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Cosmic ray investigations

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Contents

Abstract. **The history of cosmic ray research at the Lebedev Institute beginning with the first work and continuing up to now is reviewed. The milestones and main avenues of research are outlined. Pioneering studies on the nuclear cascade process in extensive air showers, investigations of the Vavilov–Cherenkov radiation, and some work on the origin of cosmic rays are discussed. Recent data on ultrahigh-energy particle detection at the Pierre Auger Observatory and the High Resolution Fly's Eye (HiRes) experiments are presented.**

> *The earth's atmosphere is under the continuous bombardment of high-energy particles coming from outer space. These particles are the primary cosmic rays. As they penetrate into the atmosphere, primary cosmic rays lose energy and gradually disappear on colliding against the oxygen and nitrogen atoms of the air.... The primary cosmic radiation consists of protons, α-particles, and, to a smaller extent, heavier nuclei.*
>
> B Rossi *High-Energy Particles* [1]

1. Introduction

Researchers examine primary cosmic rays (PCRs), bombarding Earth from outer space, and the secondary rays produced by PCRs in the atmosphere as a result of their interactions with atomic nuclei in the air. Moreover, high-energy PCRs (up to 10^{20} eV), coming to Earth from outside of the Solar System and having a galactic (or extragalactic) origin (GCS), and solar cosmic rays (SCRs) of moderate energies ($\leqslant 10^{10}$ eV), related to the Sun's activity, are distinguished.

The spectrum of cosmic rays (CRs) spreads over 10 orders of magnitude in energy and obeys a power law. The intensity of cosmic rays sharply decreases with an increase in their energy. The particle flux over an area of 1 m^2 is one particle per second for the energy 10^{11} eV and one particle per year for the energy 10^{15} eV, but it is only one particle per year over an area of 1 km^2 for the energy 10^{19} eV. There exist peculiarities in the PCR spectrum (spectral breaks) for energies $\approx 3 \times 10^{15}$ and $\approx 10^{18}$ eV, and there is probably a cutoff (termination) of the spectrum at an energy $\approx 6 \times 10^{19}$eV. These features can be related to possible transitions from one class of CR sources to another, as well as to CR propagation processes in the interstellar medium.

Energies of CR particles significantly exceed particle energies obtained in modern accelerators. In Tevatron accelerator experiments, energies $\sim 10^{15}$ eV were observed, in Large Hadron Collider (LHC) experiments, energies $\sim 10^{17}$ eV will be achieved, while particles with energies greater than 10^{19} eV are present in CRs. For this reason, since the time of their discovery, there has been a nuclear-physical aspect to CR research — the investigation of characteristics of CR particle interactions with atomic nuclei in the air or with the substance of detectors. It was in CRs that many new particles (the muon, the neutron, the pion, etc.) have been discovered.

The energy density of cosmic rays, which is $W_{\text{CR}} \sim 10^{-12}\,\text{erg cm}^{-3}$, is comparable to the magnetic field energy density $W_B = B^2/8\pi$ and the kinetic energy density of mater $W_T = (3/2)\,k_{\text{B}}T$; here, B is the magnetic field strength (3×10^{-6} Gs), n is the gas number density ($\sim 1\ \text{cm}^{-3}$), k_{B} is the Boltzmann constant, and T is the temperature of the interstellar gas. From the very beginning of CR research, questions have been raised over their origin (in which objects and as a result of which processes they appear) and accelera-

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tion and propagation in the interstellar medium. The astrophysics of cosmic rays gives answers to these questions; its foundations were laid in the work of Ginzburg and Syrovatsky in the mid-fifties [2]. The CR astrophysics research is currently the main aspect in the setup of new experiments on cosmic rays.

For small energies, when the main contribution to the cosmic ray flux is made by particles of solar origin, the solar and heliospheric processes are essential. These processes determine time modulations of the galactic cosmic ray flux with energies up to 10^{11} eV and violent changes in SCRs during solar bursts. Investigations of these energy ranges are closely related to geophysics, magnetospheric physics, and the physics of plasma. There are recent studies indicating that SCRs affect Earth's climate change.

Therefore, investigations of cosmic rays appear to be closely related to various fields of modern physics: high-energy physics, astrophysics, the physics of low-temperature plasma, geophysics, meteorology, etc.

The history of cosmic ray research in Russia began 80 years ago with Skobeltsyn's first experiments with the Wilson cloud chamber in a magnetic field [3]. The first CR studies at the Lebedev Physical Institute (LPI) coincide with the founding of the institute: in 1934, the first high-mountain expedition to Elbrus took place, with the participation of I M Frank, P A Cherenkov, and N A Dobrotin. The Elbrus work was further expanded, and V I Veksler joined the team in 1937. On Elbrus, strongly ionizing particles as a part of cosmic rays, the transition effect of the soft component, and the first experiments on extensive air showers (EASs) originating in the atmosphere upon interaction of particles of primary cosmic radiation with atomic nuclei in the air were studied in detail. In the pre-WWII years, S N Vernov fulfilled an extensive program of high-altitude CR radiosonde investigations at various geomagnetic latitudes (Leningrad, Yerevan, and the equator). The analysis of the latitude dependence of CR fluxes demonstrated that most of their energy is carried by charged particles deviated by the magnetic field [4].

2. High-mountain research of extensive air showers

After being interrupted by WWII, the cosmic ray experiments were resumed in 1944. High-mountain expeditions to Pamir were commenced. Dobrotin played a major role in expanding the work. In 1946, a Chechekty Gorge station was constructed (3380 m above sea level) and a large-scale experimental program was started on shower formation processes by nuclear-active particles, laying the foundation for all further CR research in Russia. A new experimental technique was used and developed at Pamir: the use of various types of hodoscope devices and the Wilson chamber (in a magnetic field) combined with an ionization calorimeter.

In the course of the Pamir work of the late 1940s to early 1950s, the nuclear cascade process that allowed formulating new mechanisms of EAS development at high energies ($10^{12} - 10^{14}$ eV) were discovered and investigated by G T Zatsepin. The overall picture of hadron passage through a substance was clarified, and important characteristics of an elementary process of strong interactions at high energies were determined: the approximate constancy of the inelastic interaction cross section for a primary nucleon, the conservation by a primary nucleon of about half of its energy in an inelastic collision, the scaling behavior of pion birth cross sections in the fragmentation region, etc. were demonstrated [5]. Only after a quarter of a century were all these relationships confirmed by accelerator experiments. In the 1950s, a mathematical description of the nuclear cascade process was suggested and an effective method to solve the nuclear cascade equations, the method of consecutive generations, was developed [6].

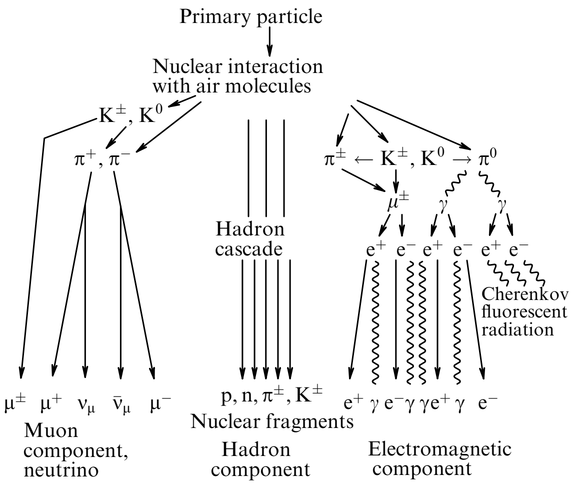

Figure 1. Development of the nuclear cascade process in the atmosphere.

Figure 1 shows the development scheme for a nuclear cascade process in the atmosphere. It presents the processes that occur in individual interactions of a primary particle with atomic nuclei in the air and repeat in secondary interactions of the hadron cascade particles. As a result, an electromagnetic component, a hadron component, muons and neutrinos, as well as Vavilov–Cherenkov radiation and fluorescent radiation appear. All these secondary components are distributed in the plane perpendicular to the direction of the primary particle propagation (the EAS front). The spatial distribution is related to the transverse momenta of secondary particles appearing in the interaction process, as well as to the multiple and single Coulomb scattering of charged particles. The nuclear physics aspect of cosmic ray physics is to recover the nuclear interaction on the basis of energetic, spatial, and temporal characteristics of the secondary cascade components.

In the 1950s, A E Chudakov (also an LPI researcher at that time) performed pioneering studies of the Cherenkov radiation of extensive air showers in Pamir. In 1955, an installation was constructed consisting of nine narrow-angle and nine wide-angle Cherenkov detectors and a set of gas-discharge counters to detect EASs [7]. The idea of a cascade energy measurement that is 'calorimetric for the whole atmosphere' was realized in this experiment by recording the Cherenkov radiation of the EAS; the relation between the cascade energy and the observed number of particles was also measured for the first time. That allowed determining the slope of the energy distribution within a wide energy range of the order $10^{14} - 10^{15}$ eV and estimating the mass composition of PCRs [8].

We note one more pioneering LPI-related work using the Cherenkov radiation of air showers based on Chudakov's proposal in the early 1960s to use Cherenkov radiation of EASs to detect CR sources. To search for local sources of gamma quanta with energies 10^{12} eV, the first Cherenkov gamma telescope was built in 1960–1963 in the Crimea, and consisted of 12 parabolic mirrors (each with the diameter 155 cm) assembled in groups of three mirrors on a common rotary device. The telescope had a large aperture ratio and could detect EASs caused by particles with energies greater than 2.5×10^{12} eV in a small solid angle ($\sim 10^{-3}$ sr). It was shown that even at such energies, a considerable flux of optical quanta (observed for a few dozen nanoseconds) can be detected in the atmosphere [9]. This experiment was ahead of its time and significantly affected the development of modern gamma astronomy. Only a decade later did telescopes with comparable parameters began to be constructed abroad. The developed technique predetermined advances in the observation of galactic and extragalactic objects.

Presently, the development of gamma astronomy at LPI is related to the SHALON experiment, which began in 1991–1992 in Tien-Shan. The mirror gamma telescope SHALON is currently the only one in Russia. In 1992–2008, observations of galactic and metagalactic gamma-quanta sources were made using the set of SHALON-1 and SHALON-2 telescopes [10, 11]. According to Refs [10, 11], the detailed analysis of the arrival directions of gamma showers reveals the presence of a new gamma-ray source whose coordinates coincide with those of the supernova SN 2006gy burst outside the Galaxy.

For the last 30 years, the EAS detection method based on Vavilov–Cherenkov radiation has been widely used in our country and abroad. Detectors of Cherenkov radiation were included in complex EAS installations in Tien-Shan and Yakutsk. In the early 1990s, in the Tunkin Valley (Buryatiya), the Tunka facility was constructed; it is now used to measure the mass composition of PCRs in the energy range $10^{15} - 10^{17}$ eV [12].

Another significant point must be noted. In the mid-1950s, when studying the Vavilov–Cherenkov radiation of EASs, the 'ionization luminescence' of EASs — the air luminescence by ionizing radiation — was observed. On the basis of an isotropy of the fluorescent light, Chudakov [13] (simultaneously with Japanese physicist K Suga [14]) suggested in 1962 using ionization luminescence at large distances ($\geqslant 10$ km) from the axis to monitor giant EASs with energies 10^{18} eV. Thus, the development of modern ground-based (for example, at the Pierre Auger Observatory [15]) and satellite (Extreme Universe Space Observatory — EUSO [16]) detectors of fluorescent light for the investigation of EASs of extremely high energies was anticipated.

EAS research was continued at the LPI Tien-Shan high-altitude scientific station (3340 m above sea level), which opened near Almaty (Alma-Ata) in 1960. There, the major complex facility was constructed to investigate the primary cosmic radiation (PCR) of ultrahigh energies ($10^{14} - 10^{17}$ eV), and a wide international collaboration with Bulgarian, Hungarian, Polish, and Czechoslovakian scientists was established. Work was organized in two areas. In the first one (1961–1970), studies of the characteristics of elementary processes of particle interactions at energies $10^{11} - 10^{12}$ eV by means of a Wilson chamber (in a magnetic field) combined with an ionization calorimeter were organized by S A Slavatinsky. As a result, asymmetric showers were observed [17]. In the second area (1967–1982, under the general supervision of S I Nikolsky), studies of PCR were organized using the complex installation to investigate EASs in the energy range $10^{12} - 10^{15}$ eV. The setup included the world's largest (36 m^2) ionization calorimeter (LIC) with a lead absorbent, a shower installation (scintillators and Geiger–Müller counters) with a dense central part, an underground ionization calorimeter to detect muon interactions, a muonic hodoscope, and a set of Cherenkov light detectors. By using the complex Tien-Shan installation, very important results were obtained: the mass composition of PCR in the energy range $10^{15} - 10^{16}$ eV [18] was determined; the CR energy spectrum was measured in the energy range $10^{13} - 10^{17}$ eV [19]; the distribution of full and partial (k_γ) inelasticity coefficients was obtained for interactions of protons with energies $10^{12} - 10^{13}$ eV with the nuclei of lead atoms [20]; the cross section of the interaction of protons with energies $10^{12} - 8 \times 10^{13}$ eV with atomic nuclei in the air was measured [21]; the birth of direct muons by high-energy EAS hadrons was investigated [22]; and long-flying cascades in the central part of the EAS hadronic core were investigated [23] (it was suggested that this component is formed by charmed particles appearing in interactions of the shower core hadrons in a calorimeter). In the mid-1980s, the 'Hadron' setup was constructed in which the LIC was substituted by an impact recording facility (162 m^2) with an X-ray emulsion chamber (XREC) above it. The 'Hadron' installation was used to investigate the properties of gamma-families compared with accompanying EASs [24].

In the early 1980s, the project design of an installation to study EASs on Aragats Mountain in Armenia was prepared at LPI in collaboration with researchers from the Yerevan Physical Institute [25]. LPI researchers directly participated in the setup construction, operation, and data analysis (the last of these still continues up to the present time).

By continuing the LPI traditions, a new comprehensive ATHLET (Almaty THree Level Experimental Technique) experiment has recently begun in Tien-Shan [26] with the use of three facilities to monitor EASs: Hadron-M, ISCR (Intermediate Station of Cosmic Rays), and KAZNU (Kazakhstan National University), located at the respective altitudes 3340 m, 1750 m, and 850 m above sea level. The core of the installation is Hadron-M, with an ionization neutron calorimeter (INCA), XREC, thunderstorm detectors, shower system, and underground detectors. The ATHLET experiment is designed to solve a wide range of problems in modern cosmic ray physics and astrophysics in the energy range $10^{13} - 10^{18}$ eV, high-energy gamma-astronomy ($\geqslant 2 \times 10^{14}$ eV), solar physics, and space weather, and to investigate processes of EAS development and accompanying phenomena in the atmosphere (radio-frequency radiation and correlation of EAS development with lightning [27]).

To summarize EAS experimental studies at high-mountain stations, we note that for the more than half a century of these experiments, a complex and fundamental approach to investigations, combined with a wide analysis, has always been maintained. Such an approach has allowed obtaining results of primary importance and laying the theoretical and observational foundations for further EAS research.

3. Emulsion experiments

We consider one more avenue of CR research that was initiated at LPI after WWII and is currently being actively explored — experiments with the use of nuclear emulsions. The emulsion allows distinguishing particles under a very high density of tracks and determining the coordinates of the primary particle interactions with high accuracy. It is by using nuclear emulsions in cosmic rays that new particles have been discovered. The first experiments with nuclear emulsions were set up in Pamir in the early 1950s. These investigations were further continued by G B Zhdanov and M I Tretiakova and relocated to accelerators. At LPI, the emulsion group worked effectively and became a world-renowned authority.

In the 1970s, stratospheric experiments using emulsion chambers were initiated by Dobrotin and Nikolsky. We note the major role of K A Kotelnikov, at that time the head of LPI's Volsky expeditionary base, in the organization of these experiments. For scientific research — to expose emulsion detectors at stratospheric heights ~ 30 km — a unique extensive line of automated balloon flights from the Kamchatka peninsula to the Volga river was tested and used [28]. In 1975, a unique (with the extremely high energy $\sim 10^{16}$ eV) gamma-hadron family STRANA (STRAtospheric hadron superfamily, recorded under the supervision of N A Dobrotin) [29], which is a result of the nuclear–electromagnetic cascade in the atmosphere, was registered in one such long-duration flight. Experimental observations and processing and the analysis of the events (with a variety of unusual characteristics) detected in the balloon flights of X-ray emulsion chambers allowed identifying a new phenomenon — the formation of ring structures in interactions. To interpret this phenomenon, a hypothesis of a nuclear analogue of the Vavilov–Cherenkov effect was proposed [30]. Recently, new processing of the STRANA family data has demonstrated the presence of large perpendicular momenta and coplanar particle scattering in the interactions forming this family [31]. In the 1990s, a Russian–Japanese balloon experiment, RUNJOB (RUssia–Nippon JOint Balloon), investigating the CR spectra and composition in the energy range $10^{13}-10^{15}$ eV, was conducted on the Kamchatka–Volga line with the LPI participation [32].

Nuclear emulsions are a unique investigation tool because of the high spatial resolution. But the emulsion processing has always been quite a labor-consuming procedure, hardly allowing automation. The situation changed significantly in the last decade when modern precision microscopes (with video capture and image processing systems) were used in emulsion processing. The scanning rate reached several dozen cm^2 per hour for such microscopes. For the first time in Russia, the transition to full automation of the photographic data analysis was done at LPI with PAVICOM (the Russian acronym for a fully automated measuring facility) [33]. With the use of this installation, more than ten experiments, including the EMU-15 and RUNJOB experiments, were analyzed. The high processing efficiency achieved allowed LPI researchers to participate in major international projects, for example, in the OPERA (Oscillation Project with Emulsion-Tracking Apparatus) experiment [34, 35] on direct observation of $\nu_\mu \to \nu_\tau$ neutrino oscillations. Currently, the problem of searching for tracks of heavy and superheavy nuclei in meteoritic olivine crystals (project OLIMPIYA, the Russian acronym for olivines from meteorites, the search for heavy and superheavy nuclei), which is fundamental for the physics of cosmic rays, is being solved at the initiative of Ginzburg with the use of the PAVICOM facility [36].

4. Studies of interactions of primary cosmic rays at energies $10^{14}-10^{17}$ eV using X-ray emulsion chambers

In 1971, LPI returned to Pamir. Near Murghab, in Ak-Arkhar gorge (4370 m above sea level), a large-scale emulsion experiment was launched with the aim to investigate PCR interactions at energies $10^{14}-10^{17}$ eV using the method of large X-ray emulsion chambers (supervised by Slavatinsky) [37]. This experiment used X-ray emulsions to detect particles appearing in nuclear interactions. The experimental program was continued until 1991, and the total exposure of the Pamir installations, which exceeded 9000 m^2 per year, was record high compared to exposures in similar experiments abroad. Every summer, the exposed X-ray films were taken out from the detectors and replaced by new ones. The films were developed and then processed to search for events — congenitally bound particle tracks resulting from of a nuclear-cascade shower development in the atmosphere. These events were named gamma–hadron families. In the Pamir experiment, their spatial energy characteristics, as well as the dependence of these characteristics on the total event energy directly related to the energy of the primary particle that caused the nuclear cascade shower, were investigated. The experimental processing, done in a semi-automated mode by using photometers, was quite labor-consuming. For this reason, the Pamir collaboration was established with the participation of physicists from seven Soviet and three Polish research institutes. Japanese physicists joined this collaboration in the 1980s.

Highly important and interesting results were obtained as an outcome of the Pamir experiment. The mass composition of primary cosmic radiation in the range of energies exceeding 10^{16} eV was estimated. It was shown that the scaling (independence of the shape of the inclusive spectra from the energy) is violated at high energies in the fragmentation energy region for secondary particles of the nuclear interaction; the cross section of formation of jets with large transverse momenta ($p_t > 1.5$ GeV$/s$) was estimated [38]. It was shown that the halo phenomenon — the formation of a diffuse spot ~ 1 cm^2 in size — can be explained without accounting for new processes [39]. Figure 2 shows a halo in the Fianit family.

In the Pamir experiment, the phenomenon of 'alignment' of the most energetic secondary particles along a straight line, related to coplanar particle scattering in the nuclear interac-

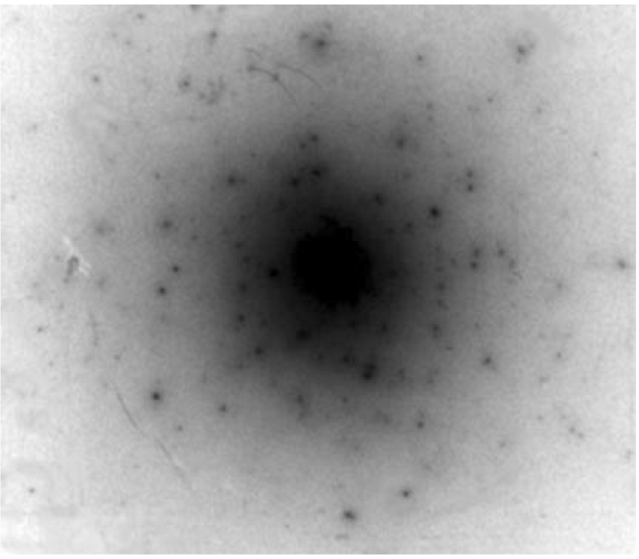

Figure 2. Photograph of a halo in the Fianit family [39].

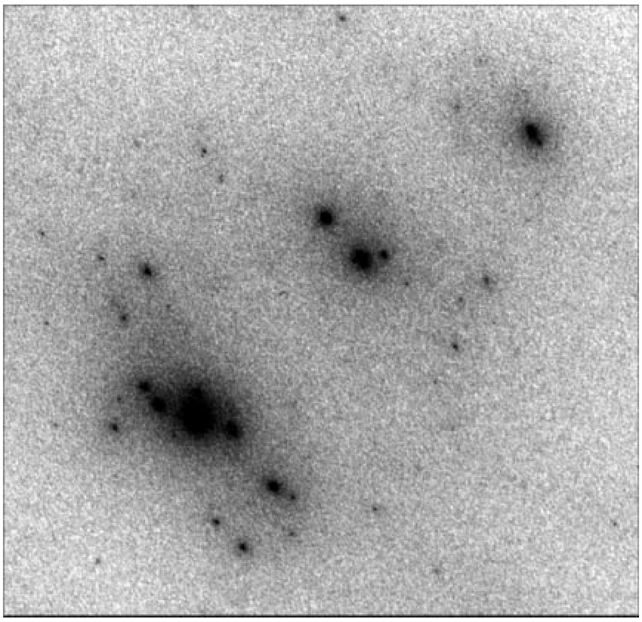

Figure 3. Photograph of the 'aligned' family [44].

tion process, was observed [40, 41]. Figure 3 shows a family where the alignment of energetically separated centers takes place. In the deep lead chamber experiment, the existence of a long-range component was observed in 1987 [42].

The results obtained in the Pamir experiment are widely discussed up to this day. Of special interest is alignment; to explain it, a number of hypotheses (including, in particular, the mechanism of quark–gluon string breaking [43] and the model of peripheral nuclear interaction [44]) were proposed. The Pamir experimental results are unique. The spatial resolution reached for this energy range and determined by the X-ray film capabilities was record breaking, as was the vast statistical material compiled in experiments at energies $\sim 10^{15}-10^{16}$ eV.

5. Cosmic ray research in the upper atmosphere and on spacecraft

The first measurements of cosmic rays in the stratosphere using rockets were made under the supervision of S N Vernov by researchers at the LPI Dolgoprudnyi station established in 1946. The aim of the research was to clarify the nature of cosmic rays and the mechanisms of their interaction with substances. Unique devices were developed, the electron–photon, muon, and nuclear-active components of cosmic rays in the stratosphere were studied, and the East–West asymmetry (corresponding to the positive charge of particles of the primary component) of primary cosmic ray fluxes in the geomagnetic equator area was reliably measured.

At the same time, studies were further expanded with the use of stratospheric sonde balloons at different latitudes. Since 1958, regular daily launches of sonde balloons have been conducted at a number of points on the territory of the former USSR and since 1963 in Antarctica. The unique data collected has allowed discovering giant events of CR intensity in the stratosphere after solar bursts, and clarifying the detailed pattern of the effect of 11- and 22-year solar activity cycles on cosmic rays arriving from the Galaxy. The monitoring of CR intensity at heights up to 30–35 km has allowed obtaining unique sets of experimental data on charged particle fluxes in the atmosphere at different latitudes (over the course of 5 solar activity cycles). Inversion effects of the general solar magnetic field in CRs were observed for the first time. Figure 4 shows the experimental data on charged-particle fluxes in the atmosphere at different latitudes [45]. For the series of studies on the investigation of the modulational effects of cosmic rays in the stratosphere, A N Charakhchyan, G A Bazilevskaya, J I Stozhkov, and T N Charakhchyan were awarded the Lenin Prize in 1976.

The most important component of the CR research program was related to satellite experiments and experiments on interplanetary space stations, which began in 1958. Already at the time of the first Soviet satellite launches, a major discovery was made: Earth's outer radiation belt was detected [46]; this detection was formally registered as a discovery. Vernov and Chudakov were awarded the Lenin Prize in 1962 for the discovery and investigation of Earth's radiation belts.

From 1958 to 1960, seven experiments set on five satellites and space rockets were conducted at LPI under the supervision of L V Kurnosova. The most noteworthy were the results on the radiation intensity distribution at heights 200–300 km, which led to "The detection of radiation anomalies over the southern part of the Atlantic Ocean at heights of 310–340 km" (subsequently, this result was registered as the discovery of "The phenomenon of sink of particles of Earth's radiation belts over negative planetary magnetic anomalies" [47]).

From 1964 to 1979, 12 devices to record cosmic rays and radiation in the near-Earth space, as well as three devices for methodological experiments (superconducting magnets for a magnetic spectrometer, onboard development of nuclear emulsions, etc.), were constructed at LPI and launched. In 1990–1991, the gamma telescope Gamma-1 aboard the international space station *Gamma* was launched, and solar gamma radiation with the energy greater than 1 GeV was detected for the first time by a telescope [48, 49]. The gamma telescope Gamma-400 is now engineered to detect gamma radiation in the energy range $(10^9-3\times10^{12})$ eV.

The first rocket experiments conducted by researchers from the LPI Dolgoprudnyi scientific station are now being continued by satellite studies in the international PAMELA (Payload for Antimatter–Matter Exploration and Light nuclei Astrophysics) experiment [50]. In 2006, the PAMELA setup was launched aboard the Resource-DK1 satellite. In this experiment, which is continuing to date, unique results have already been obtained. For the first time, the ratio of the antiproton flux to the proton flux in the energy range 10^9-10^{11} eV was measured with high accuracy [51]. The ratio of the positron flux to the combined electron and positron flux in the energy range 10^9-10^{11} eV was also measured for the first time. An increase in this ratio for particles with energies greater than 2×10^{10} eV was detected; this can point to the existence of new CR sources or new processes of positron formation in the interstellar medium [52].

6. The theory of cosmic rays

Advances in the experimental physics of cosmic rays at LPI have been closely related to theoretical works that were the basis for the interpretation of the results obtained; they

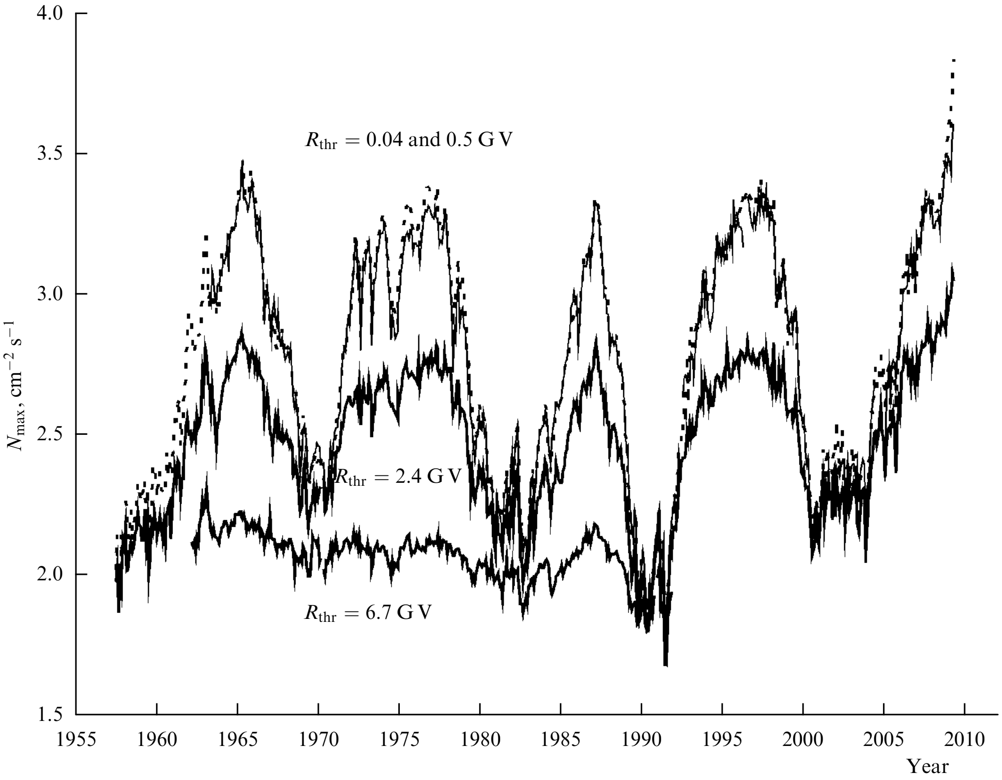

Figure 4. Sets of experimental data on charged particle fluxes in the atmosphere at different latitudes [45]. The dotted curve corresponds to the northern polar latitudes (Murmansk, from 1957; the threshold rigidity of the geomagnetic cutoff is $R_{\rm thr} = 0.5$ G V), the upper continuous curve is for Antarctica (Mirnyi, from 1963; $R_{\rm thr} = 0.04$ G V), the middle curve is for Dolgoprudnyi, Moscow region ($R_{\rm thr} = 2.4$ G V), and the lower cueve is for Almaty ($R_{\rm thr} = 6.7$ G V; the data end in 1992).

predicted the research directions and laid the foundations of the theory of cosmic rays.

In the 1940s–1960s, S Z Belen'ky, G T Zatsepin, I L Rosental, and others developed the theory of high-energy particle passage through matter. The monograph *Avalanche-type Processes in Cosmic Rays*, published by Belenky in 1948 [53], is still the classic textbook on the basic development patterns of electron–photon cascades.

In the 1960s, Rosental first demonstrated the possibility of cascade occurrence initiated by cosmic rays in the interstellar medium [54]. The conclusion concerning the influence of photon fields was made by Rosental before the discovery of the cosmic background radiation.

Finally, we note the development of the theory of the origin of CRs, which laid the foundation for a new field, the astrophysics of cosmic rays. In 1951, a relation was established between the characteristics of the electron component of cosmic rays and the magneto-bremsstrahlung intensity caused by CRs in galactic magnetic fields [55, 56]. Progress in the theory of the origin of cosmic rays was achieved by extensively using astrophysical (in particular, radio-astronomical) data combined with studies of primary CRs near Earth. In the works by Ginzburg and Syrovatskii published in 1951–1963, the hypothesis that galactic CR sources are supernova and probably nova stars was substantiated. Mechanisms of radio emission were considered, a relation between characteristics of the electron CR component and the magneto-bremsstrahlung intensity was established, and an equation describing particle propagation in the interstellar medium, called the Ginzburg–Syrovatskii equation, was proposed [57–60].

7. The cutoff at ultrahigh energies in the spectrum of cosmic rays

In the mid-1960s, Zatsepin and Kuzmin predicted the effect called the Greisen–Zatsepin-Kuzmin effect (GZK effect) [61]. The work by Greisen [62] was published at the same time. It was shown that for cosmic rays of metagalactic origin, the energy spectrum is cut off at ultrahigh energies above 3×10^{19} eV due to the interaction of CRs with the microwave ($T \approx 3$ K) radiation of the Universe. Since then, any consideration of the origin of ultrahigh-energy CR has always taken the GZK effect into account. The theory in [61, 62] strictly limits the existence time of cosmic rays at ultrahigh energies ($> 10^{19}$ eV) in the Universe, which is important for the identification of CR sources.

The prediction of the GZK effect stimulated the construction of giant installations to study CRs of ultrahigh energies. With the direct participation of LPI researchers, a comprehensive setup, where measurements still proceed up to this day [63, 64], was constructed in 1970 near Yakutsk. The distinctive feature of this installation is its major size (≈ 20 km^2); the energy was estimated via the widely used method of optical Cherenkov radiation accompanying EASs. In 1982, D V Skobeltsyn, N N Yefimov, D D Krasilnikov, S I Nikolsky, and G B Khristiansen were awarded the Lenin Prize for their investigations of ultrahigh-energy primary space radiation, including, in particular, the use of the Yakut EAS installation.

Investigations using scintillation counters were conducted in Japan in 1991–2003 in the AGASA (Akeno Giant Air Shower Array) experiment [65]. In the USA, facilities using the fluorescent light technique, Fly's Eye [66, 67] and HiRes

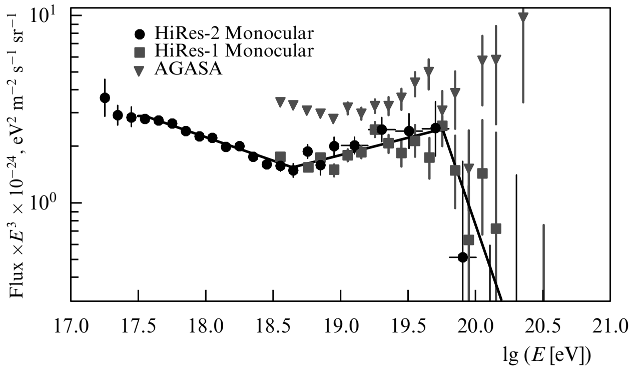

Figure 5. The spectrum of cosmic rays [70] measured by the AGASA [65] and HiRes [68-70] experiments. The spectra of HiRes-1 and HiRes-2 monocular experiments are given separately.

(High Resolution Fly's Eye) [68–70], were constructed. Figure 5 shows results of the AGASA and HiRes experiments, which do not correspond to each other. In the HiRes experiment, two breaks in the energy distribution are observed. These breaks, according to Ref. [70], correspond to two characteristic features of the CR spectrum: an ankle and the GZK cutoff. The statistical significance of the GZK effect is 5σ. The cutoff energy is $(5.6 \pm 0.5 \pm 0.9) \times 10^{19}$ eV.

In 2004, studies of primary radiation of ultrahigh energies began in a complex experiment at the Pierre Auger Observatory in Argentina [15]. About 100 institutes and universities from 17 countries are participating in this experiment. Four detectors observe EAS fluorescent light and 1660 ground-based detectors measure the Cherenkov light generated in water detectors by EAS charged particles. The facility is located at the altitude of 1390 m above sea level (875 g cm^{-2}) and occupies a record large area (about 3000 km^2).

Figure 6 shows the results in Ref. [71] on shower intensity measurements in the GZK cutoff range. As can be seen from this figure, the Pierre Auger Observatory data and the HiRes data agree (within the statistics limits) at the highest energies, demonstrating a flux reduction at the energies higher than 4×10^{19} eV. For energies smaller than 4×10^{19} eV, the HiRes-1 experiment shows a softer spectrum. The AGASA data are not presented because the authors of Ref. [71] conclude that they changed based on Ref. [72]. The hypothesis that the CR spectrum continues with the same slope for energies exceeding 4×10^{19} eV is rejected with a 6σ reliability. It was suggested in Ref. [73] that sources of CRs with energies greater than 5.7×10^{19} eV are extragalactic at distances less than 75 Mps. The authors of Ref. [71] believe that the results obtained do not contradict the GZK effect. Full understanding of the reasons for the steepening of the CR spectrum, according to Ref. [71], will be achieved after the mass composition of extremely high-energy particles is determined and the systematic uncertainties are reduced.

There are obvious difficulties in conducting experiments at energies $10^{19} - 10^{20}$ eV. It is also obvious that the statistics can be considerably improved only when increasing the setup areas by at least 10 times (it is expected to record only a few events per millennium over an area of around 1 km^2).

8. Conclusion

The history of cosmic ray research at the Lebedev Institute already covers more than 80 years. Throughout this time, new experiments have been set up, and detailed original research methods have been developed. Fundamental results have been obtained at high-altitude CR stations in Pamir and Tien-Shan, as well as at Aragats, where comprehensive installations were constructed and pioneering investigations using the EAS method were conducted (the nuclear cascade process was discovered). New phenomena such as the halo, alignment, etc., have been discovered with the use of X-ray emulsion chambers. Calorimeter methods based on recording the Cherenkov EAS radiation were developed for the first time. The first experiments on gamma astronomy were also conducted at LPI.

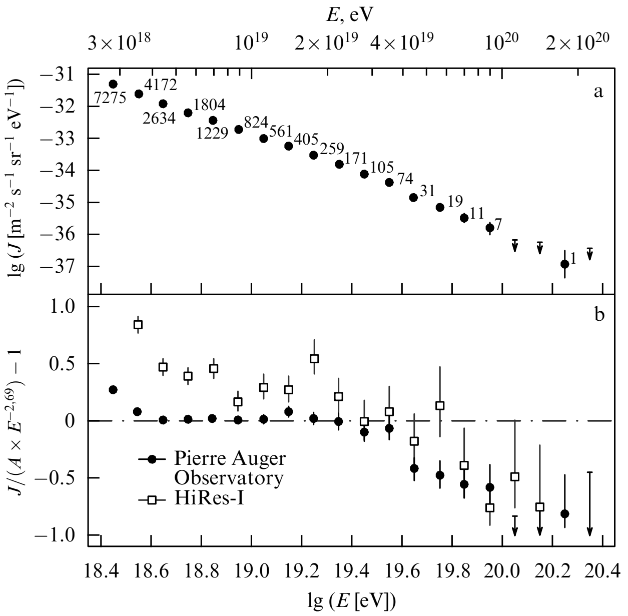

Figure 6. The spectrum of ultrahigh-energy particles [71]: (a) the differential flux of ultrahigh-energy cosmic rays as a function of energy. The numbers at the points correspond to the available statistics. (b) Comparison of the Pierre Auger Observatory and HiRes-1 data, divided by the power-law spectrum with the exponent 2.69: J is the intensity of the differential energy distribution and A is the spectrum intensity measured in the Pierre Auger Observatory at the energy 4×10^{18} eV.

LPI has always been on the frontline of science: the first experiments on board rockets and spacecraft were aimed at cosmic ray research and allowed obtaining fundamental results (for example, discovering Earth's exterior radiation belt). As a result of regular cosmic ray measurements at altitudes up to 30–35 km by sonde balloons, unique sets of data were obtained, which, for example, allowed relating the CR intensity to solar activity.

At LPI, the astrophysics of cosmic rays was born, the theory of high-energy particle passage through matter was created, and the mechanism of the spectrum cutoff for particles of ultrahigh energies (the GZK cutoff) was suggested; the last effect is currently being investigated at major ground-based facilities and its study on future spacecraft is planned.

It is of course impossible to cover all aspects of the CR research at LPI in a brief review, and it is therefore difficult to claim completeness here. The authors apologize for that and express their sincere gratitude to all LPI researchers who provided numerous pieces of the evidence of famous LPI achievements in cosmic ray studies. We are especially grateful to N M Nesterova, V P Pavlyuchenko, V S Puchkov, and

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References

1. Rossi B B *High-Energy Particles* (New York: Prentice-Hall, 1952) [Translated into Russian (Moscow: GITTL, 1955) p. 5]
2. Ginzburg V L, Syrovatskii S I *Proiskhozhdenie Kosmicheskikh Luchei* (The Origin of Cosmic Rays) (Moscow: Izd. AN SSSR, 1963) [Translated into English (Oxford: Pergamon Press, 1964)]
3. Skobelzyn D *Z. Phys.* **54** 686 (1929)
4. Vernov S N *Dokl. Akad. Nauk SSSR* **23** 141 (1939)
5. Zatsepin G T, Doct. Thesis (Moscow: LPI, 1954)
6. Zatsepin G T, Rozental' I L *Dokl. Akad. Nauk SSSR* **99** 369 (1954)
7. Chudakov A E et al., in *Extensive Air Showers and Cascades Process* Vol. 2 *Proc. of the 6th Intern. Cosmic Ray Conf.: ICRC, Moscow, 1959* (Eds V I Zatsepin, B A Khrenov) (Moscow: IUPAP, 1960) p. 50
8. Kulikov G V et al., in *Extensive Air Showers and Cascades Process* Vol. 2 *Proc. of the 6th Intern. Cosmic Ray Conf.: ICRC, Moscow, 1959* (Eds V I Zatsepin, B A Khrenov) (Moscow: IUPAP, 1960) p. 85
9. Chudakov A E at al., in *Extensive Air Showers: Proc. of the 8th Intern. Cosmic Ray Conf., ICRC, Jaipur, 1963* Vol. 4, p. 199
10. Sinitsyna V G et al. *Izv. Ross. Akad. Nauk. Fiz.* **73** 696 (2009) [*Bull. Russ. Acad. Sci.* **73** 657 (2009)]
11. Sinitsina V G *Izv. Ross. Akad. Nauk. Fiz.* **71** 941 (2007) [*Bull. Russ. Acad. Sci.* **71** 906 (2007)]
12. Korosteleva E E et al. *Nucl. Phys. B Proc. Suppl.* **165** 74 (2007)
13. Chudakov A E, in *Proc. of the 5th InterAmerican Seminar on Cosmic Rays, La Paz, Bolivia, 1962* Vol. 2 (La Paz, Bolivia: Laboratorio de Fizica Cosmica de la Univ. Mayor de San Andres, 1962) p. 44
14. Suga K, in *Proc. of the 5th InterAmerican Seminar on Cosmic Rays, La Paz, Bolivia, 1962* Vol. 2 (La Paz, Bolivia: Laboratorio de Fizica Cosmica de la Univ. Mayor de San Andres, 1962) p. 49
15. Abraham J et al. (AUGER Collab.) *Nucl. Instrum. Meth. Phys. Res. A* **523** 50 (2004)
16. Takizawa Y et al., in *Proc. of Intern. Workshop on Cosmic-Rays and High Energy Universe* (Eds T Shibata, N Sakaki) (Tokyo, 2007) p. 187
17. Slavatinskii S A *Tr. Fiz. Inst. Akad. Nauk SSSR* **46** 40 (1970)
18. Stamenov J A, Doct. Sci. Thesis (Moscow: LPI the USSR, 1982)
19. Nesterova M N et al., in *Proc. of the 24th Intern. Cosmic Ray Conf.: ICRC, Rome, Italy 1995* Vol. 2 (Eds N Iucci, E Lamanna) (Rome: IUPAP, 1995) p.748
20. Pavlyuchenko V P et al. *Tr. Fiz. Inst. Akad. Nauk SSSR* **109** 30 (1979)
21. Nam R A et al. *Tr. Fiz. Inst. Akad. Nauk SSSR* **109** 131 (1979)
22. Vavilov Yu N, Doct. Sci. Thesis (Moscow: LPI the USSR, 1987)
23. Yakovlev V I *Voprosy At. Nauki Tekh. Ser. Tekh. Fiz. Eksp.* (3) 20 (1984)
24. Abdrashitov S F et al. *Izv. Ross. Akad. Nauk. Fiz.* **50** 2203 (1986) [*Bull. Acad. Sci. USSR Phys.* **50** (11) 123 (1986)]
25. Avakyan V V et al. *Usp. Fiz. Nauk* **132** 395 (1980) [*Sov. Phys. Usp.* **23** 711 (1980)]
26. Mukhamedshin R A et al., in *Proc. of the 28th Intern. Cosmic Ray Conf., ICRC, Tsukuba 2003, Japan*, Vol. 3 (Eds T Kajita et al.) (Tsukuba: IUPAP, 2003) p. 977; Amurina I V et al. *Izv. Ross. Akad. Nauk Ser. Fiz.* **69** 353 (2005)
27. Gurevich A V et al. *Phys. Lett. A* **325** 389 (2004)
28. Kotelnikov K A et al. *Indian J. Radio Space Phys.* **20** 209 (1991)
29. Goncharova L A et al., in *Proc. of the 23d Intern. Cosmic Ray Conf., ICRC, Canada, 1993* Vol. 4 (Eds D A Leahy, R B Hickws, D Venkatesan) (Singapore: World Scientific, 1993) p. 21
30. Chernavskaya O D et. al. in *Proc. of the 24th Intern. Cosmic Ray Conf., ICRC, Rome 1995* Vol. 1 (Eds N Iucci, E Lamanna) (Rome: IUPAP, 1995) p. 68
31. Managadze A K et al. *Pis'ma Zh. Fiz. Elem. Chast. At Yadra* (3) 19 (2002)
32. Derbina V A et al. *Astrophys. J.* **628** L41 (2005)
33. Kalinin S A et al. *Nauka Proizvodstvu* (12) 29 (2000)
34. Acquafredda R et al. (OPERA Collab.) *New J. Phys.* **8** 303 (2006)
35. Galkin V I et al. *Izv. Ross. Akad. Nauk. Fiz.* **71** 594 (2007) [*Bull. Russ. Acad. Sci. Phys.* **71** 579 (2007)]
36. Ginzburg V L et al. *Dokl. Ross. Akad. Nauk* **402** 472 (2005) [*Dokl. Phys.* **50** 283 (2005)]
37. Dobrotin N A et al., Preprint No. 172 (Moscow: LPI, 1972)
38. Baiburina S G et al. (Pamir Collab.) *Tr. Fiz. Inst. Akad. Nauk SSSR* **154** 3 (1984)
39. Puchkov V S et al. *Nucl. Phys. B Proc. Suppl.* **122** 263 (2003)
40. Borisov A S et al. ("Pamir Experiment" Collab.) *Izv. Akad. Nauk SSSR. Ser. Fiz.* **49** 1285 (1985) [*Bull. Acad. Sci. USSR* **49** (7) 38 (1985)]
41. Baradzei L T et al. ("Pamir Experiment" Collab.) *Izv. Akad. Nauk SSSR Ser. Fiz.* **55** 650 (1991)
42. Rakobol'skaya I V et al. *Osobennosti Vzaimodeistviya Adronov Kosmicheskikh Luchei Sverkhvysokikh Energii* (Features of Interactions of Hadrons of Cosmic Rays of Ultrahigh Energies) (Moscow: Izd. MGU, 2000)
43. Royzen I *Mod. Phys. Lett. A* **9** 3517 (1994)
44. Borisov A S et al. *Fiz. Elem. Chast. At. Yad.* **36** 1227 (2005) [*Phys. Part. Nucl.* **36** 643 (2005)]
45. Svirzhevsky N S et al., in *Proc. of the 31st Intern. Cosmic Ray Conf., ICRC, Łódź, Poland, 7 – 15 July 2009* (submitted)
46. Vernov S N et al. *Dokl. Akad. Nauk SSSR* **120** 1231 (1958) [*Sov. Phys. Dokl.* **3** 617 (1958)]
47. Kurnosova L V et al. *Iskusstv. Sputniki Zemli* (8) 90 (1961) [*Planetary Space Sci.* **9** 513 (1962)]
48. Akimov V V et al. *Pis'ma Astron. Zh.* **18** 167 (1992) [*Sov. Astron. Lett.* **18** 69 (1992)]
49. Akimov V V et al. *Pis'ma Astron. Zh.* **19** 579 (1993) [*Astron. Lett.* **19** 229 (1993)]
50. Picozza P et al. *Astropart. Phys.* **27** 296 (2007)
51. Adriani O et al. (PAMELA Collab.) *Phys. Rev. Lett.* **102** 051101 (2009)
52. Adriani O et al. *Nature* **458** 607 (2009)
53. Belen'kii S Z *Lavinnye Protsessy v Kosmicheskikh Luchakh* (Avalanche-Type Processes in Cosmic Rays) (Moscow: Gostekhizdat, 1948)
54. Rozental I L *Astron. Zh.* **44** 563 (1967) [*Sov. Astron.* **11** 448 (1967)]
55. Ginzburg V L *Usp. Fiz. Nauk* **62** 37 (1957)
56. Syrovatskii S I *Astron. Zh.* **36** 17 (1959)
57. Ginzburg V L, Syrovatskii S I *Usp. Fiz. Nauk* **71** 411 (1960) [*Sov. Phys. Usp.* **3** 504 (1961)]
58. Ginzburg V L *Usp. Fiz. Nauk* **51** 343 (1953)
59. Ginzburg V L *Izv. Vyssg. Ucheb. Zaved. Radiofiz.* **1** 3 (1958)
60. Ginzburg V L, in *Trudy Mezhdunar. Konf. po Kosm. Lucham, Moskva, 1959* Vol. 3 (Moscow: AN SSSR, 1960) p. 200
61. Zatsepin G T, Kuzmin V A *Pis'ma Zh. Eksp. Teor. Fiz.* **4** 114 (1966) [*JETP Lett.* **4** 78 (1966)]
62. Greisen K *Phys. Rev. Lett.* **16** 748 (1966)
63. Yefimov N N et al., in *Problemy Fiziki Kosmicheskikh Luchei* (Problems of Physics of Cosmic Rays) (Ed E V Gorchakov) (Moscow: Nauka, 1987) p. 288
64. Pravdin M I, in *Proc. of the 26th Intern. Cosmic Ray Conference: ICRC, Salt Lake City, USA, 1999* Vol. 3 (Eds D Kieda, M Salamon, B Dingus) (Berlin: Springer-Verlag, 1999) p. 292
65. Takeda M et al. *Astropart. Phys.* **19** 447 (2003)
66. Bird D J et al. *Phys. Rev. Lett.* **71** 3401 (1993)
67. Bird D J et al. *Astrophys. J.* **441** 144 (1995)
68. Abu-Zayyad T et al., in *Proc. of the 26th Intern. Cosmic Ray Conference: ICRC, Salt Lake City, USA, 1999* Vol. 5 (Eds D Kieda, M Salamon, B Dingus) (Berlin: Springer-Verlag, 1999) p. 349
69. Boyer J H et al. *Nucl. Instrum. Meth. Phys. Res. A* **482** 457 (2002)
70. Abbasi R U et al. (High Resolution Fly's Eye Colab.) *Phys. Rev. Lett.* **100** 101101 (2008)
71. Abraham J et al. (Pierre Auger Collab.) *Phys. Rev. Lett.* **101** 061101 (2008)
72. Teshima M, in *1st Roma Intern. Conf. on Astroparticle Physics, RICAP'07, June 20 – 22, 2007, Roma, Italy*
73. Abraham J et al. (Pierre Auger Collab.) *Astropart. Phys.* **29** 188 (2008)
74. Abraham J et al. (Pierre Auger Collab.) *Science* **318** 938 (2007)