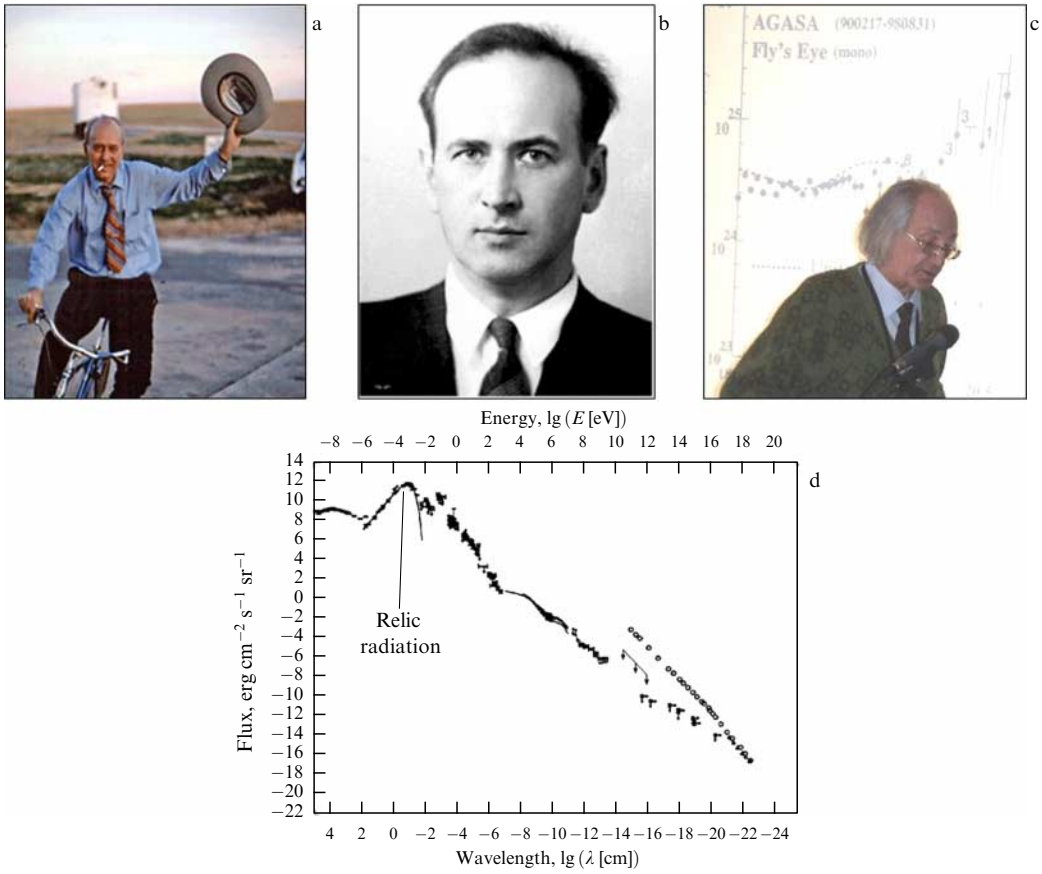

Figure 3. Authors of the theoretical model of the UHECR spectrum cutoff: Greisen (a), Zatsepin (b), and Kuzmin (c). (d) Spectrum of the electromagnetic radiation in the Universe; the arrow points at the maximum at a temperature of 2.7 K, which corresponds to the CMB with a wavelength of 0.1 cm.

protons with energies higher than $E_5 = E_{\max} = 5 \times 10^{19}$ eV efficiently interact with the background radiation, whose intensity peaks at 3.5 eV.

To honor the authors of [17, 18], this phenomenon was called the Greisen – Zatsepin – Kuzmin (GZK) cutoff (Fig. 3). The protons interacting with the CMB lose up to 10% of their initial energy, producing pions and baryons:

$$\begin{aligned} \mathrm{p} + \gamma_{2.7\,\mathrm{K}} &\to \mathrm{n} + \pi^+ \\ &\to \mathrm{p} + \pi^0 . \end{aligned}$$

In other words, at energies in the GZK cutoff region, a decrease in the CR proton flux is observed. The maximum distance $D_{\max}$ was estimated beyond which protons with energies this high cannot reach Earth. Depending on particle energy, this distance is of the order of several dozen or hundred Mpc. For example, for a UHECR proton with the energy $E = 10^{20}$ eV, $D_{\max} \approx 100$ Mpc.

For heavier nuclei (A), the mean free path to full absorption is determined by photo splitting of nuclei of chemical elements (see, e.g., [9]) in the background of ultraviolet and infrared CMB photons:

$$\mathrm{A} + \gamma \to \mathrm{A}' + \mathrm{p} .$$

Owing to this process, the mean free path of heavy nuclei becomes longer than that of light nuclei. For example, for nuclei of iron with $E = 10^{20}$ eV, $D_{\max} \approx 1000$ Mpc. Those reactions should also result in a cutoff of the spectra of heavy nuclei in UHECRs at energies comparable to the cutoff energy for protons at $E_{\max} = E_5$.

An experiment in the specified CR energy range dedicated to determining UHECR energy characteristics and the mass composition can apparently verify the validity of the model results. Also of importance is the study of the anisotropy in the arrival of such particles on Earth: if any anisotropy in CR fluxes is detected, it could provide information about the location of CR sources.

This means that UHECR studies are important: by exploring the most energetic particles in the Universe, we can find answers to the following questions, which are significant for astrophysics:

— which astrophysical objects are specifically responsible for UHECR generation, i.e., can accelerate particles to 10^{20} eV and in what regions of the Universe are they located?

— what is the nuclear composition of those particles; does it differ from that of galactic cosmic rays and solar CRs?

The history of the experimental exploration of UHECRs in the energy range of the possible GZK cutoff is interesting and dramatic; therefore, it deserves a more detailed presentation.

2. Experimental searches for the Greisen–Zatsepin–Kuzmin effect

The deployment of detectors with large effective areas commenced in the 1960s and 1970s. One of those detectors was the Yakutsk-based ShAL-13, the area of which was

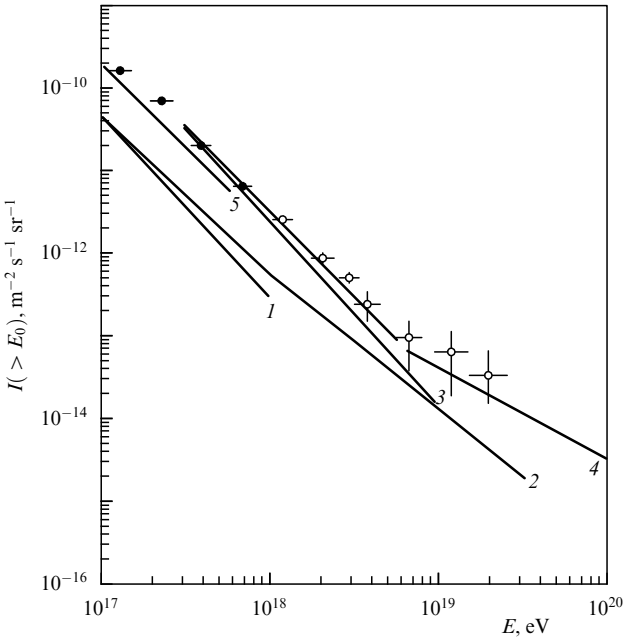

Figure 4. Integral CR energy spectra plotted using data published in 1973. The data show the absence of a cutoff at $E > 10^{19}$ eV according to [20]. Circles and dots are data from the Yakutsk facility (ShAL-13). Curve *1* is for the data of the AGASA facility (1961), curve *2* — Volcano Ranch (1963), *3* — La Pointe (1968), *4* — SUGAR (1970), and *5* — Haverah Park (1971).

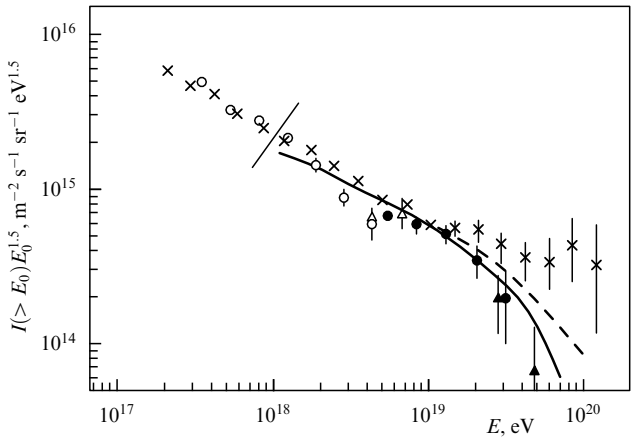

Figure 5. Integral CR energy spectra plotted using data published in 1985. Dots, circles, and triangles are for data from the Yakutsk facility (as in Fig. 3) and crosses are for the Haverah Park data. The curves show results of calculations [22] for extragalactic CR sources.

13 km^2. Its first results based on limited statistics were published in 1971, and new data using larger statistics of events appeared in 1973 [20]. Figure 4 shows the results for integral UHECR spectra measured by the Yakutsk facility, together with the results for facilities based outside Russia. The data obtained from the Volcano Ranch, SUGAR (Sydney University Giant Air-shower Recorder) and ShAL-13 facilities do not allow reaching any conclusion about the existence of the GZK cutoff because the statistics on UHECR EAS events were not sizable enough.

By the early 1980s, the data from the Yakutsk facility with extended statistics were compatible, as was noted in [21], with the existence of the relic cutoff of UHECRs. On the other hand, the data from the SUGAR and Haverah Park facilities indicated that there was no such cutoff. Those facilities registered a rather significant number of events with energies above 10^{20} eV (Fig. 5).

In 1985, the Yakutsk facility data indicating spectrum steepening at energies above 10^{19} eV were confirmed by the US-based Fly's Eye, a facility that registers UHECR EAS events by the their fluorescence in the atmosphere, i.e., using a calorimetric method.

In the 1980s, construction of a high-aperture facility began in Japan on the basis of a small-size Akeno facility. Observations at Akeno-20, whose area is about 20 km^2, commenced in 1985 and, in 1992, the AGASA (Akeno Giant Air Shower Array) facility with the area ≈ 100 km^2 started operations. The data provided by that facility were rather impressive: many UHECR EAS events with $E > 10^{20}$ eV were detected. Those data were especially intriguing for the scientific community because they indicated the absence of the theoretically predicted relic cutoff of the UHECR spectrum. However, they substantially disagreed with the results obtained at the HiRes (upgraded Fly's Eye in the USA) and Yakutsk facilities, which indicated the existence of the UHECR spectrum cutoff.

In the late 1980s, it was proposed to build large-scale ground facilities to register UHECR EASs and ensure a high statistical significance of measurements at the CR spectrum 'end'.

The ShAL-1000 project initiated in Russia by Khristiansen in the 1990s was never implemented due to financial reasons. In 2000, the large Argentina-based Pierre Auger Observatory (Auger) proposed by J Cronin and A Watson started operations. The Telescope Array (TA) based on the HiRes fluorescent facility based in Utah, USA also commenced observations.

At an international conference held in 2007, both international collaborations, Auger and TA, announced that they had observed a statistically significant change in the slope of the UHECR spectrum at energies of several units of 10^{19} eV [23, 24]. Those results gave strong momentum to both further explorations of UHECRs and the interpretation of the data obtained.

To verify the theoretical models, the following main physical characteristics of CRs are needed: the energy spectrum, the nuclear composition, and anisotropy. It should be taken into account that in propagating across the interstellar medium, UHECR particles lose energy in interactions with the background radiation (primarily in photo splitting of nuclei and photo production of pions by protons). This can result in a distortion in both the initial composition and energy spectrum of the particles accelerated in the sources and can therefore impede identification of the nature of CRs.

We discuss the experimental data on UHECRs available today and the problems of interpretation in more detail.

3. Energy spectrum of ultra-high-energy cosmic rays

Figure 6 shows the results of measurements for the differential energy spectrum of CRs at energies above 10^{16} eV compiled in [25]. According to the Auger and HiRes data, a change occurs in the power spectrum slope for all particles from less to more steep [-4.3 (Auger) and -4.7 (HiRes)], and the position of the region where the spectral index changes is close to the theoretically estimated GZK cutoff energy

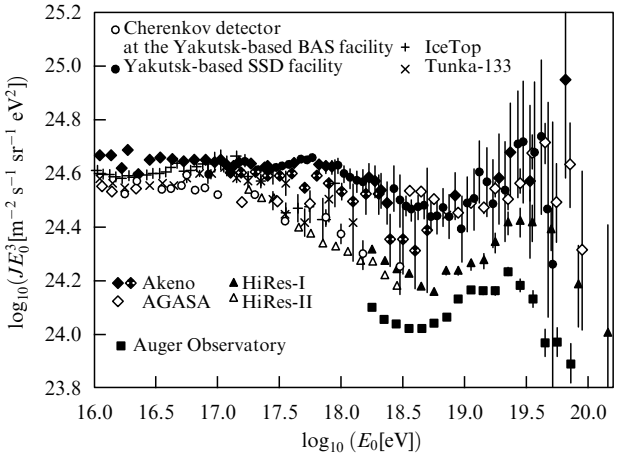

Figure 6. Differential CR energy spectrum plotted using data from various ground facilities. In addition to statistical uncertainty, we can note differences in the determination of the absolute rate of UHECR particles according to ground facility data. (Courtesy by Pravdin [25].)

5×10^{19} eV. Nevertheless, issues persist that are related to the accuracy with which spectral characteristics of UHECR were measured at those facilities. This can easily be seen in Fig. 6, which shows the Yakutsk facility spectrum obtained in 2017 with a new estimated energy. We can conclude that the data from the Yakutsk facility are compatible with the relic cutoff of the CR spectrum, similarly to TA and Auger data, but the intensity of the Yakutsk spectrum is higher than that of other facilities. The Yakutsk facility spectrum agrees well with the AGASA spectrum, with the exception of the energy region $\gtrsim 10^{20}$ eV. According to the Auger data, the UHECR fluxes are lower than follows from the HiRes data. An even stronger mismatch is observed in comparison with today's data of the Yakutsk facility. Thus, the issues related to the accuracy of measurements of the UHECR energy spectrum by ground facilities persist beyond any doubt.

In this regard, we mention paper [26], where 'recalibration' of the energy scales of various facilities provided fairly good agreement of the UHECR results measured by those facilities (Fig. 7).

The results in [26] suggest that the models of particle interaction used in analyzing experimental data have to be improved. The main problem is the absence of accelerator data on particle interaction cross sections at such high energies. To reconstruct the type and energy of the primary particles using experimental data, we need to know how hadrons interact at ultra-high CR energies. Currently, such data are unavailable; it is apparent that the experimentally determined upper boundary of the UHECR spectrum is no less than 3×10^{20} eV, a value that is three orders of magnitude higher than the equivalent energy attained at the Large Hadron Collider. For this reason, modern theories of hadron interaction are based on data obtained at lower energies; therefore, the results of EAS event reconstruction may significantly differ depending on the calculation model applied.

4. Mass composition of ultra-high-energy cosmic rays

The first published data on UHECR mass composition obtained by the Auger and TA facility were incompatible with each other. According to the Auger data, the mass composition was dominated by protons at energies $E < 3 \times 10^{18}$ eV and enriched with heavier elements at higher energies (Fig. 8) [27], but the TA data could be interpreted as the dominance in UHECRs of protons alone (Fig. 9) [28]. After a joint task force of the TA and Auger collaboration was established to analyze the data, the results for the measured composition coincided within systematic errors (Fig. 10 [29]). However, both collaborations note that the TA and Auger results cannot be compared directly because the methods used to analyze the data were different.

The data from the Auger, TA, and Yakutsk facilities identified a new feature in the behavior of the UHECR spectrum (Fig. 11): the occurrence of an effect of local hardening of the spectrum, a 'sole', in the range $E_4 < E < E_5$ ($10^{18} - 5 \times 10^{19}$ eV). According to [30], this phenomenon is due to proton losses in the CMB radiation field in the process of generating electron–positron pairs. This spectral feature, a dip in the terminology of [30], is immediately adjacent to the spectrum cutoff region beyond $E > E_5 = 5 \times 10^{19}$ eV. Because of that, constraints can be imposed on the conclusions pertaining to the mass composition of particles: namely, this mechanism of losses can only be of importance if the light component, UHECR protons,

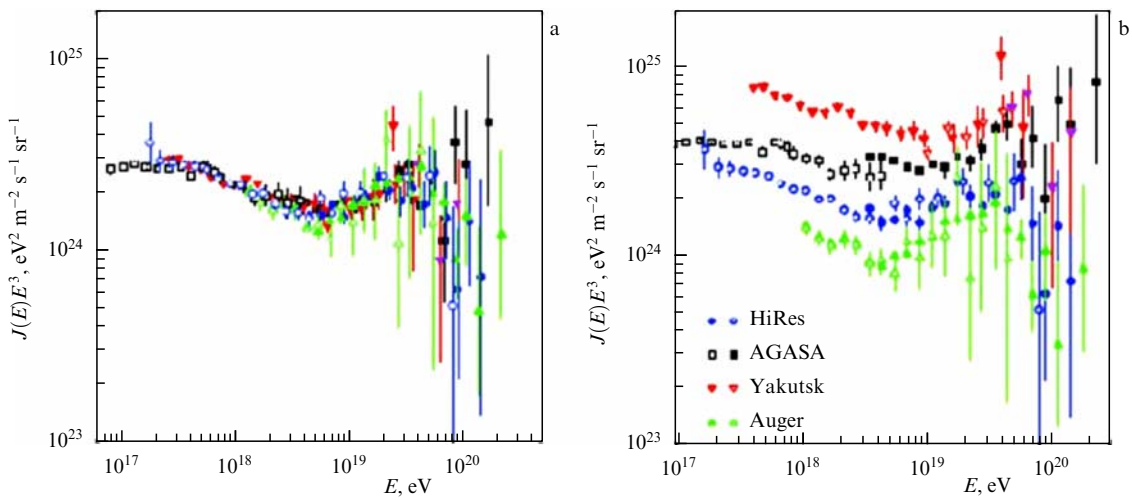

Figure 7. Results from [26] of (a) 'recalibration' of (b) primary experimental data from various facilities.

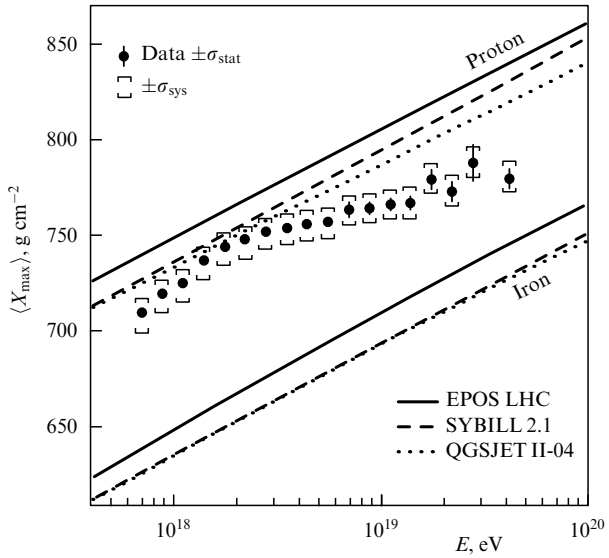

Figure 8. Depth of the maximum X_{max} of UHECR EASs that characterizes the nuclear composition of CRs according to the Auger facility data. A trend is observed toward enrichment with heavy elements with increasing energy [27]. Curves show the results calculated in various models indicated in the figure.

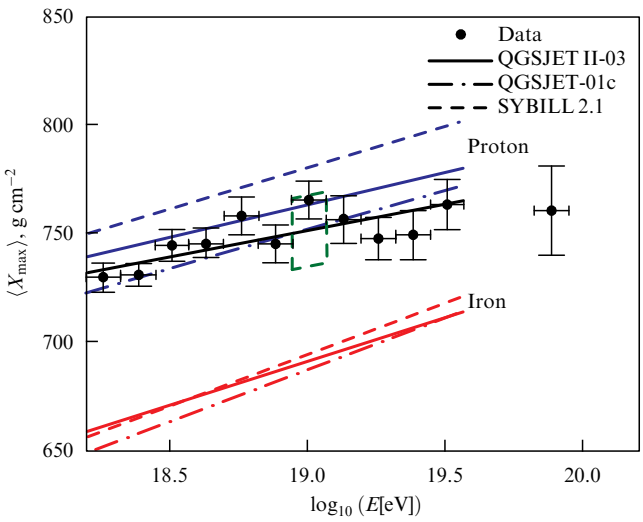

Figure 9. Depth of the maximum X_{max} of UHECR EASs that characterizes the nuclear composition of CRs according to TA facility data (2015): domination of the light component is observed for energies up to 10^{19} eV [28]. Results of calculations in various models are also presented.

dominates in this energy range. This observation can be naturally interpreted as the onset of domination of extragalactic CR sources that consist of light nuclei, predominantly protons.

We note, however, that the recently published data of the Auger facility [49] for UHECRs in the energy range 10^{18} – 10^{19} eV (the 'sole' region), which are based on studying correlations between the depth of the EAS maximum X_{max} and the number of muons, indicate that UHECRs have a mixed rather than a purely proton composition. Data from another facility, TA [38], are compatible with the dip model [30]: according to those data, the fraction of protons in the mixed UHECR flux is over 50%. On the other hand, we note that the heavy component can hardly

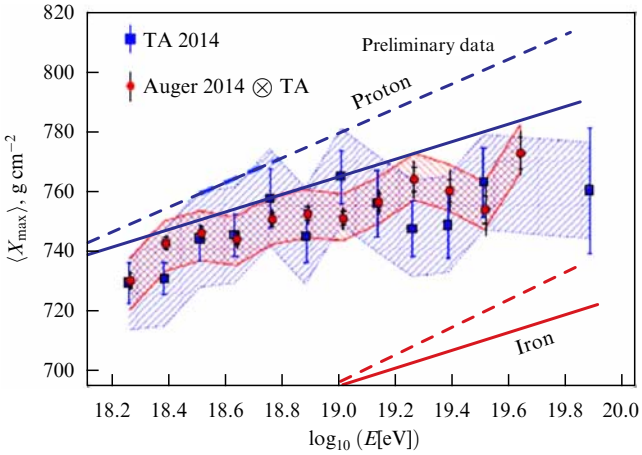

Figure 10. Results of a review of combined data from the Auger and TA facilities. Note the agreement within the statistical errors in measurements of the depth of maximum X_{max} of UHECR EASs [29].

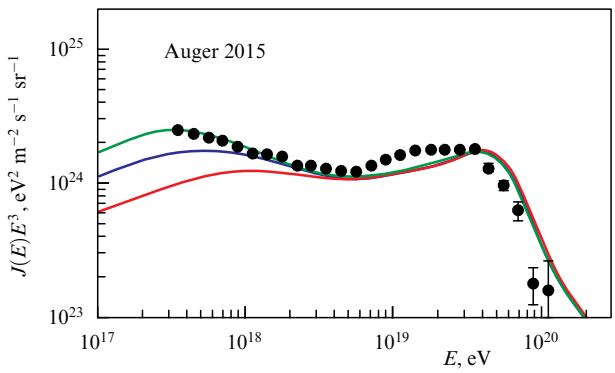

Figure 11. Forming the 'dip' structure for various model parameters (curves) for a uniform distribution of UHECR sources. Experimental data of the Auger facility are used (dots).

be observed near Earth due to photo splitting of the primary UHECR component.

The ambiguity in interpreting current experimental UHECR data regarding the nuclear composition of UHECRs necessitates also considering energy spectrum formation mechanisms alternative to the GZK cutoff. Indeed, if the enrichment of UHECRs with heavy elements with increasing energy is confirmed, this may indicate that the particle spectrum depends on Z (or the hardness) of the particles. This may in turn be an indication that particle acceleration in astrophysical objects is dominated by a mechanism similar to that proposed for galactic cosmic rays, namely, acceleration on shock waves in supernova remnants [3–6], albeit for objects containing much more energy. These two scenarios of the UHECR spectrum formation can only be verified using high-precision measurements of mass composition, a task which currently cannot be fulfilled.

5. Anisotropy of ultra-high-energy cosmic rays and the search for their possible sources

The search for UHECR sources based on EAS directions is only possible for protons and light nuclei. Indeed, the Larmor radius for protons with $E = 10^{19}$ eV in a magnetic field several μG strong (the value characteristic of interstellar space) is

about 50 kpc, more than double the size of the Galaxy. For iron nuclei, the corresponding radius is an order of magnitude smaller, about 2 kpc. For the same total energies, the Larmor radius of heavy nuclei is smaller than that of light ones; therefore, trajectories of the nuclei in interstellar fields deviate from the initial direction of their escape from the source. As regards the light UHECR nuclei, we can therefore talk about 'proton astronomy' that enables visualizing the astrophysical objects in the Universe where they are generated.

Various astrophysical objects are considered to be possible sources of UHECRs. The most important of them are active galactic nuclei (AGNs), starburst galaxies, Seifert galaxies, and gamma-ray bursts (GRBs) (see, e.g., [33]). Among AGNs, the most probable candidates for UHECR sources are so-called radiogalaxies, a special class of AGNs producing intensive localized synchrotron radiation. These are astrophysical objects where the kinetic energy of jets injected from the AGN center is sufficient to accelerate a particle to characteristic UHECR energies (see, e.g., [34, 35]). These astrophysical objects are selected under the assumption that the Hillas condition is satisfied [22]. According to that condition, the Larmor radius R of a UHECR particle cannot exceed the acceleration region size (as was noted in Section 2, the same condition determines the maximum energy of galactic CRs (10^{17} eV) accelerated in supernova remnants).

In searching for probable sources of UHECRs with $E > 5.7 \times 10^{19}$ eV, the northern TA facility found an excess of UHECR EASs (in total, 109 EAS events were detected) coming from a localized area in the Northern Hemisphere in a range of zenith angles of about 20°. This area was named a hot spot (Fig. 12) [36]. This experimental fact caused immense interest because no significant astrophysical objects are observed directly in the hot spot area that could be considered a source of light nuclei in UHECRs.

In some studies (see, e.g., [37]), starburst galaxy M82 (see Fig. 12) containing an intermediate-size black hole ($10^2 - 10^4$ solar masses), located 'close' to the hot spot, was considered to be a possible UHECR source. Among possible mechanisms of UHECR acceleration in such galaxies, acceleration on shock waves related to accretion of matter on a black hole is usually considered. Nevertheless, 'close' to the TA hot spot, there is also a significant star cluster Ursa (located at a distance of 20 Mpc) and blazars Mrk 421. These objects are also considered UHECR sources (see, e.g., [38, 39]).

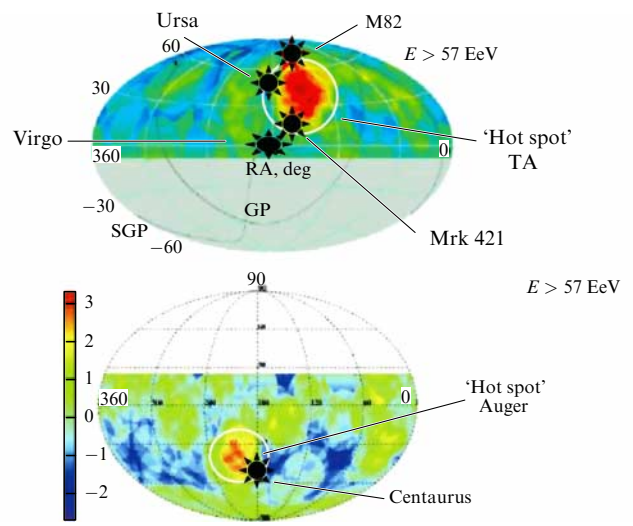

Figure 12. Anisotropy (shown with circles) of UHECR EASs according to data from the Auger facility [38] in the Southern Hemisphere and the TA facility [36] projected onto the Northern and Southern Hemispheres of the celestial sphere. Stars show stellar clusters and astrophysical objects located closest to the 'hot spots'.

The Auger collaboration studied UHECR anisotropy in the direction of the Centaurus A (Cen A) constellation, the radio galaxy closest to Earth (see Fig. 12). For a long time, it has also been considered a probable UHECR source. In total, 157 UHECR EASs with $E > 5.7 \times 10^{19}$ eV events have been localized. Of these events, some number (about 9%) were detected within a narrow 15° cone in the direction of Cen A [40]; this observation definitely cannot be a solid basis for identifying the source of particles.

The absence of spatial correlation of the northern (TA) and southern (Auger) hot spots with significant nearby astrophysical objects that could be UHECR sources similar to those listed above is an indication in favor of heavier UHECR composition rather than a lighter one, as a result of a stronger deviation of heavy nuclei than protons in magnetic fields. This conclusion, which is of importance for the very nature of UHECRs, is inconsistent with the mechanism of 'sole' formation in UHECR energy spectra (which specifically assumes the presence of a lighter component). It is noteworthy that currently there is no unambiguous correspondence between the data on UHECR anisotropy and mass composition.

A question now arises: given that the data of the facilities registering UHECRs fail to provide reliable evidence of a correlation between an identified UHECR anisotropy (hot spot coordinates) and the location of astrophysical objects, does it mean that the generation models related to acceleration in such sources (models of the top–down type) should be discarded? It is premature to discuss discarding these models. If we consider CRs in our Galaxy, then both the history of studies of those CRs and the gathered experimental data are far from prompting us to discard current astrophysical models (CR generation and acceleration in supernova remnants): quite the opposite, they support them in many respects (see the Introduction). Therefore, the paradigm of similar processes in other galaxies seems quite natural. We only note that if those models are discarded, there are alternative UHECR generation models (bottom–up models): the decay of a hypothetical super-heavy dark matter particle (see, e.g., [41]) or annihilation of topological defects of a space-string type (see, e.g., [42]).

Additional and very important information about UHECR sources can be obtained by studying gamma quanta and neutrinos, the secondary particles generated by UHECR in the process of transport. Unlike UHECRs, these secondary particles are not subject to the effects of interstellar magnetic fields in the process of transport and can be used as an efficient 'astronomical' tool for identifying UHECR sources. However, an analysis of alternative models and other types of cosmic radiation is beyond the scope of this paper.

The experimental data based on the analysis of UHECR EASs, which were quoted above, show that the main problem in interpreting those data and comparing them with models is the insufficient statistical and, possibly, systematic accuracy of measurements. The effective area of the South-America-based Auger facility, which is currently the world's largest, is about 3000 km^2. Creating such immense facilities is restrained not only by costly infrastructure but also by a limited number of locations on the globe where they could be efficiently used.

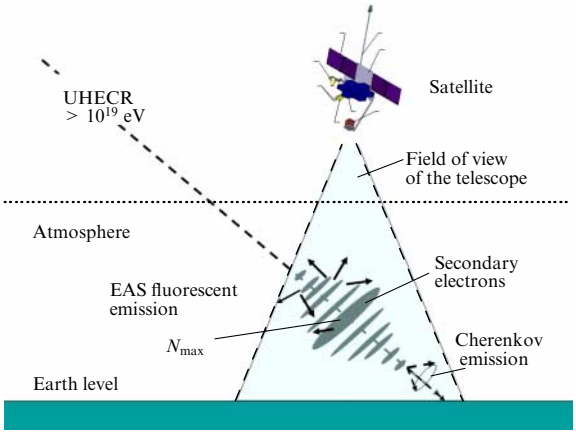

Figure 13. Concept of UHECR EAS space registration: Earth's atmosphere is used as a detector of fluorescent radiation that results from interaction of secondary electrons of UHECR EASs with atoms in air.

The list of limiting factors also includes climatic conditions, safety requirements, and accessibility for personnel. Therefore, employing space-based facilities for registering UHECR seems to be not an alternative but rather a complementary solution, because is provides vast options for experimentalists from the perspective of gathering sufficient statistics of UHECR measurements.

The space method for measuring UHECR was proposed by Linsley and Benson [43] in 1981. The method is based on registering fluorescent radiation from UHECR EASs in the atmosphere using an ultraviolet concentrating telescope installed on a spacecraft (Fig. 13). The accompanying Cherenkov radiation of UHECR EASs can be used as a trigger to launch EAS measurements; it can also provide additional information on the trajectory of the EAS itself.

Estimates show that in the case of moderate dimensions of space telescopes and relatively low spacecraft orbits, UHECRs can be registered in areas that are comparable to or even significantly greater than those of ground facilities; in other words, exposure and measurement statistics can be collected that would be sufficient for drawing unambiguous conclusions. Furthermore, unlike ground measurements, in orbital measurements, the UHECR particles coming from the entire celestial sphere can be detected. In what follows, we consider the major space projects aimed at exploring UHECRs that are currently under development.

6. Space projects for studying ultra-high-energy cosmic rays

Shortly after Linsley had published his idea [43], a space facility project was proposed, based on the scheme of an optical telescope consisting of three wide-angle Fresnel lenses, OWLs (Orbiting Wide-angle Light collectors) [44]. The project was not implemented, but it was used as a basis for another project, EUSO (Extreme Universe Space Laboratory), proposed by Scarsi [45]. A sketch of that telescope is shown in Fig. 14. The orbital wide-angle telescope with a 60° aperture enables observing UHECRs in an atmosphere area of no less than 10^4 km^2 if the spacecraft orbits at an altitude of 400 km. This corresponds to a geometric factor of the facility of about 2×10^4 km^2 sr year. However, to date, this project has not been finished either.

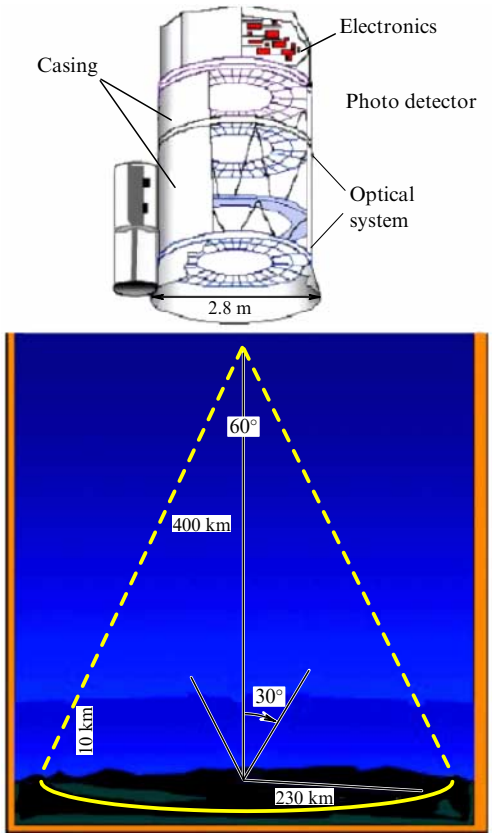

Figure 14. Plan for the EUSO orbital telescope [44].

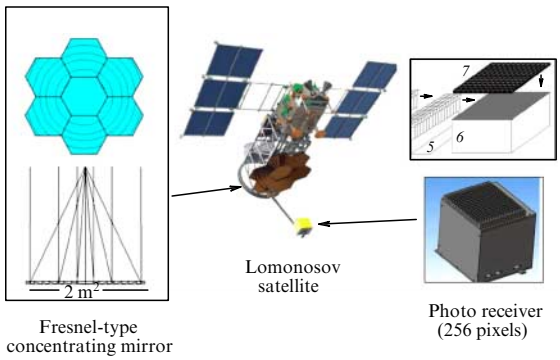

Figure 15. Main components of the TUS orbital telescope installed aboard the Lomonosov satellite.

Another approach to creating orbital detectors for registering UHECRs proposed in [46, 47] is based on the design of a telescope consisting of a concentrating mirror and a photo receiver located in its focus. A sketch of such a telescope that was used as a basis for the Russian projects TUS (Tracking facility) and KLPVE is shown in Fig. 15. The TUS experiment commenced in 2016 on the Lomonosov satellite that was launched on February 28, 2016 to the Sun's synchronous orbit with an altitude of about 500 km. A Fresnel-type mirror of the TUS telescope (area 2 m^2) concentrates the flux of ultraviolet (UV) radiation onto a photo receiver consisting of 256 photomultipliers that form the image of the EAS track in the atmosphere. The projection of each pixel to a lower atmosphere layer is 5×5 km and the total viewing area is 80×80 km. A detailed description of the TUS telescope is presented in [48].

The main goal of the TUS experiment is to check the very feasibility of registering UHECR particles using Earth's atmosphere as a giant detector. The difficulty of conducting such an experiment is that there are many background sources of both transient and quasistationary UV radiation. The former type includes transient luminous events in the upper troposphere layers (altitudes of several dozen kilometers), flashes of lightning in a near-ground atmosphere layer, UV tracks of meteors and neutral dust particles, and bioluminescence. Among quasistationary UF radiation sources in the atmosphere, aurora fluorescence and anthropogenic light sources are distinguished. Due to the presence of such a 'multicomponent' atmospheric background, the very task of distinguishing UV signals from actual UHECR EASs is far from trivial.

Nevertheless, the first results obtained in the TUS experiment aboard the Lomonosov satellite have already shown that it is conceptually possible to separate UHECR EASs from the complex atmospheric background [49].

The TUS telescope is now operational aboard the Lomonosov satellite. The next and larger project, KLPVE, which is based on the same concept, is intended for the International Space Station. The diameter of the concentrating mirror is increased to 10 m. The KLPVE project has been redesigned to increase its geometric factor. These facilities offer a conceptually new tool to researchers for explorations of UHECRs.

7. Conclusion

The theoretical study by Greisen, Zatsepin, and Kuzmin of the relic cutoff of the UHECR spectrum played a prominent role in the development of experimental studies of the most energetic particles in the Universe that are currently known. This model fostered development of both large-scale facilities on Earth's surface and space methods for studying UHECRs. Unlike ground facilities, which have already provided a number of important results, space projects are now at the initial stage of implementation. The special importance of space experiments that distinguishes them from their ground-based counterparts is that they enable observing the entire celestial sphere and increasing measurement statistics. The latter advantage is due to the large effective area (compared to ground facilities) of the UHECR EAS detector, the role of which is played by Earth's atmosphere.

We emphasize that the set of ground facilities currently under operation does not provide unambiguous conclusions regarding the nature of the particles observed in UHECR or even the (non)existence of the GZK cutoff. Further development and combination of ground and space measurements of UHECRs will facilitate progress in research in this important area of cosmic-ray astrophysics.

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