ISSN 0027-1349, Moscow University Physics Bulletin, 2017, Vol. 72, No. 2, pp. 144–156. © Allerton Press, Inc., 2017.
Original Russian Text © M.Yu. Zotov, O.E. Kalashev, M.S. Pshirkov, 2017, published in Vestnik Moskovskogo Universiteta, Seriya 3: Fizika, Astronomiya, 2017, No. 2, pp. 45–57.

ASTRONOMY, ASTROPHYSICS, AND COSMOLOGY (REVIEW)

The Current Status of Research in Ultrahigh-Energy Cosmic Ray Physics: A Brief Review

M. Yu. Zotov[a]*, **O. E. Kalashev**[b], **and M. S. Pshirkov**[b,c]**
[a] *Skobeltsin Institute of Nuclear Physics, Moscow State University, Moscow, 119991 Russia*
[b] *Institute of Nuclear Research of the Russian Academy of Sciences, Moscow, 117312 Russia*
[c] *Sternberg Astronomical Institute, Moscow State University, Moscow, 119992 Russia*
*e-mail: *zotov@eas.sinp.msu.ru, **pshirkov@sai.msu.ru*

Received June 24, 2016

Abstract—The origin and nature of ultrahigh-energy cosmic rays (UHECRs, $E > 10^{18}$ eV) is one of the most intriguing unsolved problems of modern astrophysics. This review is dedicated to the current status of research in this field. We describe the largest ongoing experiments carried out at the Pierre Auger Observatory and Telescope Array, at the first orbital detector of UHECRs, that is, TUS, and for the KLPVE and JEM-EUSO orbital telescopes, which are currently being developed. We discuss the latest results on the energy spectrum and mass composition of UHECRs and the relationship between UHECRs on the one hand and ultrahigh-energy neutrinos and photons on the other. Finally, we review the latest results on the anisotropy of the arrival directions of UHECRs, which is a crucially important area of research in the search for astrophysical sources of cosmic rays in the highest energy range.

Keywords: ultrahigh-energy cosmic rays, review, energy spectrum, mass composition, anisotropy, experiments.

DOI: 10.3103/S0027134917020138

INTRODUCTION

A cosmic particle with an energy of approximately 55 EeV (1 EeV = 10^{18} eV) (more precisely, the so-called extensive air shower generated by it) was detected for the first time 55 years ago [1]. An event with a higher energy of approximately 100 EeV was observed 2 years later [2]. Since then, considerable experimental and theoretical resources have been invested searching for ultrahigh-energy cosmic rays, but their nature and origin still remain one of the most important unsolved problems of modern astrophysics. This study provides a brief review of experiments in the domain of UHECRs and the most significant latest results on the energy spectrum, mass composition, and anisotropy of cosmic rays (CRs), as well as on the search for the events from neutrinos and photons of ultrahigh energy. In addition, this study describes promising experiments that are being developed. The main attention is paid to the results obtained in the $\gtrsim$50 EeV ultrahigh-energy range, which is far beyond the capacities of ground-based elementary-particle accelerators.

One particular vast theme that is not considered in this review is the mechanisms of acceleration of UHECRs and their possible sources (active galactic nuclei, gamma-ray bursts, shock waves in the large-scale structure of the Universe, rapidly rotating magnetars, particle decay of superheavy matter, etc.). For an introduction to these subjects, we recommend recent reviews [3, 4].

1. EXPERIMENTAL INSTALLATION

The most prominent installation for observing UHECRs is the Pierre Auger Observatory located at the western part of Argentina. The observatory uses a hybrid technique of CR observation that consists of 1660 Cherenkov detectors spaced 1.5 km apart over a surface of more than 3000 km^2 and 24 fluorescent telescopes gathered into four stations installed at the borders of the installation. The Cherenkov detectors are water tanks with a volume of 12 m^3 equipped with three photoelectric multipliers. The observatory also operates a group of Cherenkov detectors distributed on a regular grid with a spacing of 750 m, three fluorescent telescopes that observe the atmosphere above the installation at higher angles than the main set of the telescopes does, and other instruments [5]. The experiment started to collect data in 2004. During 10 years of observation, the total exposure has exceeded 50000 km^2 sr year [6]. More than 500 researchers from 16 countries work for the Auger Collaboration. Recently, the plans of further development of the installation were published. First of all, they consist of an additional scintillation detector with a surface area of 4 m^2 at the top of each water tank. These additional detectors will make it possible to distinguish the electromagnetic and muon components of EASs, which is necessary for studying the UHECR composition [7].

The second significant experiment in the domain of UHECRs is carried out at the Telescope Array (TA) situated in Utah, United States. Similarly to the Auger experiment, the TA experiment is also equipped with both ground-based detectors and fluorescent telescopes, but as ground-based detectors they use dual-layer scintillators with a surface area of 3 m^2. The array consists of 507 detectors spread on a square grid with a spacing of 1.2 km that covers a surface of approximately 680 km^2, i.e., a fourth of the surface area of the Auger experiment. At the corners of the installation are three stations consisting of 38 fluorescent telescopes [8]. The experiment has been carried out since March 2008 and is sensitive to UHECRs with an energy higher than 3 EeV. During 7 years of the experiment's operation, the total exposure has reached 8600 km^2 sr year [9]. In the near future, 500 detectors (with a spacing of 2.08 km) will be added to the installation and its surface area will reach 3000 km^2, so it will be equal to the surface area of the Auger experiment [10]. The installation also uses a Telescope Array Low Energy (TALE) extension: "an extension" with a more dense filling with ground-based scintillation detectors and with a larger elevation angle of the fluorescent telescopes. TALE provides the sensitivity to CRs in the energy range higher than $\sim 3 \times 10^{15}$ eV.

In the Russian Federation, the complex Krasilnikov Yakutsk EAS array has operated since the beginning of the 1970s. Simultaneous recordings of three main components of extensive air showers (EASs), namely, the flux of protons, muons, and the Cherenkov radiation, are performed only at the Yakutsk array [11, 12]. The surface area of the array is 12 km^2.

The ANITA (Antarctic Impulsive Transient Antenna) balloon experiment is worth mentioning, whose aim is to detect the radio emission generated while an ultrahigh-energy neutrino is passing through ice (the so-called Askaryan effect [13]) [14]. Thus far, ANITA has performed three flights over the Antarctic Continent.

The Askaryan effect is the basis of the method for recording ultrahigh-energy cosmic rays and neutrinos in the LORD (Lunar orbital radio detector) experiment [15]. The gist of the method is as follows: a detector that operates in a circumlunar orbit detects radio-frequency radiation generated by a cascade initiated by a high-energy particle in the regolith of the Moon. The main element of the detector will consist of two conic log-periodic antennas, one of which will provide the detection of a signal with a left circular polarization, while another will detect a signal with a right circular polarization. According to calculations, at energies higher than 500 EeV the exposure of the experiment will be several times greater than that of the Auger experiment. The launch of the detector, which is part of the instrumentation of the Luna-26 spacecraft (Luna-Resurs OA) is planned for 2020.

Finally, on April 28, 2016, TUS, the world's first ultrahigh-energy CR detector, which is part of the scientific equipment of the *Lomonosov* satellite, was launched from the Vostochnyi spacecraft launching site. The detector is designed on the principle of a refracting telescope. Its principal elements are a concentrating mirror with an area of 2 m^2 and a focal distance of 1.5 m and a photodetector consisting of 256 pixels [16]. The field of view is $\pm 4.5°$. On an orbit of approximately 500 km, this corresponds to an area of approximately 6400 km^2 at the Earth's surface. The angular resolution is equal to 10 mrad, or 5 km at the Earth's surface. This instrument is designed to detect photons of fluorescent and Cherenkov radiation in the ultraviolet wavelength range that occur due to the development of an extensive air shower in the atmosphere and its reflection from the Earth's surface. It is expected that TUS will be able to detect CRs with an energy of higher than 100 EeV. In addition, TUS can detect slower processes, first of all, so-called transient atmospheric phenomena, and can gather a great volume of information about the value and variations of the UV background of the nocturnal atmosphere, which is of great importance for the orbital detectors of the next generation.

2. THE ENERGY SPECTRUM

The most important parameter of the cosmic ray flux is the energy spectrum. Shortly after the first recording of CRs with an energy higher than 50 EeV was made, Greisen [17] and, independently, Zatsepin and Kuz'min [18] showed that at such energies the flux of protons must be suppressed due to interaction with the photons of the relict microwave radiation. This effect, which was predicted theoretically, was named the GZK cut off. The situation with the GZK cut off was unclear for many years because different experiments gave contradictory results. The riddle was solved only in 2007–2008, when the cut off of the CR flux at an energy of approximately 60 EeV was detected in the High Resolution Fly's Eye (HiRes) experiment, a predecessor to the TA experiment, at a level of statistical significance higher than 5σ [19, 20]. Soon afterwards, this discovery was supported by the Auger Collaboration [21] and later by the TA Collaboration [22].

From the time when the discovery was first made, the spectrum of UHECRs has been measured with increasing statistical accuracy. The last results published by the Auger and TA collaborations are shown in Fig. 1 [6, 23]. It is clearly seen from Fig. 1 that the spectra obtained in both experiments are similar to each other at energies higher than $\log_{10}(E/\mathrm{eV}) = 17.5$. Both spectra demonstrate a so-called "ankle" in the

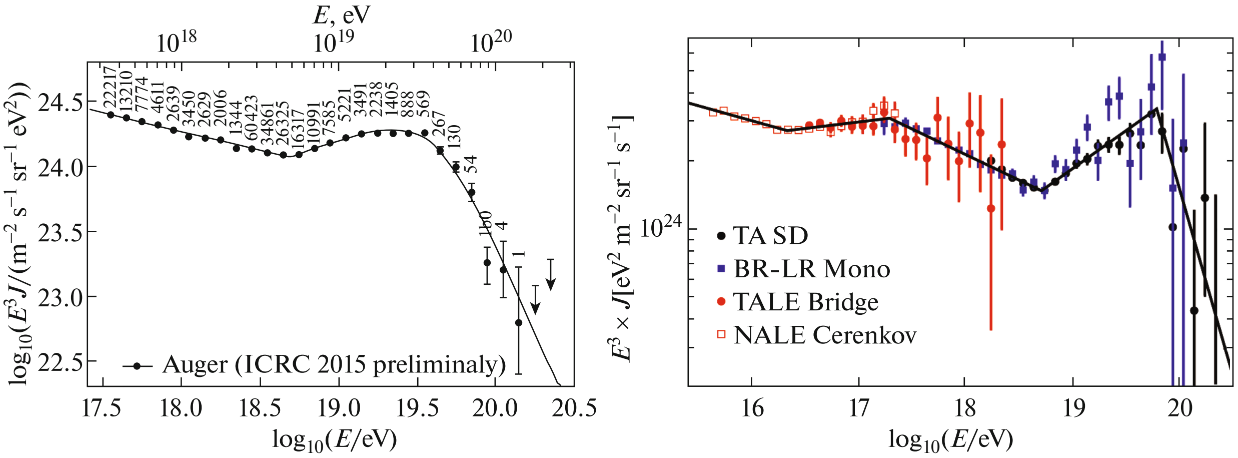


Fig. 1. Left side: The combined energy spectrum of CR on the basis of data of the Auger experiment [6]. The number of events is indicated above the experimental points. Right side: Energy spectrum measured by the TA experiment using four different methods [23].

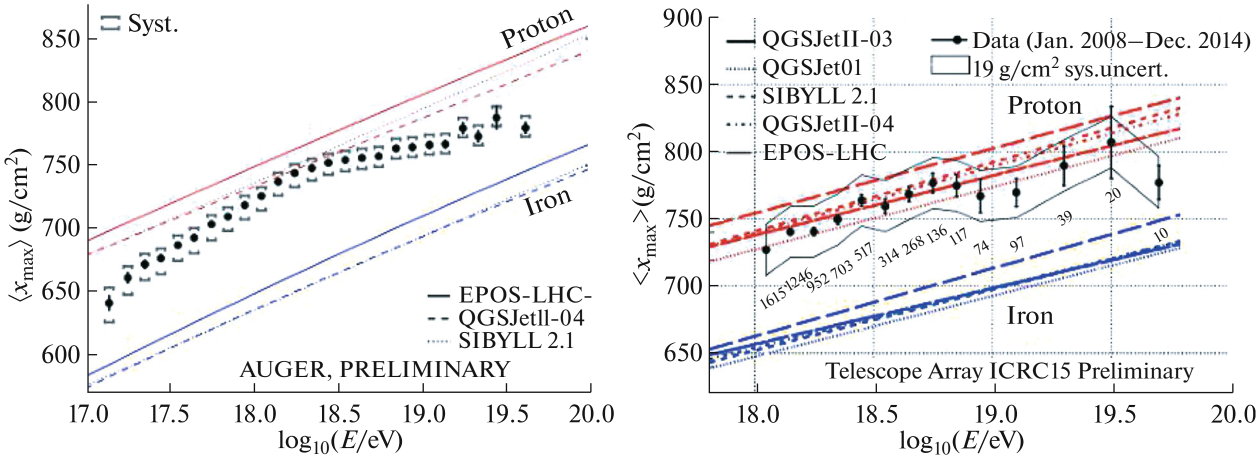


Fig. 2. The experimental dependence of $X_{\max}$ on energy in comparison with the results of a computer simulation for protons (red) and for iron nuclei (blue). Left side: Auger [86]. Right side: Telescope Array [87].

range of approximately 5 EeV and a drastic steepening of the spectrum (cut off) at energies predicted by Greisen, Zatsepin, and Kuz'min.

A joint working group of the Auger, TA, and Yakutsk Array collaborations has come to the conclusion that after energy scaling the spectra obtained by the Auger and the TA collaborations are in agreement with each other with respect to normalization and shape within the margin of error [24]. Nevertheless, there is a considerable difference in the region of the GZK cut off: in the case of the Auger experiment, the steepening of the spectra starts at an energy of approximately 30 EeV, whereas in the case of the TA experiment it occurs at 60 EeV; in this case, the spectrum of the Auger experiment becomes steeper than the spectrum of the TA experiment. This difference in the spectra along with some results related to the chemical compositions of UHECRs (see below), do not allow one at present to determine whether the observed behavior of the spectrum can be explained by the GZK effect or by achieving the maximum of the possible energy of acceleration in the sources, or by a combination of both factors.

In this connection, it is necessary to note that the absolute energy of CRs is calibrated on the basis of fluorescent observations, for which it is possible to relate the energy release in the form of ultraviolet radiation to the total energy of an EAS and, thus, to the energy of a primary particle. At the present time, there is a systematic difference of 20–30% between the energy scales of the scintillation and fluorescent detectors, which has not been explained yet in a satisfactory way and is corrected by calibration against the fluorescent scale. It is possible that considerable progress will be achieved by calibration methods on the basis of Cherenkov radiation [25] and radio-frequency signals from EASs [26, 27].

3. UHECR COMPOSITION

One more characteristic of cosmic rays that is of an essential importance for the identification of their origins is their chemical (mass) composition. The conclusions about CR composition are made principally on the basis of observations of the depth of the EAS maximum $X_{\max}$ measured in units of g/cm^2 and by modeling EASs generated by different primary particles. It is assumed that the mean value of $X_{\max}$ depends on the energy E and the mass number A as follows:

$$\langle X_{\max} \rangle = a(\ln E - \langle \ln A \rangle) + b,$$

where a and b are constants. Using data obtained by fluorescent detectors in 2004–2012, the Auger Collaboration executed a detailed analysis of $X_{\max}$ distribution [28, 29]. The experimental dependence of mean values and variations in $X_{\max}$ distributions were compared with the results of modeling carried out using a number of models of hadron interactions: EPOS-LHC [30], QGSJet II-4 [31], and Sybill 2.1 [32]. The conclusion was made that the UHECR flux in the energy range of 2 EeV consists mainly of light nuclei, but the fraction of heavy nuclei increases up to 40 EeV [29].

The TA Collaboration also carries out an intensive study of the mass composition of CRs using the data on the $X_{\max}$ distribution. The reconstruction procedure uses results obtained simultaneously, whether by any two fluorescent detectors (FD), or by surface detectors and one FD detector (so-called hybrid regime).

Recently published results obtained in the hybrid regime were based on data obtained from 5 years of observations using surface detectors and the Middle Drum station equipped with 14 modernized telescopes of the HiRes experiment. The analysis was similar in many ways to that provided by the Auger experiment. It was made for the purpose of simplifying the comparison of the results of these two experiments. The mean values and the elongation rate of $X_{\max}$ obtained by the TA Collaboration demonstrated good agreement with the results obtained by the Auger experiment, but the data from the TA proved to be inconsistent with a purely iron composition of CRs over the entire investigated energy range [33]. The latest results published by both collaborations are shown in Fig. 2. Since the determination of the CR mass composition requires the use of results of observations by fluorescent telescopes with a relatively small part of the effective operation time (~10%), the study of the CR mass composition for the energies higher than 4×10^{19} eV is nearly impossible because of insufficient statistics. Enhancement of surface detectors and a more complete use of different characteristics observed by them will make it possible to investigate the CR mass composition for higher energies in the region of the “GZK cut off” in the future.

Comparing the results of the Auger experiment and TA, it is necessary to bear in mind that measuring the mass composition of primary CRs is one of the most challenging problems in the range of ultrahigh energies, since it is based on the data of the hadron interaction models at energies far beyond those achievable at nuclear accelerators like the LHC, which leads to the necessity of the extrapolation by approximately two orders of magnitude. It is worth mentioning that the Auger and TA experiments use different methods of data selection and data treatment. As an example, the value $\langle X_{\max} \rangle$ published by the TA Collaboration were obtained on the basis of the data on the $X_{\max}$ distribution, which contained some detection effects. The interpretation of such data is carried out by their comparison with the results of modeling that considers the operating particularities of a concrete detector, in particular, its resolution and recording efficiency. In turn, the analysis provided by the Auger Collaboration was based on EAS geometry, which made it possible to obtain a practically unbiased $X_{\max}$ distribution that considered residual errors related to the recording efficiency, resolution, and reconstruction [34, 35].

A joint working group of the TA and Auger collaborations has analyzed the energy dependence of $\langle X_{\max} \rangle$ on the basis of data obtained in both experiments. After having considered the differences in the characteristics of both installationes and in the methods of data treatment, the conclusion was made that the results are in a good agreement with each other within the limits of systematic errors (Fig. 3). However, a more detailed analysis is continuing.

4. ANISOTROPY OF ARRIVAL DIRECTIONS

One of the most important aspects in searching for the sources of UHECRs is the analysis of the anisotropy of their arrival directions. It is also an indirect test of the CR mass composition, because it is expected that protons and light nuclei of ultra-high energies would be only insignificantly deflected by extragalactic magnetic fields in the process of propagation from their sources.

One of the traditional approaches in this domain is the investigation of large-scale anisotropy. Recently, the Auger Collaboration presented the result of harmonic analysis of the arrival direction distribution of CRs with an energy higher than 4 EeV and zenith angles up to 80° in declination and right ascension (Fig. 4) [36].

The greatest deviation from the isotropic flux was found for the events with an energy $E > 8$ EeV. The amplitude of the first harmonic in the right ascension is found to be $(4.4 \pm 1.0) \times 10^{-2}$. The probability of

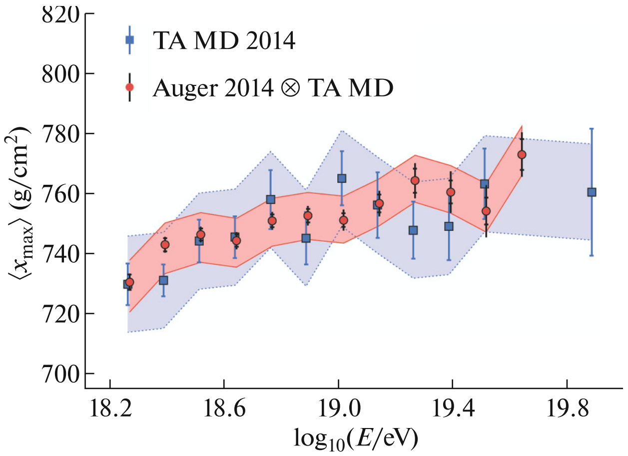
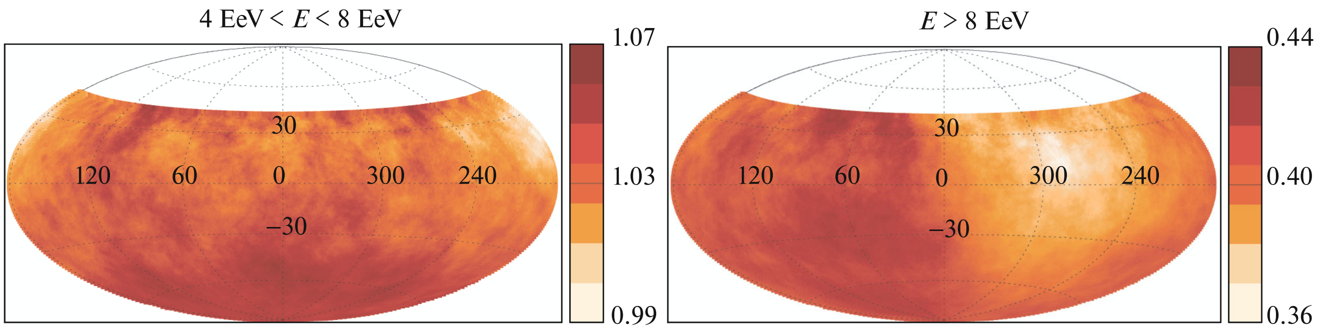


Fig. 3. The dependence of the mean values of $X_{\max}$ on the basis of the data obtained by the Middle Drum experiment of the TA Collaboration (blue squares). For better illustration, the experimental points are slightly shifted along the abscissa axis. The color bars indicate the systematic uncertainties of the $X_{\max}$ values [35].

such a deviation is 6.4×10^{-5}. On the assumption that the only considerable contribution to the anisotropy is made by the dipole component, the flux can be described by a dipole with an amplitude of 0.073 ± 0.015 in the direction $(\alpha, \delta) = (95° \pm 13°, -39° \pm 13°)$. This supports the result obtained earlier for the events with zenith angles up to 60° [37]. The study has been performed recently with new data, and the key conclusions remained the same [38]. The TA Collaboration has also analyzed the large-scale UHECR anisotropy using a different technique [39]. Due to the GZK effect, the propagation of UHECRs is bounded by distances of approximately 100 Mpc. At these scales, the Universe is still considerably inhomogeneous. In the overwhelming majority of models of the generation of CRs of such energies, one should expect a correlation between their arrival direction and the distribution of galaxies in this volume, which is well known from observations. Under the assumption of a purely proton composition of CR, it was found that the distribution of events with an energy higher than 10 EeV and higher than 40 EeV agrees with the isotropy hypothesis and does not follow the large-scale matter distribution at "smearing" angles of the arrival directions of less than 20° and less than 10°, respectively. In contrast, for the events with energies higher than 57 EeV their distribution agrees with the matter distribution and does not agree with the isotropy hypothesis at the significance level of approximately 3σ.

It is important to note that the investigation of the large-scale anisotropy of the CR arrival directions is a challenging problem, because an accurate determination of a complete set of multipole coefficients requires knowing the CR flux over the entire celestial sphere; however, existing ground-based experiments cannot provide it. Therefore, the investigation of the anisotropy of UHECRs carried out jointly by the TA and Auger collaborations [40, 41] is of special interest. The data obtained within the swath width of the declination band that is available for the observation by both experiments were used for the purpose of intercalibration of fluxes. The analysis was carried out on the basis of 2560 events with zenith angles up to 55° and an energy higher than 10 EeV observed by the TA Collaboration during 6 years of operation and 16 835 events with zenith angles up to 80° and an energy higher than 8.8 EeV of the Auger Collaboration during 10 years of operation. The results did not reveal any statistically significant deviations from the isotropic distribution of the CR flux; however, they made it possible to obtain an upper estimate for the amplitudes of the dipole and quadrupole moments as functions of the direction on the celestial sphere. The value of the dipole amplitude was found to be $(6.5 \pm 1.9)\%$ with a probability equal to 5×10^{-3} along the direction $(\alpha, \delta) = (93° \pm 24°, -46° \pm 18°)$ (see Fig. 5). It is interesting that the angular spectral density obtained in [41] demonstrates a clear dipole moment, in contrast to the result from a previously published paper [40]. The value of the amplitude of the dipole moment is found to lie within the interval of expected fluctuations of the isotropic flux.


4 EeV < E < 8 EeV

E > 8 EeV

Fig. 4. The distribution of the CR flux with energies 4 EeV < E < 8 EeV (on the left) and E > 8 EeV (on the right), smoothed over the regions with an angular radius of 45° in the units km^{-2} sr^{-1} year^{-1}. Equatorial coordinates are used [36].

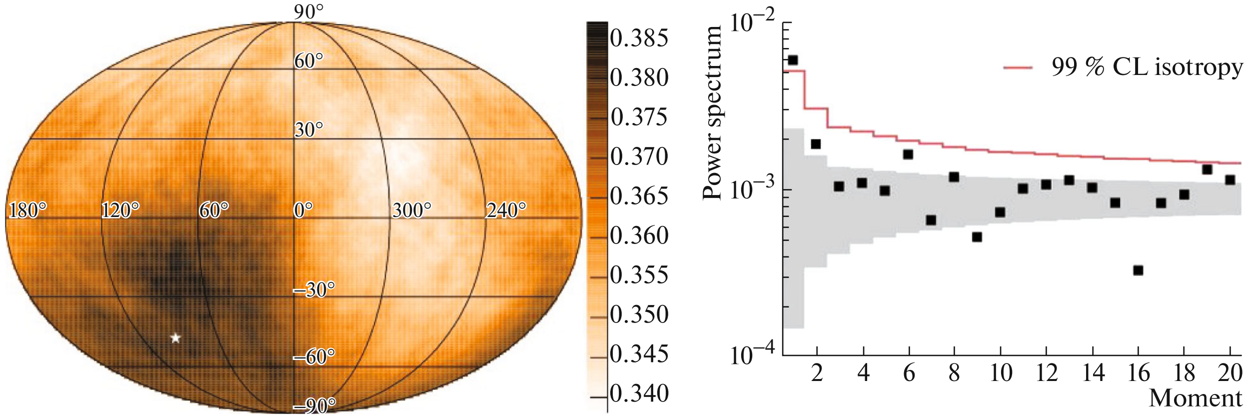


Fig. 5. Left side: The map of the flux of CRs with energies higher than 10 EeV in the units km^{-2} sr^{-1} year^{-1} obtained by the Auger and the TA experiments and smoothed over the regions with an angular radius of 60°. The equatorial coordinates are used. The white asterisk indicates the location of a dipole that was found. Right side: Joint angular spectral density based on the Auger and TA data [41].

Studies intended to study anisotropy at a less angular scale are also of a great importance, since they enable searching for the correlations with the matter distribution in the local region of the Universe, as well as with possible sources of cosmic rays of ultrahigh energies. In particular, at the end of the 2000s great interest was excited by the result obtained by the Auger Collaboration that demonstrated the correlation between the arrival directions of CRs with energies higher than 55 EeV and the arrangement of active galactic nuclei (AGN) at the distance of up to 75 Mpc, including correlation with the Centaurus A radio galaxy (Cen A) located at a distance of less than 4 Mpc from the Solar system [42–44]. Recently, the results of a number of tests intended to search for the anisotropy of CRs with an energy higher than 40 EeV were published. Among them, there were 231 events with an energy of ≥52 EeV [45]. None of those tests revealed a statistically significant deviation from the isotropic distribution, however, it was shown that there was certain excess of events with the energy of ≥58 EeV in the direction towards Cen A and AGN indicated in the Swift-BAT catalog, which are situated at distances of up to 130 Mpc and have a luminosity of more than 10^{44} erg/s. In both cases, the probability of the random occurrence of such an excess was found to be 1.3–1.4%. On the other hand, a similar investigation undertaken by the TA Collaboration on the basis of the data on CRs with the energy higher than 40 EeV observed by surface detectors during the first 40 months of its operation did not reveal any statistically significant correlation with AGN from several catalogs [46]. Searches for the sources of energies higher than 10^{17} eV carried out by the Auger and TA collaborations did not find any statistically significant candidates for this role [47, 48].

Undoubtedly, the most intriguing result obtained in the domain of the UHECRs in recent years is the discovery of a so-called "hotspot" with an excessive flux of CR with an energy higher than 57 EeV [49]. At the time when the paper was published, the "hotspot" was a region with a radius of 20° and with its center at the point $(\alpha, \delta) = (146.7°, 43.2°)$. Inside of this region, 19 events were detected (from 72 events detected during 5 years of the operation time of this installation) with an expected number of events equal to 4.49. The prior statistical significance of such a deviation from the isotropic distribution was found to be 5.1σ; the posterior significance considering the probability of a random appearance of such a "hotspot" is 3.4σ. Observations carried out during the next 2 years proved the existence of a hotspot, but did not increase the statistical significance of the deviation from the expected isotropic distribution: at the time of the most recent publication, the number of the events detected inside the hotspot was 24, while the expected number was 6.88 [50] (Fig. 6).

Thus far, it is not clear what could lead to the appearance of a hotspot that is located near the supergalaxy plane but does not contain any clear candidates for the role of an accelerators of CR at such high energies. The TA Collaboration suggested that the hotspot could be related to the cluster of galaxies located in the vicinity of the Milky Way or to the structure connecting the Milky Way with the Virgo galactic cluster. If the detected CRs are heavy nuclei, as follows from the results of the Auger experiments, they could be accelerated by sources situated in the supergalaxy plane and then deflected by magnetic fields [49].

5. NEUTRINOS AND PHOTONS OF ULTRAHIGH ENERGIES

An important direction of UHECR studies consists of attempts to detect the events generated by neutrinos and photons with energies higher than 1 EeV. The

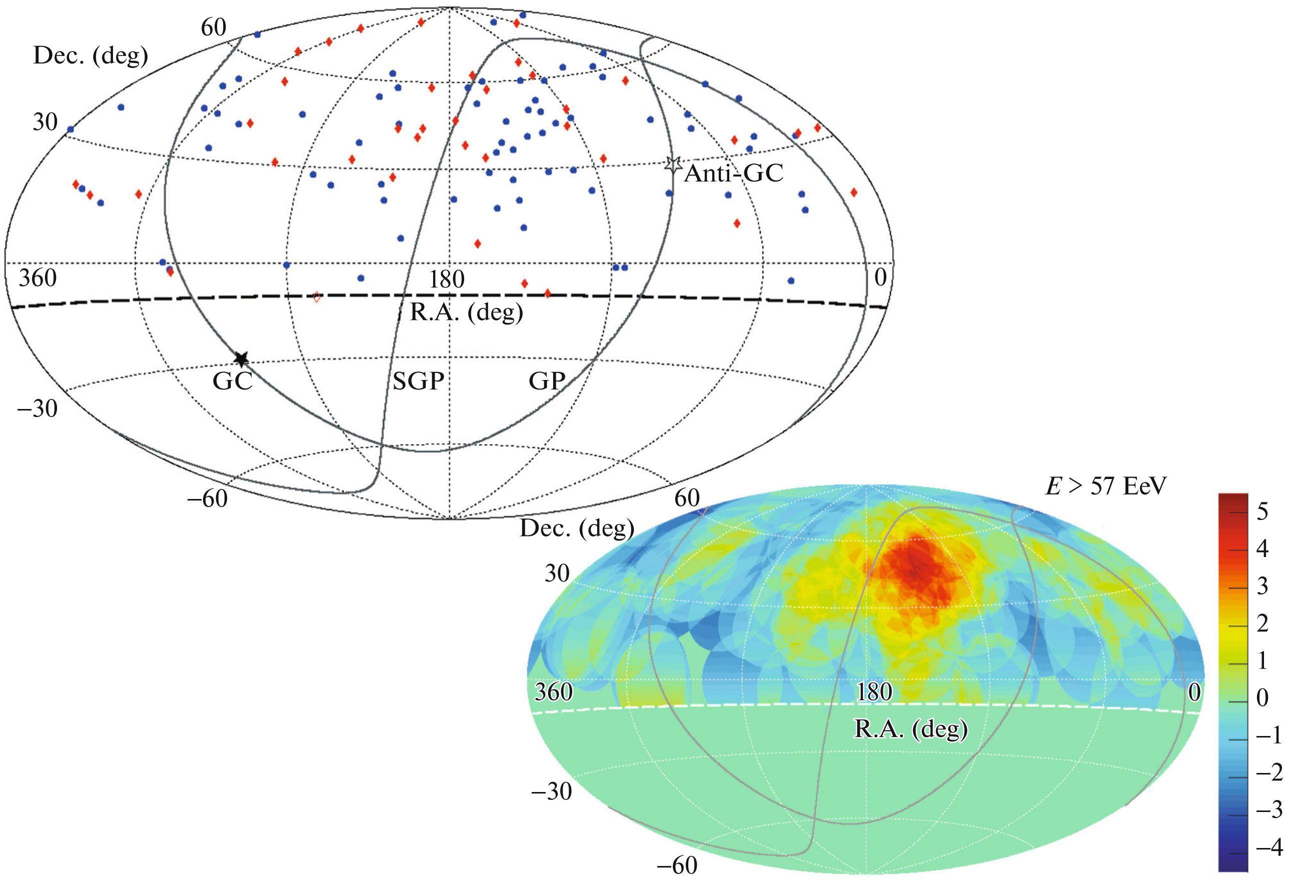


Fig. 6. Left side: Arrival directions of CRs with $E > 57$ EeV detected in the TA experiment (in equatorial coordinates). Blue dots represent events detected in the first five years of observations, while red dots correspond to events recorded in the following two years. Right side: Map of statistical significance of deviations from the 7-year isotropic flux smoothed over circles with a radius of 20° [50].

recording of astrophysical neutrinos in the energy range from 30 TeV to several PeV made by the IceCube experiment [51] gave a new impetus to these studies. The interest in neutrinos and photons of UHE occurs for a number of reasons.

Being electrically neutral particles, neutrinos and photons propagate in space with no deflections in magnetic fields and, thus, point to the direction of their origin. Neutrinos interact weakly with matter and thus can travel to practically infinite distances (at least to the red shift $z \sim 30$) carrying information about sources located far beyond the sphere bounded by the GZK effect. Moreover, in the case of transient sources, for example, gamma-ray bursts, the detection of neutrinos and photons (and, perhaps, gravitational waves) may be the only way to obtain data for understanding the processes that occur in such a source [52].

As noted above, at energies of approximately 50 EeV, protons and heavier nuclei interact with the relict microwave radiation, which leads to the generation of so-called cosmogenic neutrinos, whose typical energy is approximately 1/20th of the energy of a primary particle [53], as well as photons. In this sense, UHECRs are an "assured" source of neutrinos and photons. Protons that interact with the photon background generate, as a rule, a greater number of cosmogenic neutrinos than compound nuclei of the same energies [54, 55]. This can be explained by the fact that the threshold of photopion production, which is the main process that generates neutrinos of UHE, is proportional to the mass of the nucleus. At the same time, the nuclei lose actively their energy due to photodisintegration on the microwave and infra-red background. The last process may also lead to the generation of neutrinos due to the beta decay of unstable compound nuclei and neutrons; however, in this case, the energy of secondary neutrinos is 3–4 orders of magnitude lower than the energy of the primary nuclei. This reasoning allows one to determine the mass composition of the primary CRs on the basis of a neutrino signal or its absence.

One can say almost the same concerning photons of UHE, but with one reservation. In contrast to neutrinos, UHE photons interact actively with the relict background producing electron–positron pairs; thus, at the energies of approximately 100 EeV, they have a chance to be detected on Earth only when they come from distances of up to 10 Mpc. This is a fundamental difference between the neutrino signal and the signal from GZK photons. The first accumulates at cosmological distances and, thus, strongly depends on the evolution of the source, whereas the second is sensitive only to the configuration of the sources inside the GZK sphere.

One more source of neutrinos is their generation in the process of decay of charged pions that occur due to the interaction of CRs with matter or with radiation in such potential accelerators of UHECRs as gamma-ray bursts, AGN [56, 57]. If UHECRs are generated in the processes of decay of heavier particles ("top-down" models), this must lead to considerable fluxes of secondary photons and neutrinos [58], significantly exceeding the fluxes one can expect in the case when neutrinos and photons are the secondary product of the interaction between hadrons and relict radiation. The constraints to the flux rating obtained up to the present time (see below), deny, or at least considerably limit, the possibility for the processes suggested in the top-down models to provide a substantial part of the flux of UHECRs, except perhaps for the highest energies $E \simeq 100$ EeV, i.e., in the energy range where the accumulated statistics still do not enable one to draw reliable conclusions. In particular, the constraints on the parameters of supermassive dark matter were obtained in this way [59].

The constraints on the flux of photons or the recording of even a single UHE photon event can be of key significance for the quantum gravitation theories that allow breaking the Lorentz invariance (see, for example, [60, 61]). Similarly, the observation of UHE neutrinos would make it possible to limit the possible breaking of the Lorentz invariance in the neutrino spectrum [62]. All this stimulates active searching for neutrinos and photons of UHE.

Up to the present time, the Auger Collaboration has carried out a number of investigations intended to search for UHE neutrino and photon events (see, for example, [63–66]). In what follows, we will dwell upon only the latest results.

A recently published paper [64] presents the results of the search for two types of events: "descending" (the zenith angles lie within an interval from 60° to 90°) and "ascending" (the zenith angles lie within the interval from 90° to 95°). The events of the first type develop in the atmosphere similar to hadron air showers (but with a significantly greater depth of the first interaction) and can be generated by neutrinos of all types. The events of the second type can occur in the case when a tau neutrino "scratches" the earth's crust.

The results revealed no candidate for the role of a UHE neutrino; however, a constraint on the diffusion flux of neutrinos of one type was found at the significance level of 90% based on the assumptions of the exponent spectrum $dN(E_\nu)/dE_\nu = kE^{-2}$ and equal contents of neutrinos of various types in the energy range from 1.0×10^{17} eV to 2.5×10^{19} eV; $k < 6.4 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}, which made it possible to come to some important conclusions:

(1) The obtained limit is four times lower than the Waxman–Bahcall bound for the generation of neutrinos in optically thin sources [67, 68];

(2) Some models of neutrino generation in astrophysical sources such as ANG are excluded for the significance level equal to 90%;

(3) Cosmogenic neutrino models that assume a purely proton composition of CRs in sources are considerably limited.

In addition, the Auger Collaboration obtained the bounds for a flux of photons with energies in the EeV range for the first time. At the 95% significance level, it is shown that at energies higher than 2, 3, 5, and 10 EeV, the photon's fraction in the common CR flux does not exceed 3.8%, 2.4%, 3.5%, and 11.6%, respectively [65], which supported the estimates obtained earlier for the photon flux with an energy of higher than 10 EeV [69] that have imposed significant constraints on some of the top-down models of UHECR generation.

The Auger experiment undertook a search for the point sources of photons with energies of approximately 1 EeV [66]. The results revealed no source; however, the upper estimates of the photon flux for all possible directions in the range of declinations δ from −85° to 20°. This made it possible to impose constraints on the models in which UHE protons accelerate in galactic sources. On the basis of the data that were collected during 7 years of operation, the TA Collaboration obtained the constraints for the flux of photons with energy of 3 EeV [70]. In particular, it was shown that at $E > 10$ EeV, the photon flux does not exceed 4.7×10^{-3} km^{-2} sr^{-1} year^{-1} at the significance level of 95%.

Thus, up to the present time, no experiment has succeeded in reliably detecting any neutrino or photon event with an energy of $\gtrsim 1$ EeV, although there are some candidates for the role of UHE photons [52]. Figure 7 demonstrates the constraints for the fluxes of photons and neutrinos of ultrahigh energies.

Joint research intended to find a correlation between the arrival directions of astrophysical neutrinos detected in the experiment IceCube and the UHECRs detected by the Auger ($E > 52$ EeV) and TA collaborations ($E > 57$ EeV) studied different groups of neutrino events ("cascade" and "track") and various models of deflection of CRs in magnetic fields [71]. No statistically significant correlation between the arrival directions of neutrinos and CRs was found. The collaborations plan to continue research in this direction as far as new data are obtained.

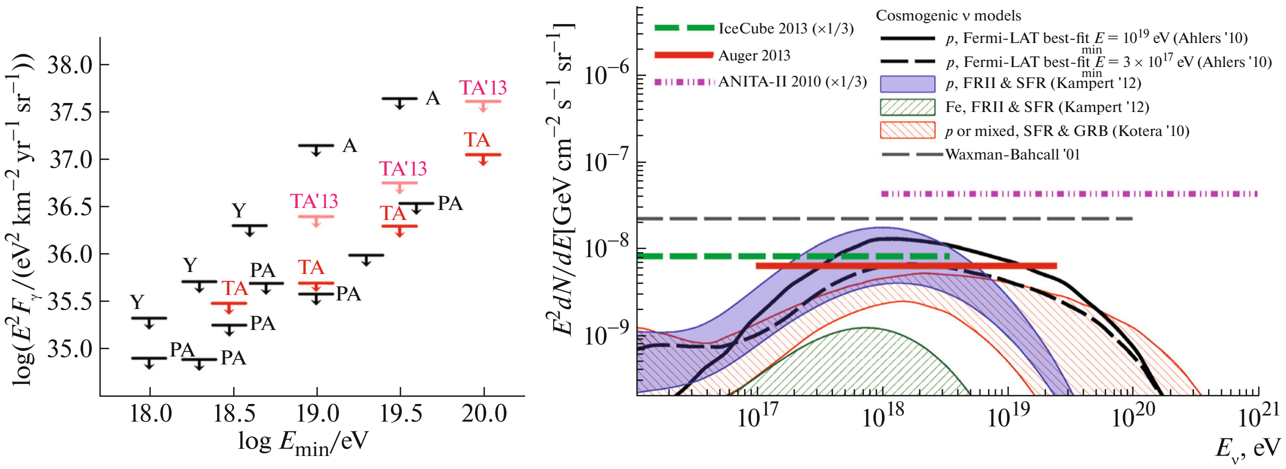


Fig. 7. Left side: Constraints for the photon flux obtained in experiments from AGASA (A), Auger (PA), and TA, as well as at the Yakutsk experiment on EASs (Y) [70]. Right side: Experimental constraints for the neutrino flux and predictions of some models [7].

In view of the attempts to find UHE neutrinos, the detection of three approximately horizontal events and one ascending event in the energy range of 0.6–10 EeV that was recently performed by ANITA [72] is of interest. From the viewpoint of the Collaboration, if the source of the ascending event is the decay of a tau lepton, it may require revising the interaction cross section of the tau neutrino in the standard model.

6. DIFFUSE GAMMA RAYS AND THE SOURCES OF UHE COSMIC RAYS

Information about the nature of UHECRs and their possible sources can be obtained not only by direct measurements but also through the secondary signals that must occur due to the interaction of CRs with the intergalactic photon background. These include the cosmogenic neutrinos and photons mentioned above, as well as the diffuse γ-rays. Protons and nuclei with an energy higher than EeV produce electron–positron pairs. The electron–positron pairs initiate a fast electron-photon cascade due to the chain of the Compton backscattering of electrons on the background photons and the generation of electron–positron pairs by photons on the same background. As a result, electrons and photons quickly lose their energy; thus, their quantity grows exponentially. The rapid development of the electron–photon cascade finishes when the photons attain the threshold energy for pair production on the infrared background, i.e., in the energy range of a few TeV. For photons with an energy below 200 GeV, the Universe becomes transparent. Practically the entire energy of electrons is gradually transferred to the sterile photons. Therefore, all the energy emitted by UHECRs in the form of photons and electrons is accumulated in the form of diffuse γ-ray radiation in the energy range from tens of MeV to TeV.

Presently, due to the Fermi LAT satellite experiment [73], as well as to its predecessor EGRET, the spectrum of the diffuse γ-ray radiation is being measured in the energy range from 100 MeV to 820 GeV. It is thought that in addition to UHECRs, the contribution to the diffuse radiation is made by photons emitted in astrophysical objects, in particular, in AGN, as well as by products of annihilation or decay of dark matter. In [74], it was demonstrated for the first time that the definite contribution from UHECRs may exceed the direct contributions from astrophysical objects. Similar to the situation with neutrinos, the flux of diffuse γ-ray radiation is sensitive to the supposed evolution of sources and to the primary composition of UHECRs. The last peculiarity is related to the fact that protons and light nuclei produce electron–positron pairs more efficiently than heavy nuclei of the same energies. As the data on the γ-ray radiation were defined more precisely the constraints on the evolution and composition of the sources of UHECRs became more precise as well [75, 76].

At the present time, the models that assume a purely proton character of the primary composition of UHECRs are at the point of being excluded from consideration because of the overproduction of cascade radiation in the energy range higher than 500 GeV [76, 77]. At the same time, as was noted above, the analysis of the UHECR mass composition obtained in the Auger, Telescope Array, and HiRes experiments indicates their light composition, at least in the energy range of 1–4 EeV. This contradiction can be avoided by assuming that the population of the CR sources is concentrated in the region of relatively moderate red shifts. Among the candidates for the role of astrophys-

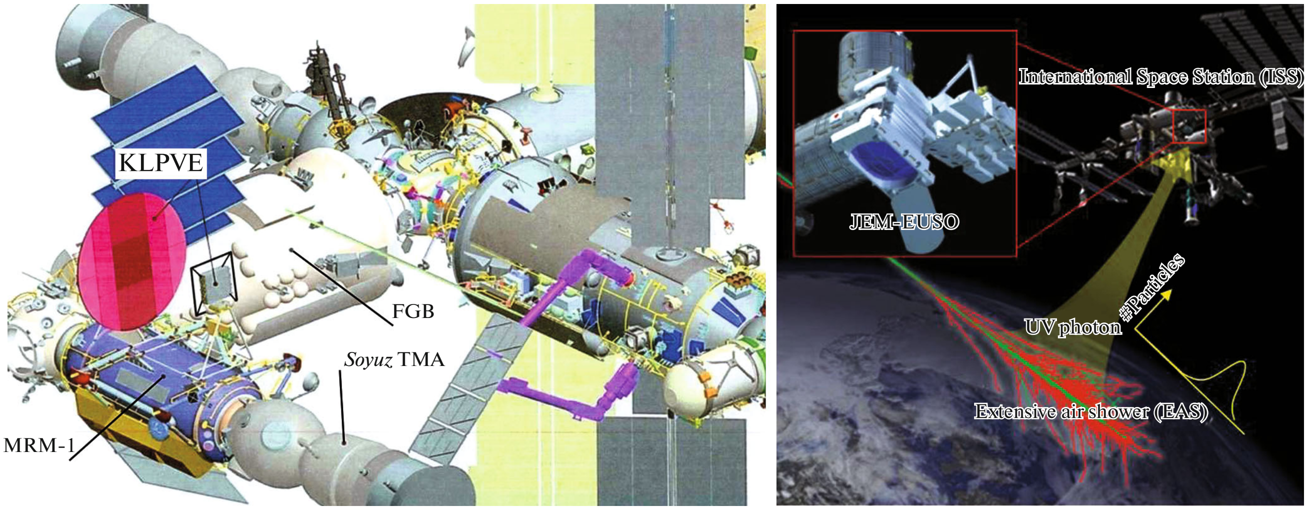


Fig. 8. Left side: A possible schematic of the placement of the KLPVE detector at the small research module of the Russian segment of the ISS [79]. Right side: A possible design of the JEM-EUSO detector and the scheme of its operation [80].

ical accelerators, BL Lacertae objects satisfy such a criterion. However, it should be noted that the density of such objects in the Universe is not high, which, in its turn, can lead to consequences for the anisotropy of the UHECR flux.

7. FUTURE EXPERIMENTS

As we have already noted in the first section of this review, all ongoing experiments are being modernized, expanded, and enhanced. Nevertheless, as noted above, all operating ground-based experiments have fundamental deficiencies that cannot be easily eliminated in the foreseeable future due to their enormous costs. First of all, these deficiencies consist of the relatively small exposure that makes it impossible to collect sufficient data to statistically come to conclusions on the compositions and sources of UHECRs, as well as the incomplete coverage of the celestial sphere, which is of great importance for the study of the anisotropy of the arrival directions of CR. It is evident that an experiment that could provide independent data with high accuracy and sufficient statistics, as well as drawing inferences about the energy spectrum and mass composition of CR, in particularly, in the ultrahigh-energy region, would be of great significance for solving the existing problems. Moreover, it is impossible to prove that the spectrum and/or the composition of UHECRs don't differ in different hemispheres (the hypothesis of nearby sources), and thus, the Auger and TA collaborations observe somewhat different objects. A cosmic experiment that can detect UHECRs that arrive from all the directions of the celestial sphere has an unique ability to verify this.

The principle of operation of all orbital UHECR detectors is based on the recording of ultraviolet fluorescent and Cherenkov radiation that occurs during the development of an EAS initiated by a primary cosmic particle that enters the atmosphere. The number of fluorescent photons emitted in any point of the EAS track is proportional to the number of charged particles in the cascade, mainly electrons and positrons. Thus, the Earth's atmosphere within the range of the detector plays the role of a giant calorimeter. The Cherenkov radiation reflected from the surface is an additional source of information about the event. The data about both types of radiation detected by the detector are used for the reconstruction of the arrival direction and the energy of a primary particle, as well as for determining the depth of the maximum and other characteristics of the air shower. The idea of detecting CRs in the orbit of the Earth was suggested for the first time by Benson and Linsly more than 30 years ago [78], but it was not performed because of a number of scientific and technological problems related to the necessity to identify and detect a weak flux of UV photons generated by an EAS on the background of the permanently changing Earth's atmosphere which is noisy because of numerous sources of light. The TUS experiment that was described in the first section of this review is the first time this idea has been carried out.

TUS is a pioneer in the domain of orbital detection of UHECRs but it is not of the highest technology and is not likely to produce a scientific breakthrough. Therefore, in Russia and abroad, one can see the active processes of the design and development of new-generation orbital detectors: the KLPVE reflecting telescope that is intended to be installed on the Russian segment of the International Space Station [79] and the JEM-EUSO refracting telescope [80, 81]. The optical system of the KLPVE detector in its basic variant will consist of a mirror with a diameter of 3.4 m and a corrector lens with a diameter of 1.7 m. The JEM-EUSO telescope will include three Fresnel lenses with a diameter of 2.65 m. Both detectors will be equipped with photodetectors with a number of pixels of approximately a few hundred thousand. The field of view will be equal to ±14° for KLPVE and ±30° for JEM-EUSO. The angular resolution will reach 1 mrad. The detectors will be entirely efficient for detecting CRs in energy ranges higher than 30 and 60 EeV for KLPVE and JEM-EUSO, respectively. The schematics of the operation and distribution of the detectors in the ISS are shown in Fig. 8.

The main scientific goals of these experiments are the recording of cosmic rays, neutrinos, and photons of ultrahigh energies with statistics that are unattainable in ground-based experiments. According to the calculations, in the energy range higher than 30–60 EeV, the annual exposure of the KLPVE and JEM-EUSO detectors will exceed the annual Auger exposure by two and nine times, respectively [79, 82, 83]. In particular, owing to this, both detectors will present excellent opportunities for an independent verification of the existence of the CR hotspot in the energy range higher than 57 EeV discovered by the TA Collaboration [84].

Finally, the ARA project (the Askaryan Radio Array), which is planned to be carried out in Antarctica, is worth mentioning [85]. In this experiment, neutrinos in the energy range of 10^{16}–10^{19} eV will be detected through their radio-frequency radiation that occurs as a result of the Askaryan effect.

CONCLUSIONS

In a short time span, a number of results of the greatest importance have been obtained in the domain of ultrahigh energy cosmic-ray physics; in particular, the cut-off of the energy spectrum in the region predicted by Greisen, Zatsepin, and Kuz'min 50 years ago has been reliably established. Nevertheless, problems of great importance concerning the composition and the sources of UHECRs still remain open. The ongoing experiments and those being developed provide hope considerable progress in solving these problems during the upcoming decades.

ACKNOWLEDGMENTS

The authors are grateful to the reviewer for valuable comments that helped to considerably improve this paper. This work was supported by a grant of President of the Russian Federation no. MK-4167.2015.2.

REFERENCES

1. J. Linsley, L. Scarsi, and B. Rossi, Phys. Rev. Lett. **6**, 485 (1961). doi 10.1103/PhysRevLett.6.485
2. J. Linsley, Phys. Rev. Lett. **10**, 146 (1963). doi 10.1103/PhysRevLett.10.146
3. K. V. Ptitsyna and S. V. Troitsky, Phys.-Usp. **53**, 691 (2010). doi 10.3367/UFNe.0180.201007c.0723
4. K. Kotera and A. V. Olinto, Annu. Rev. Astron. Astrophys. **49**, 119 (2011). doi 10.1146/annurev-astro-081710-102620
5. A. Aab, P. Abreu, M. Aglietta, et al., Nucl. Instrum. Methods Phys. Res., Sect. A **798**, 172 (2015). doi 10.1016/j.nima.2015.06.058
6. I. Valiño, in *Proc. 34th Int. Cosmic Ray Conf., The Hague, Netherlands, 2015*, p. 271.
7. A. Aab, P. Abreu, M. Aglietta, et al., arXiv:1604.03637 [astro-ph.IM].
8. M. Fukushima, EPJ Web Conf. **99**, 04004 (2015). doi 10.1051/epjconf/2015990400
9. P. Tinyakov, M. Fukushima, D. Ikeda, et al., in *Proc. 34th Int. Cosmic Ray Conf., The Hague, Netherlands, 2015*, p. 326.
10. T. Sagawa, in *Proc. 34th Int. Cosmic Ray Conf., The Hague, Netherlands, 2015*, p. 657.
11. S. Knurenko, I. Petrov, Z. Petrov, and I. Sleptsov, EPJ Web Conf. **99**, 04001 (2015). doi 10.1051/epjconf/20159904001
12. S. Knurenko and I. Petrov, EPJ Web Conf. **99**, 04003 (2015). doi 10.1051/epjconf/20159904003
13. G. A. Askar'yan, Sov. J. Exp. Theor. Phys. **21,** 658 (1965).
14. H. Schoorlemmer, K. Belov, A. Romero-Wolf, et al., Astropart. Phys. **77**, 32 (2016). doi 10.1016/j.astropartphys.2016.01.001
15. V. A. Ryabov, V. A. Chechin, G. A. Gusev, and K. T. Maung, Adv. Space Res. **58**, 464 (2016). doi 10.1016/j.asr.2016.04.030
16. M. Panasyuk, B. Khrenov, P. Klimov, et al., Exp. Astron. **40**, 315 (2015). doi 10.1007/s10686-015-9465-y
17. K. Greisen, Phys. Rev. Lett. **16**, 748 (1966). doi 10.1103/PhysRevLett.16.748
18. G. T. Zatsepin and V. A. Kuz'min, JETP Lett. **4**, 78 (1966).
19. D. R. Bergman (High Resolution Fly's Eye Collab.), Nucl. Phys. B. (Proc. Suppl.) **165**, 19 (2007). doi 10.1016/j.nuclphysbps.2006.11.004
20. R. U. Abbasi, T. Abu-Zayyad, M. Allen, et al., Phys. Rev. Lett. **100**, 101101 (2008). doi 10.1103/PhysRevLett.100.101101
21. J. Abraham, P. Abreu, M. Aglietta, et al., Phys. Rev. Lett. **101**, 061101 (2008). doi 10.1103/PhysRevLett.101.061101
22. T. Abu-Zayyad, T. Aida, M. Allen, et al., Astrophys. J. Lett. **768**, L1 (2013). doi 10.1088/2041-8205/768/1/L1
23. D. Ivanov, in *Proc. 34th Int. Cosmic Ray Conf., The Hague, Netherlands, 2015*, p. 349.
24. B. R. Dawson, I. C. Maris, M. Roth, et al., EPJ Web Conf. **53**, 01005 (2013). doi 10.1051/epjconf/20135301005
25. T. Abu-Zayyad, in *Proc. 34th Int. Cosmic Ray Conf., The Hague, Netherlands, 2015*, p. 422.
26. D. Kostunin, N. M. Budnev, O. A. Gress, et al., Nucl. Instrum. Methods Phys. Res., Sect. A **742**, 89 (2014). doi 10.1016/j.nima.2013.10.070
27. F. G. Schröder, Nucl. Instrum. Methods Phys. Res., Sect. A **824**, 648 (2016). doi 10.1016/j.nima.2015.08.047

28. A. Aab, P. Abreu, M. Aglietta, et al., Phys. Rev. D **90**, 122005 (2014). doi 10.1103/PhysRevD.90.122005
29. A. Aab, P. Abreu, M. Aglietta, et al., Phys. Rev. D **90**, 122006 (2014). doi 10.1103/PhysRevD.90.122006
30. K. Werner, F. M. Liu, and T. Pierog, Phys. Rev. C **74**, 044902 (2006). doi 10.1103/PhysRevC.74.044902
31. S. Ostapchenko, Phys. Rev. D **74**, 014026 (2006). doi 10.1103/PhysRevD.74.014026
32. E. I. Ahn, R. Engel, T. K. Gaisser, et al., Phys. Rev. D **80**, 094003 (2009). doi 10.1103/PhysRevD.80.094003
33. R. U. Abbasi, M. Abe, T. Abu-Zayyad, et al., Astropart. Phys. **64**, 49 (2015). doi 10.1016/j.astropartphys.2014.11.004
34. M. Unger, in *Proc. 34th Int. Cosmic Ray Conf., The Hague, Netherlands, 2015*, p. 307.
35. R. Abbasi, J. Bellido, J. Belz, et al., JPS Conf. Proc. **9**, 010016 (2016). doi 10.7566/JPSCP.9.010016
36. A. Aab, P. Abreu, M. Aglietta, et al., Astrophys. J. **802**, 111 (2015). doi 10.1088/0004-637X/802/2/111
37. R. M. de Almeida, in *Proc. 33rd Int. Cosmic Ray Conf., Rio de Janeiro, Brazil, 2013*, p. 0768.
38. I. Al Samarai, in *Proc. 34th Int. Cosmic Ray Conf., The Hague, Netherlands, 2015*, p. 372.
39. M. Fukushima, D. Ivanov, E. Kido, et al., in *Proc. 33rd Int. Cosmic Ray Conf., Rio de Janeiro, Brazil, 2013*, p. 0935.
40. A. Aab, P. Abreu, M. Aglietta, et al., Astrophys. J. **794**, 172 (2014). doi 10.1088/0004-637X/794/2/172
41. O. Deligny, in *Proc. 34th Int. Cosmic Ray Conf., The Hague, Netherlands, 2015*, p. 395.
42. J. Abraham, P. Abreu, M. Aglietta, et al., Science **318**, 938 (2007). doi 10.1126/science.1151124
43. J. Abraham, P. Abreu, M. Aglietta, et al., Astropart. Phys. **29**, 188 (2008). doi 10.1016/j.astropartphys.2008.01.002
44. P. Abreu, M. Aglietta, E. J. Ahn, et al., Astropart. Phys. **34**, 314 (2010). doi 10.1016/j.astropartphys.2010.08.010
45. A. Aab, P. Abreu, M. Aglietta, et al., Astrophys. J. **804**, 15 (2015). doi 10.1088/0004-637X/804/1/15
46. T. Abu-Zayyad, R. Aida, M. Allen, et al., Astrophys. J. **777**, 88 (2013). doi 10.1088/0004-637X/777/2/88
47. P. Abreu, M. Aglietta, M. Ahlers, et al., Astrophys. J. Lett. **755**, L4 (2012). doi 10.1088/2041-8205/755/1/L4
48. R. U. Abbasi, M. Abe, T. Abu-Zayyad, et al., Astrophys. J. **804**, 133 (2015). doi 10.1088/0004-637X/804/2/133
49. R. U. Abbasi, M. Abe, T. Abu-Zayyad, et al., Astrophys. J. Lett. **790**, L21 (2014). doi 10.1088/2041-8205/790/2/L21
50. K. Kawata, M. Fukushima, D. Ikeda, et al., in *Proc. 34th Int. Cosmic Ray Conf., The Hague, Netherlands, 2015*, p. 276.
51. M. G. Aartsen, M. Ackermann, J. Adams, et al., Phys. Rev. Lett. **113**, 101101 (2014). doi 10.1103/PhysRevLett.113.101101
52. T. Karg, J. Alvarez-Muniz, D. Kuempel, et al., JPS Conf. Proc. **9**, 010021 (2016). doi 10.7566/JPSCP.9.010021
53. V. S. Beresinsky and G. T. Zatsepin, Phys. Lett. B **28**, 423 (1969). doi 10.1016/0370-2693(69)90341-4
54. M. Ave, N. Busca, A. V. Olinto, et al., Astropart. Phys. **23**, 19 (2005). doi 10.1016/j.astropartphys.2004.11.001
55. D. Hooper, A. Taylor, and S. Sarkar, Astropart. Phys. **23**, 11 (2005). doi 10.1016/j.astropartphys.2004.11.002
56. F. Halzen and D. Hooper, Rep. Prog. Phys. **65**, 1025 (2002). doi 10.1088/0034-4885/65/7/201
57. J. K. Becker, Phys. Rep. **458**, 173 (2008). doi 10.1016/j.physrep.2007.10.006
58. P. Bhattacharjee and G. Sigl, Phys. Rep. **327**, 109 (2000). doi 10.1016/S0370-1573(99)00101-5
59. O. E. Kalashev, G. I. Rubtsov, and S. V. Troitsky, Phys. Rev. D **80**, 103006 (2009). doi 10.1103/PhysRevD.80.103006
60. M. Galaverni and G. Sigl, Phys. Rev. Lett. **100**, 021102 (2008). doi 10.1103/PhysRevLett.100.021102
61. G. Rubtsov, P. Satunin, and S. Sibiryakov, Phys. Rev. D **89**, 123011 (2014). doi 10.1103/PhysRevD.89.123011
62. D. M. Mattingly, L. Maccione, M. Galaverni, et al., J. Cosmol. Astropart. Phys. **2010** (2), 007 (2010). doi 10.1088/1475-7516/2010/02/007
63. P. Abreu, M. Aglietta, M. Ahlers, et al., Adv. High Energy Phys. **2013**, 708680 (2013). doi 10.1155/2013/708680
64. A. Aab, P. Abreu, M. Aglietta, et al., Phys. Rev. D **91**, 092008 (2015). doi 10.1103/PhysRevD.91.092008
65. J. Abraham, P. Abreu, M. Aglietta, et al., Astropart. Phys. **31**, 399 (2009). doi 10.1016/j.astropartphys.2009.04.003
66. A. Aab, P. Abreu, M. Aglietta, et al., Astrophys. J. **789**, 160 (2014). doi 10.1088/0004-637X/789/2/160
67. E. Waxman and J. Bahcall, Phys. Rev. D **59**, 023002 (1999). doi 10.1103/PhysRevD.59.023002
68. J. Bahcall and E. Waxman, Phys. Rev. D **64**, 023002 (2001). doi 10.1103/PhysRevD.64.023002
69. J. Abraham, P. Abreu, M. Aglietta, et al., Astropart. Phys. **29**, 243 (2008). doi 10.1016/j.astropartphys.2008.01.003
70. G. Rubtsov, M. Fukushima, D. Ivanov, et al., in *Proc. 34th Int. Cosmic Ray Conf., The Hague, Netherlands, 2015*, p. 331.
71. IceCube Collab., Pierre Auger Collab., and Telescope Array Collab., J. Cosmol. Astropart. Phys. **2016** (1), 037 (2016). doi 10.1088/1475-7516/2016/01/037
72. P. W. Gorham, J. Nam, A. Romero-Wolf, et al., Phys. Rev. Lett. **117**, 071101 (2016).
73. M. Ackermann et al., Astrophys. J. **799**, 86 (2015). doi 10.1088/0004-637X/799/1/86
74. O. E. Kalashev, D. V. Semikoz, and G. Sigl, Phys. Rev. D **79**, 063005 (2009). doi 10.1103/PhysRevD.79.063005
75. G. Gelmini, O. Kalashev, and D. Semikoz, J. Cosmol. Astropart. Phys. **2012** (1), 044 (2012). doi 10.1088/1475-7516/2012/01/044
76. E. Gavish and D. Eichler, Astrophys. J. **822**, 56 (2016).

77. R. Y. Liu, A. M. Taylor, X. Y. Wang, and F. A. Aharonian, Phys. Rev. D **94**, 043008 (2016).
78. R. Benson and J. Linsley, in *Proc. 17th Int. Cosmic Ray Conf., Paris, 1981*, Vol. 8, p. 145.
79. M. I. Panasyuk, M. Casolino, G. K. Garipov, et al., J. Phys.: Conf. Ser. **632**, 012097 (2015). doi 10.1088/1742-6596/632/1/012097
80. A. Haungs, J. Phys.: Conf. Ser. **632**, 012092 (2015). doi 10.1088/1742-6596/632/1/012092
81. J. H. Adams Jr., S. Ahmad, J.-N. Albert, et al., Exp. Astron. **40**, 19 (2015). doi 10.1007/s10686-014-9418-x
82. N. Sakaki, S. Ogio, F. Fenu, et al., in *Proc. 34th Int. Cosmic Ray Conf., The Hague, Netherlands, 2015*, p. 647.
83. J. H. Adams Jr., S. Ahmad, J.-N. Albert, et al., Astropart. Phys. **44**, 76 (2013). doi 10.1016/j.astropartphys.2013.01.008
84. D. Semikoz, P. Tinyakov, and M. Zotov, Phys. Rev. D **93**, 103005 (2016).
85. P. Allison, J. Auffenberg, R. Bard, et al., Astropart. Phys. **35**, 457 (2012). doi 10.1016/j.astropartphys.2011.11.010
86. A. Porcelli, in *Proc. 34th Int. Cosmic Ray Conf., The Hague, Netherlands, 2015*, p. 420.
87. W. Hanlon and D. Ikeda, in *Proc. 34th Int. Cosmic Ray Conf., The Hague, Netherlands, 2015*, p. 362.

Translated by E. Smirnova