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УДК 524.1: 539.12

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The energy spectrum of cosmic rays extends to beyond 10^{20} eV, i.e., to energies higher by eight orders of magnitude than the highest energies attained so far at terrestrial particle accelerators. The origin of these particles remains unknown: neither their sources, nor the underlying physical processes of emission and acceleration of them have been identified. Although many models of cosmic ray origin have been proposed, a conclusive verification of them has not been possible so far due to limited statistics of available experimental data on the cosmic ray energy spectrum and composition at the highest energies. The current experimental data are reviewed in this paper. Prospects to gather sufficiently large statistics in the near future, especially from the Pierre Auger Observatory, are discussed.

Измеренные энергии космических лучей достигают значений 10^{20} эВ и более, что примерно на восемь порядков превышает максимальные энергии современных ускорителей элементарных частиц. Происхождение частиц, вызывающих космические лучи таких высоких энергий, остается до сих пор загадкой. Неизвестно их происхождение, не поняты ключевые физические процессы их испускания и ускорения. Хотя уже было предложено немало моделей происхождения космических лучей, тем не менее до получения окончательного решения этой проблемы еще далеко, поскольку имеющиеся экспериментальные данные о составе и спектре космических лучей экстремально высоких энергий очень скудные. В данной статье дается обзор современных экспериментальных данных и обсуждаются перспективы набора достаточно большого числа событий в космических лучах экстремально высоких энергий, в частности, в эксперименте «Обсерватория Пьера Оже».

INTRODUCTION

The energy spectrum of cosmic rays extends over about 14 orders of magnitude, from nonrelativistic energies (order of 10^7 eV) to beyond 10^{20} eV. The highest energy of a cosmic ray recorded so far was 320 EeV $= 3.2 \cdot 10^{20}$ eV, i.e., about 50 J. This is a macroscopic energy, for example, the kinetic energy of a tennis ball moving at a velocity of more than 100 km/h. For a cosmic ray particle, it is a truly enormous energy: more than eight orders of magnitude higher than energies attained so far in terrestrial particle accelerators. The highest energy cosmic rays are the most energetic particles known. In the following, the «ultrahigh energy cosmic rays» (UHECR) will denote those particles with energies above 10 EeV $= 10^{19}$ eV.

Cosmic rays were discovered more than 90 years ago, yet explaining their origin continues to be one of the most interesting problems in astrophysics. It is known that most of cosmic rays originate from the sources within our galaxy. The low energy range of the cosmic ray spectrum is dominated by the Sun and processes in the heliosphere. At higher energies, galactic sources of cosmic rays prevail and there is a general consensus that the main source of cosmic rays in the range below 10^{15} eV are the supernova remnants in the galaxy, with the diffusive shock acceleration being the dominant process. Sources of particles with still higher energy are less certain, but they are expected to predominantly lay in the galaxy, since the galactic magnetic fields are sufficiently strong to confine these particles. Only at energies above about 10^{18} eV the proton gyroradius (i.e., the radius of curvature of its path) in regular large-scale galactic magnetic fields becomes larger than the radius of the galaxy, so there is no possibility to confine such cosmic rays in the galaxy. Thus the highest energy particles are likely to come from sources beyond the Milky Way. However, both the astrophysical sources and the physical processes responsible for emission of particles with so high energies remain so far unknown.

The differential spectrum of cosmic rays is shown in Fig. 1. This is a power law dependence $dN(E) \sim E^{-\gamma}dE$, with $\gamma \approx 2.7$ below the «knee» around 10^{15} eV and $\gamma \approx 3.1$ above the knee, up to energies about 10^{18} eV. A flattening of the spectrum above the «ankle» at $\sim 10^{19}$ eV ($\gamma \approx 2$) may suggest emergence of a new, presumably extragalactic component of the cosmic ray flux. The integrated cosmic ray intensity, i.e., numbers of particles above a given energy, falls steeply with energy. While at low energies the cosmic rays are abundant and can be studied with relatively small detectors, at energies above 1 EeV (10^{18} eV) the flux is merely 1 particle/km^2/y, dropping to about 1 particle/km^2/century at the highest energies known. The only way currently available to detect cosmic rays at these highest energies is to let them interact with air nuclei and initiate extensive air showers (EAS). These showers can then be detected by appropriate detector systems on the ground. In order to compensate for the small flux, very large detector areas and long exposure times are needed. The low statistics of events at the highest energies, that can be collected with existing detectors, is the main difficulty in UHECR study.

The ultrahigh energy cosmic rays are a subject of intense studies. There are excellent reviews of the subject — see, for example, [1–5]. The reader is referred to them for detailed discussion of various aspects of cosmic-ray studies. In this paper, a review of current experimental status is given.

1. QUEST FOR ORIGIN OF UHECR

Soon after the discovery of the cosmic microwave background, Greisen [6] and Zatsepin and Kuz'min [7] pointed out that the ultrahigh energy cosmic rays cannot propagate freely in the Universe due to interactions with the cosmic mi-

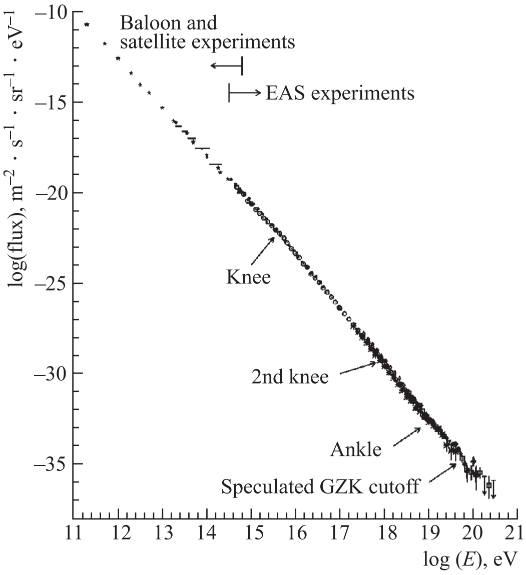

Fig. 1. Energy spectrum of cosmic rays compiled from results of various experiments. The energy ranges of direct measurements (on balloons and satellites) and indirect ones (extensive air shower detection) are shown [2]

crowave background radiation. At energies above about 50 EeV the centre-of-mass energy available in the proton–photon system reaches the threshold for production of a pion. Thus, above the threshold energy protons produce secondary pions through the process $p\gamma \to p\pi^0$ or $p\gamma \to n\pi^+$. A series of such reactions results in considerable reduction of the proton energy. This is demonstrated in Fig. 2 showing the reduction of proton energy during propagation: even if there exist sources capable of emitting particles with energies much higher than 100 EeV, after traveling a distance less than 100 Mpc these particles shall have their energies reduced to below 100 EeV. Heavier nuclei, if present among UHECR, undergo fragmentation due to interactions with photons of the microwave background, so that their range is also very limited, although at a somewhat higher energy [9]. As a consequence, the flux of protons with energies above the photoproduction threshold diminishes very quickly with the distance traveled. This effect is called the Greisen–Zatsepin–Kuz'min (GZK) cutoff. Therefore, if the sources of cosmic rays are distributed uniformly in the Universe, only nearby sources (if they exist) can efficiently contribute to the cosmic ray spectrum above the GZK threshold energy. From distant sources, the energy spectrum should be strongly suppressed above some 50 EeV. Conversely, if particles are observed with energies above the GZK cutoff, their sources must be located at distances smaller than several tens Mpc. We note that the distance of 100 Mpc is a rather small one in the cosmological scale: the possible cosmic ray sources would have to be located mainly within the local Supercluster of galaxies, which is centred at the Virgo cluster.

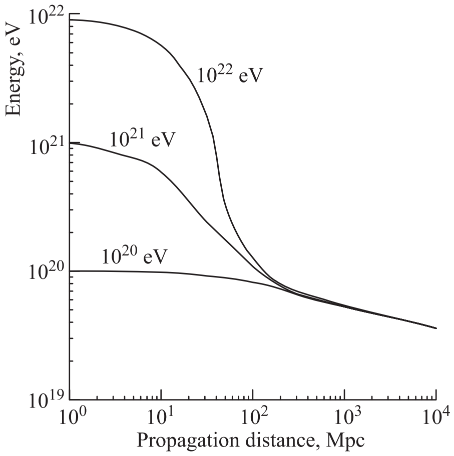

Fig. 2. Dependence of energy of a proton as a function of distance traveled, for different initial energies [8]

The available experimental data collected until now are too scarce to allow identification of sources of UHECR. As pointed out above, the main difficulty is the small cosmic ray flux: above 100 EeV it is only about 1 particle/km^2/century. Less than 20 events with cosmic ray energies exceeding 100 EeV were detected so far in several detectors: Volcano Ranch [10], Haverah Park [11], Yakutsk [12], Fly's Eye [13], HiRes [14], and AGASA [15]. On the basis of these data, it is even impossible to tell whether the GZK cutoff exists in the cosmic ray energy spectrum.

The distribution of arrival directions of UHECR is also very intriguing. At low energies, the gyroradii of cosmic rays in the galactic magnetic fields (with strengths in the microgauss scale) are much smaller than thickness of the galactic disk, so the cosmic rays are confined within the galactic disk by these fields. Propagation of low energy cosmic rays in the galaxy therefore resembles a diffusion more than a rectilinear or «ballistic» movement. In consequence, the arrival direction of a cosmic ray particle at the Earth has no relation to location of its source. This situation changes drastically at ultra high energies. The radii of curvature of particle trajectories become comparable to, or larger than the size of the galaxy, so not only the particles are not confined by the magnetic fields in the galaxy, but they are expected to propagate almost freely in intergalactic magnetic fields. Especially cosmic rays at extremely high energies, above 100 EeV, should propagate almost rectilinearly in the intergalactic magnetic fields which have strengths in the nanogauss range.

If the UHECR sources are located at distances less than 100 Mpc, then intergalactic magnetic fields can deflect the cosmic ray particles by only a small angle, of an order of several degrees. If so, the arrival direction of cosmic rays at extreme energies should point back to their sources, so that the identification of these sources should be easy. However, this pointing back does not work. The arrival directions of cosmic rays recorded so far are distributed more or less uniformly on the sky and even directions of the most energetic cosmic rays recorded by the Fly's Eye [16] and AGASA [17] do not point back to known, nearby objects which might be sources of these particles [18]. In the UHECR region, no large-scale anisotropy of arrival directions is visible. Only at lower energy, about 1 EeV, an anisotropy was reported by AGASA [19] correlated with the galaxy. Thus, both the sources of UHECR and the underlying process responsible for emission of particles with such enormous energies remain unknown.

A large number of theoretical models of UHECR origin have been proposed. They can be grouped into two broad classes which are discussed briefly below.

1.1. Acceleration Models (Bottom-Up Scenario). In a classical approach, one assumes that cosmic rays acquire their energies through being accelerated at some astrophysical objects (to be identified), via some acceleration process (not identified yet either). It is commonly accepted that the diffusive shock acceleration is an efficient acceleration mechanism in supernova remnants and it is generally assumed that this process, in different sources, can be effective also in accelerating particles to ultra high energies. However, the «cosmic zevatrons», i.e., objects capable of accelerating particles to ~ 1 ZeV ($= 10^{21}$ eV) are not easy to find. It was first pointed out by Hillas [20] that a dimensional analysis leads to excluding most astrophysical objects known from possible candidates. This is illustrated in Fig. 3. The maximum energy obtainable in the shock acceleration

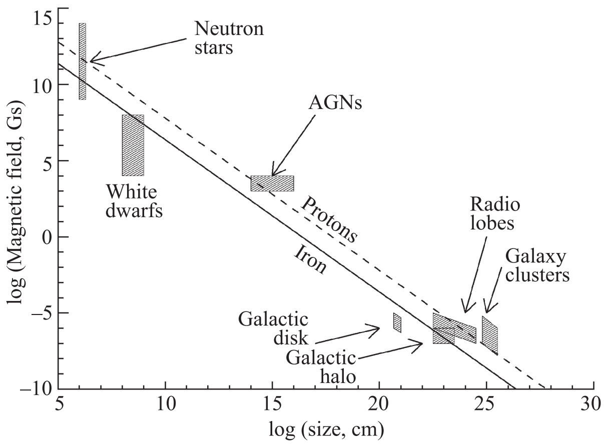

Fig. 3. Candidate astrophysical objects for proton acceleration above 100 EeV, classified according to their sizes and magnetic field strengths [4]

process is [21] $E_{\max} = \beta ZBL$, where β is the shock speed, Z is the charge of particles being accelerated, B is the magnetic field strength and L is the size of the acceleration region. A necessary condition for acceleration via the Fermi process is that the particle trajectory must be fully contained by magnetic fields within the acceleration region. Thus the candidate acceleration sites must have either strong magnetic fields or large sizes so that their product has some minimum value. In Fig. 3, in order to be a candidate for acceleration to energies above 100 EeV, an astrophysical object must lay above the diagonal lines. In addition, the magnetic field strength must be small enough so that synchrotron radiation losses do not prevail over the energy gain during acceleration. Similarly, density of matter and photons in the acceleration region must be not too large so that energy losses in inelastic collisions do not neutralize the acceleration process. There are only few objects fulfilling these conditions: pulsars, active galactic nuclei, radio galaxy hot spots, galaxy clusters.

The most commonly discussed acceleration models are shortly presented below.

Acceleration in radio galaxies and galaxy clusters [22]. The most promising candidates are radio lobes of strong radio galaxies [23]. Although there is much uncertainty in the strengths of magnetic fields and sizes of the acceleration regions, the radio galaxies seem to be able to accelerate particles to beyond 100 EeV through the first order Fermi process. Clusters of galaxies are also promising candidates, as they provide large-size shocks needed for acceleration. If the *nearby* radio galaxies are to be the UHECR sources to avoid the GZK cutoff, the apparent lack of correlation with UHECR arrival directions is a problem. In order to isotropize the arrival directions at the Earth to get agreement with the data, the intergalactic magnetic fields would have to be much stronger than currently estimated. Acceleration by relativistic shocks, like those in active galactic nuclei or microquasars in our galaxy is also a possible mechanism able to yield UHECR.

Acceleration in catastrophic events, e.g., in ultrarelativistic shocks associated with gamma-ray bursts (GRB). It was suggested [24] that the sources of gamma-ray bursts should provide conditions necessary for acceleration of particles to ultrahigh energies. If the amount of energy transferred to cosmic rays were equal to energy emitted in gamma-rays, the GRB sources could account for the observed flux of cosmic rays. Although there are a few problems with this scenario (e.g., the distances to GRB sources), it is being explored.

Strong electromagnetic fields associated with accretion disks or with compact rotating objects. Pulsars may be able to accelerate particles to EeV energies [25]. The rotating strong magnetic field of the pulsar induces electric fields sufficiently strong to enable acceleration to 100 EeV energies in «one shot», so this process is different from the diffusive shock acceleration process. Especially promising are pulsars with extremely strong magnetic fields, called magnetars [26]. The relativistic wind of a newly created magnetar should be able to accelerate cosmic rays to ZeV energies. It has been argued that galactic sources like pulsars can be ruled out because they should lead to a clear anisotropy above 10 EeV, which is not observed. However, if magnetars emit heavy nuclei, the galactic magnetic field might, at least partially, isotropize the arrival directions. Moreover, magnetars located in other galaxies might emit protons as well and still be perfectly consistent with the observed isotropy (although the problem of pointing back to the source remains). Thus, magnetars seem to be viable candidates for the UHECR accelerators.

The candidate acceleration sites, seen from the Earth, have very small angular sizes. If some of them are located relatively nearby and emit ultrahigh energy cosmic rays, the arrival directions of these cosmic rays should cluster on the sky, scattered around the location of their sources. These objects would be called «point sources» of cosmic rays. The spread of the arrival directions around the point source should depend on particle energies and magnetic fields traversed. Once the point sources are identified, the distribution of cosmic ray arrival directions from this source will provide a new way to study intergalactic magnetic fields.

1.2. Top-Down Scenarios. A very different class of models of UHECR origin are those in which cosmic rays are emitted as decay products of some supermassive exotic «X» particles. The idea is that relics of the very early Universe, like topological defects, can decay at the present time and produce the X particles with masses of the order of Grand Unified Theories (GUT) scale of $\sim 10^{24}$ eV. Other possibility might be that the X particles themselves are metastable relics of the early Universe. A comprehensive review of these models is given in [3]. The X particles should decay into quarks and leptons. The quarks would subsequently hadronize, so that «ordinary» particles with energies in excess of 100 EeV would be a natural consequence of these processes. This is the so-called «top-down scenario», in which no particle acceleration is involved. It is important to stress that in this scheme generally no correlation should be expected between cosmic-ray arrival directions and location of visible astronomical objects, so that the top-down scenario is an attractive possibility if no astrophysical model can explain the origin of UHECR. Among the most intensely discussed models are:

Topological defects are localized regions in which extremely high densities of energy are retained from the early Universe [27]. These defects, such as cosmic strings, monopoles, domain walls, etc., are supposed to have a small probability to annihilate or decay, emitting the X particles with mass $M > 10^{23}$ eV, of the order of the GUT scale. The X particles are supposed to decay into leptons and quarks, and the quarks subsequently undergo the QCD fragmentation, mostly into pions which, in turn, decay further into photons, electrons and neutrinos. Thus, among the end products of this series of decays, photons and neutrinos should be most numerous, with relatively few baryons. The energies of cosmic ray particles created in this way should extend up to the X particle mass.

Z bursts are supposed to result from resonance production of Z bosons in collisions of extremely high energy ($E > 10$ ZeV) neutrinos with 1.9 K cosmic relic neutrinos [28] (assuming at least one neutrino species has nonzero mass). This effect, although analogous to the GZK effect, occurs at much higher energies of neutrinos. The Z bosons would subsequently produce fragmentation jets, in which neutrinos and photons would dominate, but would contain also hadrons. The extremely-high-energy neutrinos might arrive even from large cosmological distances and interact within the GZK distance around the Earth. The nucleons produced in this way would easily reach the Earth, so that the GZK suppression of hadrons would be avoided. Since it is difficult to find a conventional process to produce 10 ZeV neutrinos, the most plausible scheme is that these neutrinos result from a top-down process. There are difficulties, however, to reconcile this scheme with the observed energy flux in lower energy photons.

There was a suggestion that *ultraheavy dark matter particles* which were produced in the early Universe, are the cosmic ray sources [29]. They are supposed to have long lifetimes, larger than the age of the Universe. These particles might constitute a dark matter halo of the galaxy. Their decays would produce UHECR which are not attenuated by the GZK mechanism and would be consistent with the apparent isotropy of the arrival directions.

1.3. Other New Physics Scenarios. There are also models which might be named «hybrid», since they incorporate new ideas beyond the standard model, applying them to the bottom-up scenario. In these schemes the particles which propagate from zevatrons toward the Earth are those immune to the GZK effect, so that the spectrum cutoff is avoided, or even the cutoff is not expected at all. Among the most popular models of this kind are:

Large neutrino cross section. Neutrinos are immune to the GZK process, so they can travel unimpeded through the Universe. Since the neutrino–nucleon interaction cross section increases with energy, at the extreme energies it should reach the scale of cross section for hadronic interactions. Possible realizations of this scenario might involve composite models of neutrinos [30] or extra dimension models. In this scheme, neutrinos might arrive from cosmological distances and produce air showers similar to those initiated by hadronic primaries.

New particles. It was suggested [31] that new neutral particles, like supersymmetric hadrons with masses of a few GeV («uhecrons») might be the primaries of cosmic ray showers. They could provide pointing back to powerful, distant sources. These neutral particles are difficult to accelerate, so they would rather have to be produced as secondaries in interactions of still higher energy charged particles.

Magnetic monopoles might be the ultra high energy cosmic rays [32]. Monopoles could be easily accelerated to ultra high energies by the galactic magnetic fields. The difficulty is that the monopole should have a large mass, of an order of 10^9 GeV, and this is not easily reconciled with observed properties of air showers, which indicate ultrarelativistic primaries.

Lorentz invariance violation. There are suggestions [33] that Lorentz invariance might be broken weakly, so that the violation could not be discovered at accelerator experiments, but might manifest itself at ultrahigh energies. Even a tiny violation of Lorentz invariance (order of 10^{-23}) may eliminate the GZK cutoff [34]. If this would be the case, any particles, even nucleons, could arrive from large cosmological distances.

The different models of cosmic ray origin predict different shapes of energy spectrum. Also, the composition of UHECR varies much between the models. For example, the acceleration models predict hadronic composition, with nuclei up to iron present (or even dominating) among UHECR. The top-down models, on the contrary, predict copious emission of UHE photons and neutrinos, with no nuclei heavier than proton.

It is therefore clear that precise experimental determination of cosmic ray energy spectrum and composition is fundamentally important for explaining the cosmic ray origin. Again, the main difficulty is the low statistics of available data.

2. AVAILABLE DATA

In the ultrahigh energy region, the only method of cosmic ray detection available is to record extensive air showers initiated by the cosmic-ray particles. The flux of UHECR is too small to be recorded by small-size detectors that can be put on satellites or stratospheric balloons. Large detector systems on the ground are needed to record the (rare!) air showers, in order to compensate for the small flux.

Two detection techniques are currently used for ultrahigh energy air shower detection: an array of particle detectors on the ground and the fluorescence technique. The ground array samples the air shower in many points at the ground level, so that a lateral distribution of shower particles is determined. In addition, the electron and muon components are distinguished, shower front thickness and curvature can be measured, etc. The largest detector of this type has been the AGASA array [15] with the area of 100 km^2, which ceased operation in December 2003. Other detectors are Yakutsk [12] (still working), Haverah Park [11], Volcano Ranch [10], etc.

The fluorescence technique is based on optical detectors to record fluorescence light of nitrogen molecules in the air, induced by charged particles of the shower. This is a «calorimetric» technique, in which the longitudinal profile of shower development is determined. This technique was first applied in the Fly's Eye detector [13]; currently, the HiRes detector [14] (the successor of Fly's Eye) operates in Utah.

2.1. Energy Spectrum. The newest spectra obtained by different experiments were presented at the International Cosmic Ray Conference, Tsukuba (Japan) in August 2003 [35–37]. These spectra do not coincide with each other. The spectra from the two largest experiments, AGASA and HiRes, are compared in Fig. 4. A seemingly striking disagreement is seen. In the most interesting energy range, $E > 100$ EeV, AGASA has collected 11 events, while only 1.8 events are expected if the GZK cutoff is present in the spectrum [35]. The AGASA spectrum clearly shows no GZK cutoff (on the level of 4.5σ). On the other hand, the HiRes collaboration reports only 2 events above 100 EeV [36]. The spectrum is consistent with the cutoff and can be well fitted by the galactic-plus-extragalactic sources model of Ref. [38]. It is worth noting that in the energy range above 10^{20} eV the integrated aperture of the HiRes monocular detector is about 1.5 times larger than that of AGASA [39], so that 50% more events are expected above 100 EeV in the HiRes-1 spectrum than in the AGASA spectrum. Moreover, even in the energy range below 10 EeV, in which there are plenty of events collected in both detectors, the fluxes determined in both experiments differ by a factor of 2. In addition, the Yakutsk spectrum [37] shown in Fig. 5 differs from both AGASA and HiRes: at lower end the Yakutsk flux is larger than AGASA and HiRes, while only 1 event was recorded with energy above 100 EeV, so that the Yakutsk spectrum is consistent with the GZK cutoff.

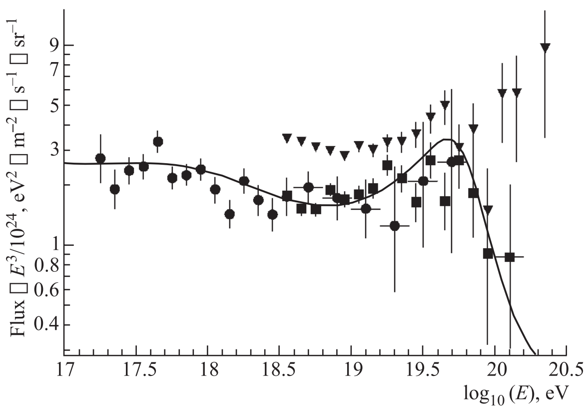

Fig. 4. Cosmic ray energy spectra determined in the AGASA and HiRes experiments [36]. The line shows predictions of the model [38] fitted to the HiRes spectrum. ● — HiRes-2 monocular; ■ — HiRes-1 monocular; ▼ — AGASA

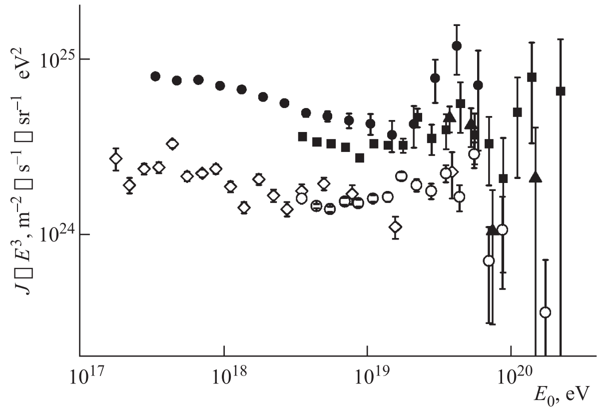

Fig. 5. Yakutsk spectrum of cosmic rays compared to AGASA and HiRes spectra [37]: ●, ▲ — Yakutsk (2003); ■ — AGASA (2001); ◇, ○ — HiRes-1,2 (2002)

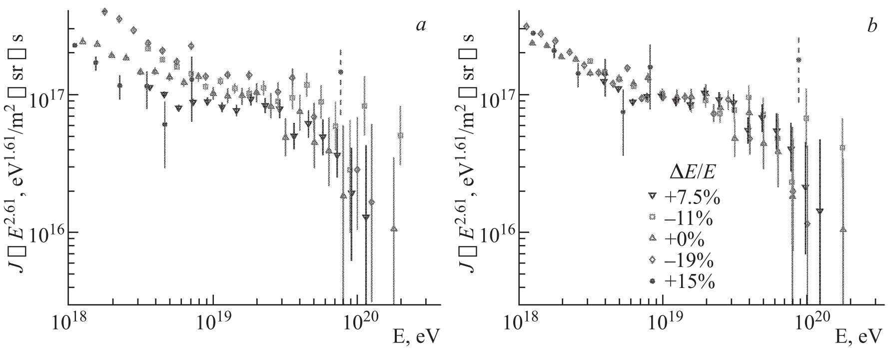

Fig. 6. Comparison of energy spectra from different experiments [40]. *a*) The spectra as published by AGASA (□), Fly's Eye (△), Haverah Park (●), HiRes (▽) and Yakutsk (◇). *b*) The same spectra after rescaling the energy calibration in the experiments to bring the spectra into agreement at 10 EeV

Among the possible causes of this discrepancy, the most important seems to be the uncertainty of energy determination. The AGASA and HiRes spectra can be reconciled if the relative energy calibration in these two experiments is changed by 30%. In fact, Bahcall and Waxman have shown on earlier data [40] that systematic shifts in energy applied to spectra determined in various experiments bring all the spectra to reasonable agreement. This is illustrated in Fig. 6. The problem is that the magnitude of the systematic shifts involved is somewhat arbitrary and not quite understood on the basis of analyses performed by the experimental teams, see, e.g., [41] and analyses of uncertainties in the apertures of the detectors. Nevertheless, it seems that the disagreement of the spectra below about 10 EeV is a matter of systematic errors in energy assignment, or in determination of the detector aperture.

In the ground array technique, the total energy of a shower is determined on the basis of measurement of the lateral distribution of particles in the shower. The standard procedure is to fit the lateral distribution function to the actual measurements done in the detector stations. The particle density at a fixed distance from the shower axis (typically the distance of 600 m is used) is directly proportional to the shower energy. Details of the procedure depend on the detector used. The effects which need calibrating and which are likely to contribute to systematic errors include: (i) the calibration of the detector response (gain, linearity, etc.); (ii) the determination of the lateral distribution function, in particular its dependence on shower inclination, and implicitly on the age of shower being recorded (one needs to keep in mind that the detectors are located at a fixed *vertical* atmospheric depth); (iii) the dependence of the energy conversion formula on the nuclear interaction model used to simulate the air showers. In case of AGASA, the total systematic error of energy determination was estimated at 18% [41].

Similarly, a number of effects may contribute to the systematic errors of energy determination in the fluorescence technique. The atmosphere serves as a calorimeter, so detailed understanding of its properties is of fundamental importance. The flux of light recorded by the detector is the measure of shower energy. Therefore, it is important to know in detail: (i) the fluorescence yield, i.e., the number of photons emitted per unit track length of a charged particle. The yield was measured in laboratory experiments, but it is still not well understood; (ii) the atmospheric effects, in particular extinction of light on the way towards the detector are very important corrections; (iii) knowledge of properties of the shower, in particular the portion of the primary particle energy which is not transferred to the electromagnetic shower, i.e., carried by neutrinos, muons and hadrons; (iv) the absolute calibration of the detector: optical properties of the detector (like mirror reflectivity, shadowing, etc.), efficiency of light recording elements, etc. The HiRes collaboration determined the overall systematic uncertainty in energy determination as 17% [42].

The question of existence of the GZK cutoff in the experimental spectra is far from being settled. De Marco et al. [43] have shown that after the AGASA and HiRes spectra are brought to agreement at low energies by an energy rescaling, the statistical significance of disagreement between them above the GZK energy is small, on the 2σ level.

An interesting question may be whether or not one really should expect the GZK cutoff. It was recently pointed out [44] that if intergalactic magnetic fields are considerably larger than known or commonly assumed, then distant sources will be unable to contribute to the observed cosmic ray flux not only in the trans-GZK energy region, but also at lower energies. Cosmic rays below the GZK threshold should get entangled by the intergalactic magnetic fields, will propagate in the diffusive regime and will not be able to travel over large cosmological distances. If so, the GZK cutoff might be absent with any distribution of sources. One has to note, however, that Faraday rotation measurements indicate small strengths of intergalactic magnetic fields, on the nanogauss scale, and that no suppression of the cosmic ray energy spectrum is observed in the sub-GZK region, so there is as yet no evidence to support the hypothesis of strong intergalactic magnetic fields. Thus, one has to conclude that the energy spectrum is not yet satisfactorily known and the very existence of the GZK cutoff is still an open issue.

2.2. Arrival Directions. The distribution of arrival directions of UHECR has long attracted attention of cosmic ray scientists. The AGASA collaboration published [45] an observation of a large scale angular anisotropy around 1 EeV, with a 4.5σ excess of cosmic rays arriving from the direction close to the galactic centre and a deficit from near the galactic anticentre. This observation was confirmed by the SUGAR data [46]. A similar galactic enhancement was found by Fly's Eye [47]. Naturally, such an excess can be interpreted as an indication of galactic origin of cosmic rays in the EeV range.

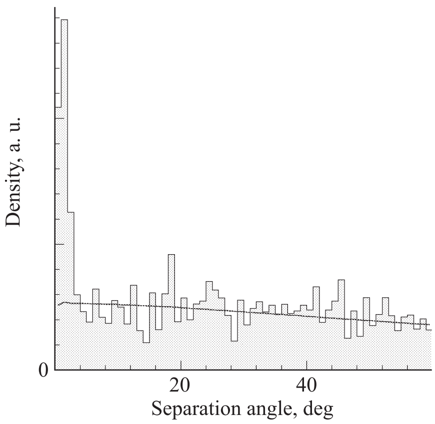

Fig. 7. Distribution of separation of arrival directions of cosmic rays above 40 EeV observed by AGASA (the histogram) and expected from an isotropic distribution (the line) [51]

The arrival directions of cosmic rays above the GZK energy are particularly interesting. As discussed above, these particles are expected to originate from extragalactic sources and the GZK effect limits the source distances to several tens Mpc, so that the arrival directions should, at least approximately, point to the sources. This, however, is not the case. A large scale anisotropy is not observed: the UHECR arrival directions are distributed almost uniformly on the sky. There have been reports, e.g., [48] on correlation with the supergalactic plane, but these results were not confirmed on a combined data set from several experiments [49].

On a small angular scale, however, a clustering of cosmic ray arrival directions was reported [50, 51]. AGASA looked for clusters of events with energies above 40 EeV and has found five doublets with angular separation of 2.5 deg and a triplet of events. The typical uncertainty of shower direction reconstruction in AGASA is 1.8° [50], so two independent showers coming from the same direction are expected to be found within 2.5° from each other. Figure 7 shows the distribution of 2-event separation angles, in which a clear excess of small separations is present. The chance probability of observing these clusters was found to be less than 10^{-4}. Since the clusters may indicate location of point sources, they have generated much interest in the cosmic ray community. There were many reports on possible correlation of the clusters with astrophysical sources of different kinds: see, e.g., [52] for a review.

On the other hand, the UHECR clusters are not seen by the HiRes experiment [53]. The HiRes-1 (monocular) data set has a larger statistics, but the shower reconstruction has a very asymmetric angular resolution: the shower axis is determined well in the direction perpendicular to the shower-detector plane, but much worse within this plane. The HiRes stereodata set has a much better angular resolution, below 1°, so it is much better suited to study small scale angular correlations. However, the data statistics is still small and as yet no clustering is seen.

An interesting study of clustering is found in a recent paper [54]. The authors analyze the directions of 72 AGASA events above 40 EeV: the initial 30 AGASA events are used as a basic set; the remaining 42 events serve as a new set of data to look for coincidences with events in the old set. Using the criteria applied by AGASA, they found in this new data set 2 new pairs of events, with 8% probability that these pairs occur by chance. Hence they conclude that there is no evidence for clustering and the data are consistent with the null hypothesis of isotropic distribution of the arrival direction. Moreover, a small increase of threshold energy (50 EeV instead of 40 EeV used by AGASA) drastically reduces the number of doublets [55]. Thus not only the interpretation, but even the significance of clustering is unclear at present.

2.3. Composition. Measuring the composition of UHECR, i.e., identification of particles arriving from space, is a very difficult task and generally cannot be done on event-by-event basis (i.e., individually for each event). Since the primary cosmic ray particle is not recorded in the detectors, its identity must be inferred from properties of an extensive air shower it initiates in the atmosphere. One has to rely heavily on modeling of shower properties to infer the primary particle mass on the basis of depth of shower maximum, muon contents in the shower, lateral particle distributions, etc. The conclusions on mass composition are difficult to make since different methods often give differing results.

The depth of shower maximum, $X_{\max}$, depends on energy per nucleon of the primary particle and increases with energy (the so-called elongation rate) in a different way for proton- and heavy nucleus-initiated showers. Modeling of shower development provides a template to be applied to experimental data in order to extract composition of primary cosmic rays. Several models of nuclear interactions are currently in use, like QGSJET [56], SIBYLL [57], DPMJET [58], etc. The details of particle production assumed in these models are somewhat different, so that the properties of air showers derived from these models are not the same and sometimes differ considerably. As a result, shower properties like muon content, lateral particle distribution or longitudinal shower profile depend on the model assumed. Figure 8 shows the experimental dependence of $X_{\max}$ on energy along with model simulations for proton and iron showers. The data indicate a composition change toward lighter nuclei as the energy increases in the UHE range [59, 60]. However, the conclusions depend again on model assumptions. This is illustrated in Fig. 8. It is clear that at the highest energies, a pure proton composition may be inferred using QGSJET01 model, or a mixed composition from the SIBYLL2.1 or DPMJET2.5 models.

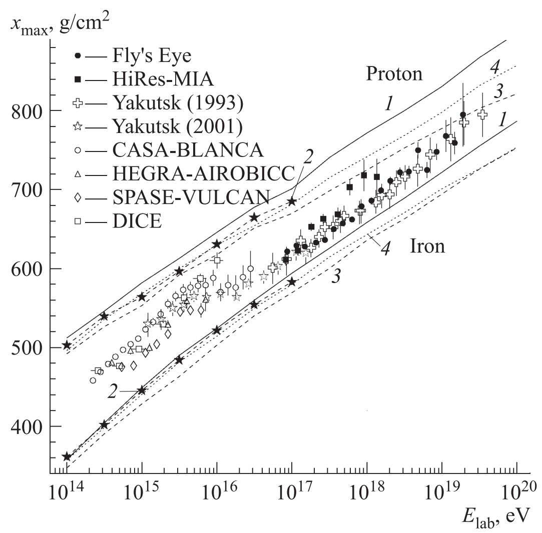

Fig. 8. Position of the shower maximum as a function of energy, determined in various experiments. The lines show predictions of several models for proton and iron primaries [60]: *1* — DPMJET 2.5; *2* — neXus2; *3* — QGSJET 01; *4* — SIBYLL 2.1

In the ground array technique, the muon content is the most important parameter for composition studies: more muons are expected in an iron-induced shower than in a proton event at the same energy. However, the fluctuations are large, and again, the muon component expected in a shower depends on the interaction model used. The AGASA results [61] are summarized in Fig. 9. It is evident that the fluctuations in muon density are large, especially when compared to the expected difference in predictions for proton, iron and photon primaries. Assuming that the cosmic rays are a proton-iron mixture, the AGASA collaboration determines the iron fraction as $14^{+16}_{-14}\%$ at 10 EeV and less than 66% at 30 EeV. The composition derived in this way depends on the model used [62].

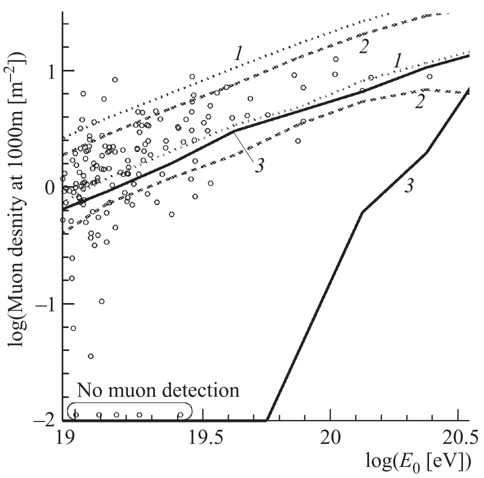

Fig. 9. Muon density versus energy in air showers recorded by AGASA [61]. The expected $\pm1\sigma$ bounds for iron (*1*), proton (*2*) and photon (*3*) primaries are indicated by the lines

The shape of lateral distribution of shower particles was used in reanalyses of old Haverah Park [63] and Volcano Ranch [64] data. Using the QGSJET01 interaction model, the authors deduce a 75% fraction of iron, as shown in Fig. 10. When using the older version of the model, QGSJET98 instead of QGSJET01, a higher limit of 88% iron fraction is derived [65]. These results contrast with the HiRes indication [66] of predominantly light primaries, especially when the QGSJET01 model is used.

The discrepancy of conclusions of different data analyses strongly suggests that the shower properties are generally not well understood and that there must be considerable shortcomings in shower modeling. One aspect of these shortcomings was shown in Fig. 8: predictions based on various models of hadronic interactions differ considerably. One has to keep in mind that properties of hadronic interactions at ultra high energies cannot be studied directly in accelerator experiments and have to be extrapolated from much lower energies. Also, understanding better the process of shower development at lower energies would considerably improve the extrapolation to ultra-high energies. One has to conclude that the accuracy of cosmic ray composition analyses accessible at present is insufficient to draw definite conclusions.

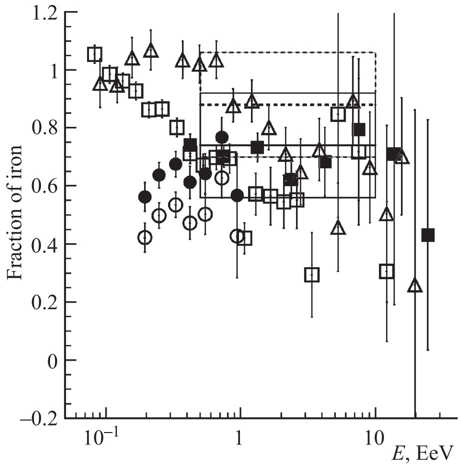

Fig. 10. Fraction of iron nuclei in the cosmic ray flux determined in various experiments: Fly's Eye (△), AGASA (□, ■), Haverah Park (○, ●) [64]. Mean composition (with its error) derived from the Volcano Ranch data using QGSJET01 is shown by the solid line rectangle; the same using QGSJET98 is shown by the dashed line rectangle

Efforts to determine the fraction of *photons* in UHECR are under way. The AGASA group, assuming a proton-photon mixture, derived an upper limit of 34% for the photon fraction at 10 EeV and 63% at 30 EeV, on the basis of muon distribution in air showers [61]. An analysis of Haverah Park data [63] shows that 10 EeV photons constitute less than 41% of the hadronic flux.

The highest energy event recorded so far, the 320 EeV Fly's Eye shower, was particularly carefully studied in the context of primary identification. An analysis of [67] indicated that the longitudinal profile of this shower was not compatible with a photonic primary. However, a recent study [68] of preshowering effect (photon conversion on the geomagnetic field) concluded that the hypothesis of a photon primary cannot be rejected.

Determining the photon flux in UHECR is very important for choosing the model of cosmic ray origin. As mentioned earlier, the top-down scenarios predict a large flux of UHE photons. The present data do not indicate the photon dominance. However, the UHE photon flux is expected to be strongly modified by interactions with the microwave background (an effect similar to the GZK effect for hadrons), so the UHE photons may be rare in cosmic rays. On the other hand, UHE neutrinos, if found, would provide a complementary supportive evidence for the top-down models.

3. SUMMARY AND OUTLOOK

The observed discrepancy between energy spectra measured by AGASA, Yakutsk, and HiRes indicates that systematic errors are present which are not yet completely understood. All these detectors are located at similar northern hemisphere latitudes, so they observe approximately the same region of the sky and the difference in spectra is unlikely to arise solely from difference in cosmic ray sources observed.

There are many systematic effects which may contribute to this spectral difference. For example, the calibration of the fluorescence yield, i.e., the number of photons emitted per unit length of a particle track, may be somewhat different from what was previously assumed [69]. Similarly, different shower simulation codes used to derive shower energy, particularly in the surface array technique, lead to slightly different energies [70]; the actual vertical profile of atmospheric density may differ considerably from the commonly used US Standard Atmosphere model [71]. There are many experimental details which still can be improved and efforts are under way worldwide to improve the detection techniques and to better understand the shower development process.

The arrival directions of UHECR continue to be a puzzle. Although there is an indication of an anisotropy towards the galactic centre, it is observed only at lower energies, around 1 EeV. Such an anisotropy is consistent with what one should expect for galactic origin of cosmic rays. At higher energy, above 10 EeV, no anisotropy is observed, but cosmic rays in this energy range are expected to be predominantly of extragalactic origin anyway. The arrival directions do not point back to apparent sources of cosmic rays. There is an indication for clustering of cosmic ray directions, so one might suspect we are starting to see point sources, even if they are not identified at the moment. This clustering, however, is not completely convincing. There are different views on its statistical significance, so that it would be premature to draw definite conclusions on point sources.

Determining the UHECR composition is the most difficult task. In both surface array and fluorescence techniques one has to rely on simulations of shower development to infer the type of primary particle. Different interaction models, and even different simulation codes with the same model give slightly differing predictions on various shower properties, which result in somewhat different composition of primary cosmic rays derived on the basis of these models. The data from both experimental techniques indicate a changing composition towards lighter nuclei with increasing energy, although the average mass of primary cosmic rays derived from the fluorescence technique is lighter than that from the surface arrays. No photons or neutrinos have been unambiguously identified as primary UHECR particles.

It is clear that the experimental data accumulated so far are not sufficient. Considerably more data are necessary for answering the questions discussed. The

AGASA detector has ceased operation at the end of year 2003; HiRes is expected to run for a few more years, but the data to come will not be enough either. The same is true with respect to the Yakutsk detector.

A large change in the experimental situation will occur when data from the Pierre Auger Observatory [72], now being constructed, become available. This Observatory will consist of two sites, one in the Southern hemisphere (in Argentina), the other in the Northern one (in USA). Each site will have an area of 3000 km^2, so that the total area will be 60 times larger than that of AGASA.

The key feature of the Auger Observatory is the concept of hybrid detection of air showers, by simultaneous use of a surface array of particle detectors and a fluorescence detector. Each of these detector systems will measure *different* properties of *the same* shower, so that a cross-calibration between these detectors will be possible. Thus the hybrid detection of air showers will enable unprecedented accuracy of primary particle identification. Although the primaries cannot be identified on an event-by-event basis, the cosmic ray composition will be measured better than ever before. In addition, the discrepancy in energy spectra of AGASA (surface array) and HiRes (fluorescence) will naturally be removed by the cross-calibration of the two detection techniques.

The surface array at each site of the Auger Observatory will consist of 1600 water tanks, each equipped with three photomultipliers to record Cherenkov light induced by shower particles in 12 m^3 of water contained in the tank. The detector stations are spaced 1.5 km apart, so that full efficiency of shower detection above 10^{19} eV is ensured. Single cosmic ray muons passing through the water tank provide a natural way for self-calibration of each tank in the field. The detector stations are powered by solar cells with batteries, and use the GPS system for time measurements. The communication with the central data acquisition system is done by radio.

The air above the surface array will be viewed by a total of 24 telescopes, grouped into 4 «eyes», to record fluorescence light induced by the showers in the air. Each telescope has a $30 \times 30°$ field of view, with aperture diameter of 2.2 m. The calibration system of this fluorescence detector includes the end-to-end calibration of the telescopes using a calibrated light source, as well as a number of ways to calibrate the atmospheric effects. These include laser beams, lidars, balloon sondes, movable calibration light sources, and cloud monitors.

When completed, the Pierre Auger Observatory will record annually 5000–10000 cosmic-ray events with energies above 10 EeV. The actual number of events depends on the true shape of the energy spectrum which is to be determined. The surface array will work continuously, while the fluorescence detector can work only during clear, moonless nights, i.e., about 10% of the time. However, these 10% of the «hybrid» events will be sufficient to fully cross-calibrate the two detector systems.

It is expected that the large statistics of events to be collected by the Auger Observatory will enable identification of air showers initiated by neutrinos (if neutrinos are present among UHECR). This will be possible through the study of showers at large zenith angles (the so-called «horizontal air showers»). The horizontal showers initiated by hadrons or photons develop high in the atmosphere, so that the electromagnetic component is mostly absorbed in the air before arriving to the detector: of the charged particles, only high-energy muons arrive to the detector. By studying the shape of the shower front, such showers will be easily recognized as «old showers», i.e., those which started far from the detector. On the contrary, neutrinos have small interaction cross section, so they have a (rather small) constant probability to interact anywhere in the atmosphere, also very deep, in the vicinity of the detector. The deep horizontal showers will be easily distinguishable from the old hadronic showers. Therefore, studying the horizontal showers provides an excellent opportunity to identify neutrinos among UHECR. In addition, the capability to record tau neutrino showers will be enhanced through upward going, «Earth-skimming» showers, i.e., those at zenith angles slightly larger than 90° [73]. The Auger Observatory is very well suited to detect horizontal showers: the water tanks 1.2 m high have the acceptance almost independent of the shower zenith angle, contrary to thin scintillator detectors used by AGASA.

The southern part of the Auger Observatory is now under construction in Argentina. At the time of writing (March 2004) Auger is already the largest air shower detector array in the world, with 250 surface detector stations operating. Although the southern site has not yet been completed, it already collects data with the existing portion of the detector system. Completion of the full southern site, which will consist of 1600 detector stations and 24 fluorescence telescopes, is expected at the end of year 2005; the northern Auger site is to be completed around year 2009. The two observatory sites, in the Northern and Southern hemispheres, will allow a detailed full sky survey for the study of anisotropy of arrival directions and identification of sources of UHECR, possibly located anywhere in the sky. For example, the galactic centre can be observed well from the Southern hemisphere, while the Virgo cluster is in the Northern hemisphere of the sky.

Another experiment which was recently approved is the Telescope Array [74], to be located in Utah, USA. Similar to Auger, the Telescope Array will be a hybrid detector with a ground array of scintillation detectors spaced 1.2 km apart, and 3 fluorescence «eyes» with fluorescence telescopes. The total area of the array will be about 9 times that of AGASA. An «infill» array, i.e., with smaller spacing between detector stations is forseen to enable detailed study of the spectra from 0.1 EeV to 100 EeV.

The next generation of experiments will be the fluorescence detectors put on satellites, like the Extreme Universe Space Observatory (EUSO) [75]. The proposed EUSO detector will be put on the International Space Station, with its cameras «looking» down to detect air showers in the atmosphere. Since the field of view will be large, $\pm 30^\circ$ corresponding to about 400 km diameter on the ground, EUSO will make another quantum leap in data statistics acquired. It is expected that considerably more than 1000 events per year will be collected above the threshold of $19^{19.5}$ eV (again, the actual number of events will depend on the true shape of the energy spectrum). Installation of EUSO is planned for year 2010. This experiment should be able to considerably extend the results of the Auger Observatory in the trans-GZK region.

Within the next several years one can expect a wealth of data which should lead to answering the question of whether or not the GZK feature exists in the cosmic ray spectrum. It should be noted that either answer will have profound implications. For example, observing point sources will support the astrophysical origin of UHECR, while the absence of GZK cutoff with lack of clustering of arrival directions may indicate that exotic scenarios play a role. Determining composition of UHECR is very important. In particular, identification of UHE photons and neutrinos may be an argument in favor of exotic models. One can conclude by saying that whatever the outcome, studying the ultra high energy cosmic rays in the nearest future is going to be a very exciting task, with large potential for discoveries in astrophysics and/or particle physics.

Acknowledgements. This work was supported in part by the Polish State Committee for Scientific Research under grants No. PBZ KBN 054/P03B/2001 and 2P03B 11024.

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