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Review Article

Cosmic Ray Investigation in the Stratosphere and Space: Results from Instruments on Russian Satellites and Balloons

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Selected activities aimed to investigate cosmic ray fluxes and to contribute to the understanding of the mechanisms behind, over a long-time period using space research tools in the former USSR/Russia and Slovakia, are reviewed, and some of the results obtained are presented. As the selection is connected with the institutes where the authors are working, it represents only a partial review of this wide topic.

1. Some Milestones until the Middle of the Last Century

The investigation of cosmic rays began in 1900-1901, more than 100 years ago. During the first ten years the researchers were not aware that what they were studying were cosmic rays. All began at the time of measurements of the conductivity of various gases including the air, when some "residual" ionization, that is, a weak "dark current," was observed even without ionizing sources. First publications of those experiments relate to the period of 1900-1901 [1–3]. One of the first researchers of the "dark current" was Charles Wilson, well known as the inventor of Wilson chamber (1911), which was widely used for studying various types of radiation, including cosmic rays. Later, in 1927, Wilson received the Nobel Prize in physics for this finding. Thanks to those experiments it became clear that at sea level some not intense but strongly penetrating radiation is always present (which was also observed in strongly shielded chambers). At the beginning it was thought that the radiation is emanating from the soil, similarly to Earth's radioactivity, and that is why it must be declining above the Earth's surface. However, the radiation was decreasing just up to the altitude about one km, while above this level its intensity was increasing. The fact that radiation intensity increases with altitude was discovered in 1912 after by the experiments of the Austrian physicist Hess [4], who measured radiation by ionization chamber up to more than 5 km. Hess called it "altitude radiation." This name was used until 1925. The nature of that radiation was not clarified for a long time. Several hypotheses of its origin have been proposed (e.g., it originated in the upper layers of the atmosphere due to atmospheric electricity). Finally, the extraterrestrial origin of "altitude radiation" was proved by Millikan et al. (USA) in 1923-1924, who introduced the term "cosmic rays" [5, 6]. At that time Millikan was already awarded the Nobel Prize (in 1923 for the measurement of the charge of electron). Cosmic rays remained the "mystery effect" for a rather long time. This is argued by the fact that Nobel Prize for his discovery was awarded to Victor Hess in 1936 only, that is, 24 years after his experiments were performed.

In this short review a few selected milestones in the cosmic ray research are discussed, to which the authors of the present paper among many other scientists of the former USSR and Czechoslovakia contributed.

In 1926, physicists in Leningrad Myssowsky and Tuwim found that the intensity of cosmic rays was changing with the pressure of air. They discovered barometric effect of cosmic rays which is well known at present [7]. Skobelzyn in 1927 when working with a Wilson chamber put it into a magnetic field and found that cosmic rays at the sea level are composed of electrically charged particles of very high energy [8].

Starting from the 1920s, scientists in the former USSR began to deal with cosmic ray research intensively. Let us mention the works of several groups in Leningrad, Kharkov, and Moscow. The basic successes of the groups are results of Myssowsky and his colleagues, Skobelzyn, and of the group of Vernov. The work in the former USSR was conducted along the same scientific directions as in other countries of the world, however, with some delay due to the tense international and domestic situation as well as to the complicated exchange of information during that time. Until the works of Myssowsky the dominant opinion was that the altitude radiation is close to the radiation of radioactive nuclei. Myssowsky and Tuwim in 1926 accomplished measurements of the absorption coefficient of the altitude radiation in the water at Lake Onega [9], which appeared to be by one order lower than that for gamma rays of Ra, indicating that the altitude radiation possesses much higher penetration ability as compared to gamma rays emitted by radioactive nuclei. These works, along with the experiments by Millikan and Cameron [10, 11] on the absorption of altitude radiation in water at various levels above the sea level led to the conclusion that the altitude radiation is coming to the ground from above and that it has a very high penetration ability.

In 1927, Skobelzyn found in a Wilson chamber inserted in magnetic field that a couple of tracks of relativistic particles were not bent by the magnetic field. He determined the energy of particles and came to the conclusion that these are particles of altitude radiation [8], which, according to Millikan, obtained the name "cosmic rays" [12].

In 1929, Skobelzyn published a paper where he showed that cosmic rays (CR) may create several particles, forming showers of cosmic rays [13]. After several years with the help of a Wilson chamber, controlled by the system of coincidence of detectors surrounding the chamber, various researchers obtained photographs of cosmic ray showers with high number of particles (see, e.g., [14]). The importance of the discovery of cosmic ray showers lies in the awareness of the fact of the processes in cosmic rays which do not exist in particle interactions at lower energies. Cosmic rays allowed to get in deeper into the structure of elementary particles and initiated the development of acceleration technique.

The third group of cosmic ray researchers was established and led by Vernov. It was especially that group which in the following period carried out the most exhaustive and numerous cosmic ray research in the USSR: on the ground, at mountain altitudes, in the stratosphere, and subsequently on satellites and other space vehicles. These investigations are shortly described below.

We should like to say few words about the leader of the works of the group—Sergey Nikolaevich Vernov (SNV, 1916–1982), who started his cosmic ray studies at the age just above 20. SNV was a student at Skobeltsyn. He was familiar with the works and results of physicists in Leningrad, and he has seen how distinguished scientists deal with cosmic ray physics, and thus his choice proved quite appropriate. In the first half of 1930s only hypotheses about the primary cosmic rays existed, that is, particles accessing the Earth's atmosphere from outer space. Thus, for understanding the nature of cosmic rays, experiments had to be performed closer to its source, near the boundary of the atmosphere. That is, why SNV decided to carry out measurements in the upper stratosphere. However, on this way there was a serious difficulty because at that time the experimenters had no chance to raise instruments to high altitudes. That is, why experimental devices with automatic recording system have been developed which could provide measurements without human assistance.

The research of stratosphere was started also by other researchers and flights of stratostats began. Near Moscow on September 30, 1933, a stratostat named "SSSR-1" was launched and reached an altitude of 19 km. Astronauts helped by the electrometers of Hess and Kohlhoester measured cosmic ray intensity and confirmed the data about cosmic (extraterrestrial) origin of the rays and about the role of atmosphere in their attenuation. One of the flights of stratostats ended with tragedy—three astronauts died. Vernov found a solution for this problem—to transmit the results of measurements by radio waves. He utilized the experience of Leningrad's professor P. A. Molchanov, who, in 1930, for the first time in the world constructed a radiosonde transmitting meteorological information by radio. SNV developed an instrument jointly with Molchanov and Mysovsky in 1934 and, for the first time, cosmic ray measurements in the atmosphere were transmitted to Earth by radio. The report of the Academy of Sciences of USSR for the year 1934 wrote that "experience with detection of cosmic rays was provided by the PhD student of Radio Institute Vernov." The first automatic-adjusting flight of a radiosonde took place on April 1, 1935 [15, 16]. In the same year Vernov defended his PhD thesis on the subject "Investigation of cosmic rays in the stratosphere by means of radiosondes." Academician S. I. Vavilov liked the thesis by Vernov and invited him for a doctoral study to FIAN (Physical Institute of Academy of Sciences) to continue his research of cosmic rays. This was the end of the research by Vernov in Leningrad. In 1935, he moved to Moscow where he continued working until his death.

By improving the method of measurement of cosmic rays on the stratospheric balloons, Vernov and Mironov conducted a successful study of the latitudinal effect of cosmic rays in the stratosphere in 1936–1938 at several sites: Leningrad, Yerevan, and in the region of the Equator [17]. For that purpose Vernov organized and led a nautical expedition. A tanker named "Sergo Ordzhonikidze" sailed from Odessa to Vladivostok and back and in the Indian ocean stratospheric balloons were flown from the board. Experiments made in the stratosphere have shown that the flux of cosmic rays near the Equator is by ~4 times lower than at high latitudes. This suggested that the magnetic field of the Earth reduces the intensity of cosmic rays and consequently, cosmic rays should consist of charged particles. Similar experiments were done somewhat earlier by Bowen et al. [18], which definitely proved that cosmic rays are not neutral particles as, for example, gamma quanta. First balloon observations showing the protons to be the main component of primary cosmic rays were by Schein et al. [19].

In that period Vernov's group was concerned with the research of cosmic rays in the upper layers of atmosphere by means of instruments flown on radiosondes. In Figure 1 the moment of launch of the instrument on the garland of balloons is seen which required quiet conditions of the atmosphere and the known expertness to get rid of

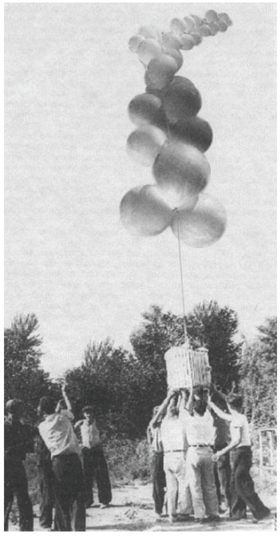

Figure 1: The moment of launch of the instrument for cosmic ray research on the garland of balloons.

the pendulum effect and avoid impact with neighboring structures.

The way in cosmic ray research by SNV was not easy. There were only a few experimental facts and they were frequently contradictory, so that his viewpoints were changing in accordance with the emerging new facts. First he supposed that cosmic ray particles have small mass so they are light particles like electrons. Later it appeared that the particles passing through materials are not behaving as electrons, as their "multiplication" is not described by quantum theory assuming even relativistic effects. SNV was moving towards the idea that primary cosmic rays are heavier, that is, protons, and proving it requires determining the charge of particles. This was done by using the geomagnetic field as a giant magnetic analyzer sensitive to the charge of analyzed particles. For that purpose an instrument was elevated into the stratosphere, where the effect is more pronounced, from the board of the research vessel "Vityaz." The first flight confirmed the assumption about positive electric charge of primary particles, which, by augmentation during passage of atmosphere, produce secondary particles, that is, electrons [20].

At present the knowledge about the composition of primary cosmic rays is almost complete. We know that primaries consist of nuclei of all elements of the Mendeleev table, predominantly protons and alpha particles; however, oxygen and nuclei up to iron are also present, and very rarely, even uranium nuclei. We now know that cosmic rays arrive to the vicinity of Earth from distant space and that they bring negligible flux of energy (10^8 times lower than that of solar light). We also know that individual particles can carry enormous energies (more than 10^3 times higher than those in the collider at CERN). We also know that these particles with enormous energy collide with the nuclei of the atmosphere producing extensive air showers, but no black holes. Cosmic rays have been interacting with the Earth for millions of years and did not crash anybody.

Regular registration of cosmic rays in the stratosphere started in the former USSR in 1957 and is still running regularly till today. This allowed obtaining continuous long-time records of cosmic ray data, studying the mechanisms of primary cosmic ray interactions with the nuclei of atmosphere, finding that the Sun is also generating cosmic rays with somewhat lower energies than the primary galactic CRs. The year 1957 marked the start of the space era. SNV immediately used the new technical tool for cosmic ray studies. The takeoff of those investigations was amazing; the scientific group led by SNV accomplished more than 300 experiments onboard various spacecrafts. The weight of the developed scientific devices carrying out measurements in space, depending on the tasks and possibilities, ranged from 500 g to 10 tons. Some of these experiments have not been repeated, and in this paper they are mentioned shortly.

For the investigation of very high-energy particles SNV created a—for that time—huge equipment at the lomonosov Moscow State University, consisting of hundreds of units placed over the territory of university campus, each of them with a complex device detecting each secondary particle produced in the Earth's atmosphere by a primary particle. Such equipments have been installed later on in Yakutsk (in Moscow there was no sufficient area available) and in Samarkand (for better atmospheric conditions). In this manner SNV's scientific activity splitted into three competitive directions: cosmic ray research in the atmosphere of Earth, in space, and on the ground. Due to his brilliant experience and large effort all three directions were successfully developed. More details about his papers and scientific results can be found in [20].

The experiments performed in the stratosphere and in space are shortly described below. The research of extensive atmospheric showers is not touched since the authors of the paper did not participate in that scientific direction.

2. Cosmic Ray Research on Artificial Satellites of Earth, on Other Spacecrafts, and in the Upper Atmosphere

2.1. Galactic Cosmic Rays. The preparation of experiments for satellites began in USSR in 1956. At a meeting of the Academy of Sciences of USSR a task was formulated for the leading specialists on upper atmosphere physics, magnetic field, ionosphere, and cosmic rays to give suggestions, that is, to create projects for experiments on artificial satellites of Earth. Academician Skobeltsyn, who participated in the meeting, authorized Vernov to conduct these activities. Along with one of the authors of the paper (Yu. I. Logachev), SNV stepped up to design and develop a device to detect cosmic ray particles. The trajectories of the first satellites were at altitudes of 300–1500 km. At these altitudes, beyond cosmic ray particles, particles trapped in geomagnetic field are present and form the radiation belts of Earth. However, during the development of the measuring device for the first artificial satellites of Earth, this was yet unknown and

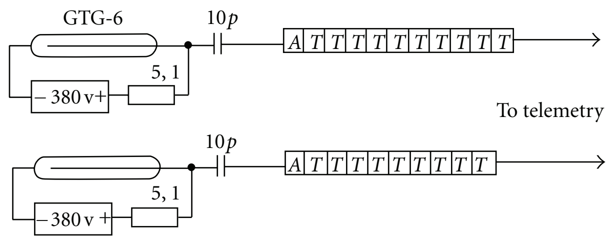

FIGURE 2: Block diagram of detectors and electronics placed onboard the second Soviet satellite. *A*: amplifier of the signal from counter, *T*: trigger of the reducer of count rate.

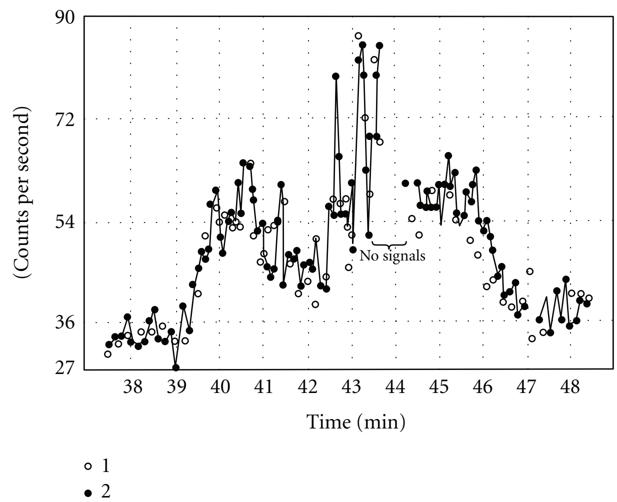

FIGURE 3: Variations of cosmic ray intensity along one of the orbits of the second satellite over the northern regions of the USSR. Nowadays it is clear that they were due to the precipitation of the particles from the outer radiation belt during geomagnetic activity. Numbers 1 and 2 correspond to the read-outs of the two detectors.

the apparatus was targeted only to cosmic ray research. Figure 2 shows the block diagram of the detectors and of the electronics for the instruments installed aboard the second Soviet satellite flown into orbit on November 3, 1957. The deadlines were tight, the technology was new, and naturally, the suggestions of the authors on the construction of the instrument were limited by very simple understanding: to utilize gas discharge counters and semiconductor electronics as detectors. Vernov fully supported these suggestions. Let us remark that presently rather sophisticated complex detector systems are working in space, utilizing practically all recent methods of particle detection: scintillation and semiconductor counters, magnetic spectrometers, track detectors, and their combinations. The orbital elements of orbit of the second Soviet artificial satellite were the following: altitude at perigee 225 km, at apogee 1670 km, and the apogee was located in the southern hemisphere at latitude ~45°. The telemetry system was switched on 2 to 3 times per day along the parts of orbits passing over the territory of the USSR. The points of acceptance of telemetry information were deployed also above the territory of USSR. There were no memory elements onboard the satellite and thus the information about the cosmic rays encompassed only the latitudes and longitudes of the USSR and the altitudes in the range of 225 to 600 km.

The flight of the second satellite confirmed the existing pieces of knowledge about cosmic rays: the observed latitudinal and altitude dependence of cosmic ray intensity did not contradict data obtained earlier, and already on a single orbit an anomalously high counting rate of detectors was registered (Figure 3), which was interpreted to be due to the penetration of solar particles into the polar regions of the magnetosphere of the Earth. Later it became clear that on November 7, 1957, the satellite observed the precipitation of radiation belt particles into the upper layers of the atmosphere due to moderate geomagnetic activity [21, 22].

The discovery of the radiation belts of the Earth (RB) substantially changed the plans for future research works, pushing cosmic ray investigations aside. Nevertheless, in all possibilities, during the flights of various space vehicles, cosmic ray measurements were carried out as well. Space flights, where detectors of primary (galactic) as well as of solar cosmic rays were used, are as follows:

(i) flights to the Moon;

(ii) interplanetary flights: to Venus, Mars, and interplanetary probes;

(iii) heavy Proton satellites;

(iv) selected satellites of the Cosmos series.

2.1.1. Lunar Programme. By the launch of three satellites and thus demonstrating the possibilities of cosmic technology of USSR, which was important during the nonquiet time period, it became necessary to provide new steps in the space programme, since the launch of just a few satellites would not induce large resonance. And the task number one became the Moon. It was necessary to send out a rocket to the Moon to demonstrate that Moon was reached. Also discussed were versions to explode an atomic bomb on the lunar surface. Fortunately, such suggestions did not find support. The first successful launch took place on January 2, 1959. The second one happened on September 12, 1959, and the third on October 4, 1959, exactly two years after the launch of the first artificial satellite of Earth. The task of the first two flights was to reach the surface of the Moon; the third was aimed to take photos of the reverse side of the Moon. Although the first space vehicle did not reach the Moon, it approached relatively close to its surface (5000 km). The second device reached the lunar surface, and before it crashed and destroyed by hitting the ground, it succeeded to measure the magnetic field and radiation in the vicinity of the Moon. The flight of that device was observed by the Jodrell Bank Observatory in UK. In Europe this was the only observatory which had a sufficiently large antenna capable to receive weak radiosignals. The Observatory confirmed the hit of the apparatus on lunar surface just in the computed time. The flight of lunar station and its "meeting" with the Moon on September 14, 1959, were absolutely important events in the history of space research and they became the triumph of

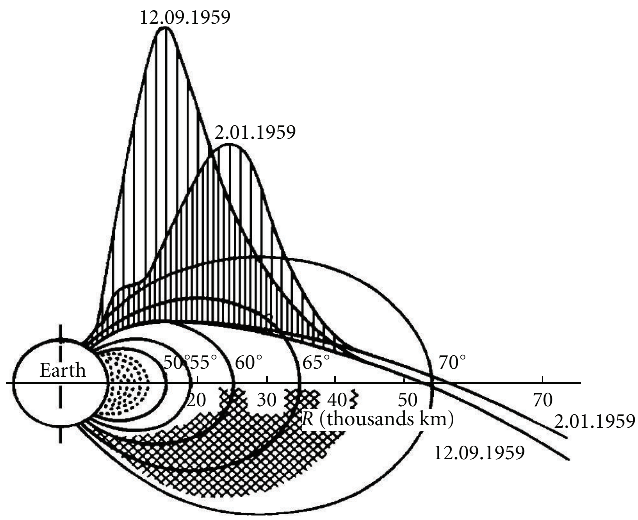

Figure 4: Ionization in NaI(Tl) crystal during the flights of the space Luna-1 (02/01/1959) and Luna-2 stations (12/09/1959) through the radiation belts of Earth.

the Soviet rocket and electronic technology. More details about the lunar flights can be found in [23].

The third device made snapshots of the lunar surface, and although not very bright, they were the first ever pictures of the reverse side of the Moon. It became clear that the reverse side of Moon is similar to the visible one; there were craters, seas, and other peculiarities as well. In the Atlas of the reverse side of the Moon issued, the peculiarities were assigned the names of important persons, who contributed to the discussions on origin of the Moon, to the new hypotheses, and so forth.

Aboard all the three of the Soviet lunar devices, named subsequently as Luna-1, Luna-2, and Luna-3, our scientific instruments were placed to measure cosmic ray particles and particles of radiation belts of Earth.

A particularly large complex of the instruments was put onboard the Luna-1 and -2 spacecrafts. Among the instruments there were scintillation and gas-discharged counters with various shieldings. The complex of devices of the first lunar missions is described in [24]. The main task of the flight of the station Luna-3 was to take photographs of the Moon and that is why the place and weight for other devices were very limited.

Aboard all the three lunar missions our device was working very well and interesting results were obtained. Along with the US probes Pioneer-1 and -3, the Soviet spacecrafts flew through the whole thickness of radiation belts and they determined the spatial distribution of the radiation at large distances from Earth and at slightly higher latitudes. In Figure 4 the dependence of ionization in the NaI(Tl) crystal is shown along the trajectory from the distance and latitudinal projections of geomagnetic field lines for Luna-1 and Luna-2 stations.

It is obvious that the two different flights at close trajectories have shown different structures of outer radiation belt, indicating the instability of the outer belt—temporal variations of the particle fluxes within the trapping region. Measurements aboard Luna-1 for the first time allowed determining the altitude profile of the intensity of trapped particles along the geomagnetic field line. Luna-1 crossed the same geomagnetic field line three times, namely, at altitudes 8700, 11000, and 18250 km, respectively. At those altitudes the scintillation detectors observed the energy deposited in the crystal corresponding to 30, 65, and 145 GeV. Such values of energy deposition show that the altitude profile at larger distances from the Earth is weaker than that observed at low altitudes on the same field line; possibly the Earth's atmosphere plays a more important role in the losses of trapped particles.

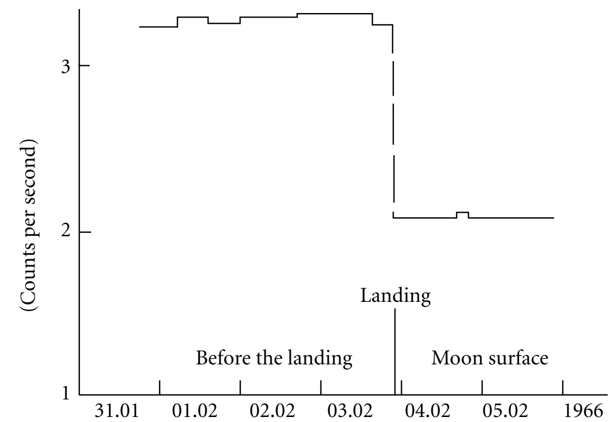

Figure 5: Radiation flux in the interplanetary space and on the lunar surface according to data of the gas-discharge counter onboard the station Luna-9.

This part of the lunar mission programme laid the foundations of the beginning of systematic research of the radiation belts of Earth, which was subsequently continued intensively using other space vehicles (Electron, Molnija, geostationary satellites, etc.). Onboard these satellites studies not only of radiation belts were carried out, but also the magnetosphere was explored in its complexity, including its structure, variations, relation to the solar activity processes, and other effects.

Later on the research of radiation belts of Earth was not conducted in the frame of lunar programmes which were targeted exclusively for studies of the lunar environment. The studies of the Moon, however, included also that of the fluxes of galactic and solar cosmic rays, the radioactivity of the lunar surface, and fluxes of lunar albedo particles, that is, secondary particles emitted from the surface due to the interaction of galactic and solar cosmic rays with nuclei of the materials of the surface. Such measurements were performed aboard all stations from Luna-4 through Luna-16 as well as during the flight of automatic interplanetary station Zond-3 (July–December 1965) which provided pictures of the reverse side of the Moon once again. Among the Luna missions a specific place belongs to the Luna-9 station which landed softly on the lunar surface on February 3, 1966. The results of our experiment operated there are depicted in Figure 5. The flux of cosmic rays in the interplanetary space should be two times higher than on the lunar surface where the field of view of the instrument was lower by factor of 2 due to screening by the body of Moon. It appears that the surface flux was lower only by a factor of 1.6 instead of 2 as expected due to the radioactivity of the surface and the albedo cosmic ray particles. Based on these factors it was possible to estimate the radioactivity emission of the surface of Moon, which was found to be close to the radioactivity of the Earth's ground [25]. This result proved that there was no dangerous radiation on the lunar surface, and that a man can stay there for a long time without specific problems.

Speaking about the investigations of the Moon from a more general point of view, not only in the context of cosmic rays, it is necessary to recall the phenomenal success of US scientists accomplishing the first landing on the Moon and the safe recovery of all astronauts visiting the Moon to the Earth. For the first time man came to Moon in 1969 and after that the expeditions were repeated five times. There is an extended literature describing these activities. These flights have shown the theoretical possibility to establish scientific stations on the Moon for long-term operations, including cosmic ray observations as well. Cosmic ray research on the Moon would possess a number of substantial advantages in comparison with Earth-based research, since the Moon stays more than 80% of the time in the interplanetary space, and only 20% of the total time within the distant magnetospheric tail, where the shielding by the magnetic field is not significant. This means that measurements of cosmic rays by lunar satellites on the Moon or in its vicinity are not affected by the influence of Earth's magnetosphere, which is not the case of inner-magnetospheric satellites of the Earth flying even within the magnetospheric boundaries into near interplanetary space (Soviet Prognoz satellites, US IMP satellites, etc.). Because of that onboard all lunar space stations that landed on the Moon, on lunokhods, and on the artificial satellites of the Moon, instruments were installed for investigations of solar and galactic cosmic rays.

2.1.2. "Proton" Satellites and Other Spacecrafts Studying Very High-Energy Cosmic Rays. In the former USSR on the initiative of Vernov studies of cosmic rays were performed aboard heavy artificial satellites for the first time. It started with the 4 heavy satellites of the Proton series, which provided the first direct measurements of the energy spectra of all particles of cosmic rays up to energy 10^{14} eV and measured the dependence of proton-proton interaction cross section in the range of 10^{11}–10^{12} eV.

In the sixties an intensive development and testing of new rockets took place both in the USSR and in the US. In the USSR, along with the rocket which launched into the space the first satellites of Earth and sondes towards Moon, in 1962, the rocket of the type Kosmos was constructed, and in 1965 the tests of a new rocket started which was at that time the most powerful one and was later used to launch heavy satellites not only of Russian production but also many satellites of other countries—rocket Proton. Its name was originated from the name of satellites of the type Proton launched by that rocket in 1965. The history of those launches is the following: when the time for the tests of the new rocket capable to launch into the Earth's orbit approached several tons, two possible loads were discussed: several tons of sand or scientific instruments. Of course sand was the simpler load having no risk if the launch proved unsuccessful. Nobody at that time has constructed any scientific instrument of such weight so to launch a unique scientific instrument for the first testing flight was risky. What would happen if the launch fails? And the deadline of the flight was approaching; only less than a year remained. However, the Institute of Nuclear Physics of the lomonosov Moscow State University suggested a scientific task, requiring to build the heavy device, and committed oneself to construct such apparatus by the required deadline (it was already hoped that people dealing with the construction of rockets would also be delayed). The scientific task consisted in the research of the energy spectra and composition of galactic cosmic rays in the energy range 10^{11}–10^{14} eV. The measurement of the energy of such particles requires its stopping within the volume of the detector system itself. Stopping the particles in the device allows determining their energy; however, the range of protons and production of secondary particles inside the system at such high energies is equivalent to the thickness more than a meter of iron; that is, the absorption requires a device of very large volume filled with heavy material (lead, iron, etc.). To accelerate charged particles to such high energies was impossible by means of accelerators in laboratories, and the planned experiments, aside the astrophysical tasks as measurements of energy spectra and of chemical composition of cosmic rays, were promising in the sense of nuclear physics aspects, as understanding the behavior of cross section of proton and/or nucleus-nucleus interactions of heavier elements at high energies.

At that time for the measurement of the energy of cosmic rays in ground-based experimental equipments ionization calorimeters developed earlier in USSR laboratories were widely used [26]. The same methodology was also applied on Proton satellites as well as on a couple of others, launched later on with the purpose of similar-type studies. The method of measurement was proposed by Grigorov et al. who led the research oriented on the construction of this type of devices and the analysis of data obtained [27]. Aboard Proton-1 satellite the device SEZ-14 was placed (an acronym of Russian words spectra, energy, and charge, up to 10^{14} eV) weighing about 7 tons. The complex device SEZ-14, along with the calorimeter, included also charged particle detectors-ionization chambers and the target composed of graphite and iron, where the interactions with the material took place. The construction of SEZ-14 is schematically shown in Figure 6. Even for the Institute of Nuclear Physics of lomonosov Moscow State University (Institute in what follows), the design and construction of such a complex device within the short time interval required an enormous effort. According to the instruction of headquarters (Vernov) to construct that apparatus all the resources of the Institute have been thrown up including financial ones. Almost the whole potential of mechanical workshops (and in 1960s it was by far not negligible) as well as the large group of electronic engineers

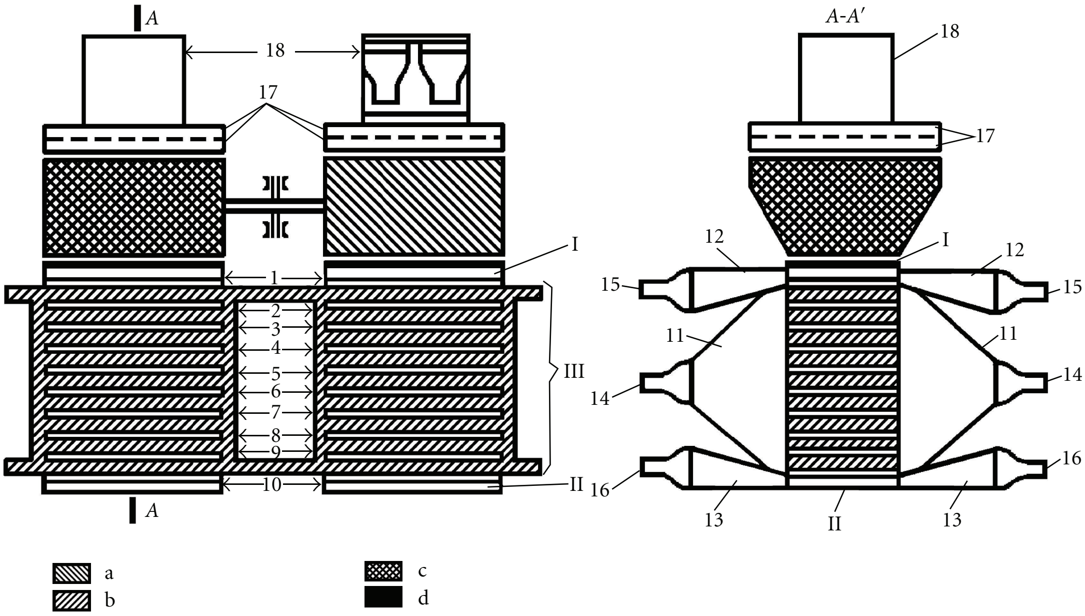

Figure 6: Schematic view of the device SEZ-14. I: detector of interactions; II: lower scintillation detector; III: ionization calorimeter; 1–10: scintillators of the detector of energy; 11: diffuser of the detector of energy; 12: diffuser of detector of interactions; 13: diffuser of lower scintillation detector; 14–16: photomultipliers; 17: charge detector (doubled proportional counter); 18: detector of the direction; a: absorber; b: iron; c: carbon; d: lead.

was involved in the work manufacturing the apparatus for Proton-type satellites. The authority of Vernov and Grigorov made it possible to prepare a prototype of the device SEZ-14 and of its basic elements (construction elements, fixation of the iron absorber) by utilizing the power of the construction department, where the rocket-carrier and the satellite itself were manufactured. This was a significant component of the successful "production" of the device; however, all the main questions of the equipment design were discussed and decided within the institute: the device was equipped by extensive electronics: for example, it involved several hundreds of pulse amplifiers. Never before the Proton satellites had such extensive and complicated devices been constructed and launched. The team of the institute accomplished a scientific record by constructing the device within a very short time—9 months. That device was operating for around 3 months in space without failure.

During the flights of Proton-1, -2, and -3 satellites a unique result about the change of the slope of the energy spectra of protons around 2×10^{12} eV was obtained. Until now this result has not been either confirmed or declined. At the same time the slope of the energy spectra of the sum of all cosmic ray primaries (protons, He, heavier elements) remained without that break, in agreement with the results of other indirect measurements. If the spectra of protons were really bent with significant change of the slope, that would mean that in the high energy part of the spectra of primary cosmic rays a significant change of chemical composition of primaries with enrichment of heavy elements had to take place, since the fraction of protons at high energies is negligibly small. This means that corrections in the mechanisms of acceleration in the source must be included, requiring predominant acceleration of nuclei with $Z > 2$. The importance of those conclusions is evident; however, it is desirable to have higher confidence in this respect.

To confirm that result and to shift towards the measurements at higher energies, a new device with a 10 times larger geometric factor named IK-15 (ionization calorimeter up to 10^{15} eV) was constructed for Proton-4. However, the results from Proton-4 did not give unambiguous result about the spectral break of the proton spectra. A couple of more flights with the device (Table 1) could provide no clear reply to that question either.

The methodological reasons of the change of slope of energy spectra may lie in the nature of the energetic particles themselves, namely, in the so-called reverse flux in the detector of charge—"converting" the event of detection of proton into an event of particle with higher charge which may reduce the count rate of protons. The importance of this effect increases with energy. The analysis of tracks in photo emulsions exposed to cosmic rays aboard Intercosmos-6 was done in collaboration with other laboratories; one of them was IEP SAS Kosice.

To cope with the reverse flux, in the device named SOKOL (acronym from the Russian words of the main target of the experiment—composition of cosmic rays) directional Cherenkov detectors with small dimensions were used to measure protons and alpha particles. Such devices were working on Cosmos-1543 and Cosmos-1713 satellites launched 10 years after the Proton satellites (Table 1). This allowed eliminating the effect of reverse flux when determining the charge. Furthermore, the passage of the particle through the device was visualized, so that it was possible to set off the particles as well as the electromagnetic cascades produced by

Table 1: Earth orbiting satellites with measurements of high-energy cosmic rays.

Satellite	Year	Device	Weight of device (in tons)	Time of active work in space	Comment
Proton-1	1965	SEZ-14	7	3 months	
Proton-2	1965	SEZ-14	7	3 months	
Proton-3	1966	SEZ-14	7	3 months	
Proton-4	1968	IK-15	12,5	8 months	
Intercosmos-6	1972	Photoemulsions	2,4	4 days	Device returned to the Earth
Cosmos-1543	1984	SOKOL	2,4	27 days	
Cosmos-1713	1986	SOKOL	2,4	25 days	

them in the alignment of the device. This approach allowed determining the energy of particle with better confidence.

The experiments aboard Cosmos-1543 and Cosmos-1713 with the SOKOL device confirmed that this device reduced the effect of reverse flux effectively. However, no unambiguous reply to the main question about the shape of primary proton spectra was achieved because the operational time of the satellites was less than one month and the statistics of protons obtained were insufficient to draw substantiated conclusions. In order to obtain a conclusive settlement about that important question the launch of a similar experiment with longer time measurement in space is required. Up to now no such experiment has been carried out yet. As an alternative the experiment ATIC that runs in the frame of international collaboration on balloons detecting cosmic rays at high altitudes over Antarctica may be considered [28, 29]. Figure 7 exhibits the energy spectra of C, O, and the Fe group. By fitting the spectra with power law the index is $\gamma = 2.5$. Nearly the same slope is obtained for the energy spectra of He nuclei. The ratios of cosmic ray fluxes at different energies characterizing the composition of particles at a particular energy are practically the same as those at low energies. This means that in the frame of that approximation, the cosmic ray composition remains practically the same throughout the energy range of 1 GeV/nucl to 1000 GeV/nucl. At higher energies there are indications for the enrichment of heavy nuclei in galactic cosmic rays.

Let us mention that these experiments allowed increasing the observed energies of cosmic rays up to about 2 TeV/nucl for C and O nuclei. The statistical errors in this energy range are still large. Such type of measurements has to be continued to accumulate better statistics, especially at high energies. Using the SOKOL equipment for this aim is an adequate approach for this task: it is necessary to enhance the duration of the measurements by factor of 10–20, which is fully possible with using the existing tools of space technology. Along with that, the institute prepared proposals for a couple of new experiments qualified to move to even higher energies of cosmic rays aboard satellites [30, 31]. The experiments described in the aforementioned publications are now under discussion and they are planned to be accomplished in nearest years. On satellites Cosmos-1543 and Cosmos-1713 He, C, O, and Fe nuclei were also observed in the energy range of 50–1000 GeV/nucl [32].

Important data on primary cosmic rays have been obtained recently from the experiment Pamela installed on the Resurs-DK1 satellite launched onto a low altitude nearly polar orbit in June 2006. More details about that mission, international collaboration, and publications can be found at http://pamela.roma2.infn.it/index.php/. The description of the experiment can be found, for example, in [33]. The recent results of the ATIC and PAMELA experiments prove that the spectra of protons and He are different and have peculiarities at energies of several hundred GeV/n (e.g., [34]). The new results do not seem to confirm the Proton findings. Nevertheless, the Proton results stimulated investigations enormously.

In the Pamela mission the increase of the fraction of positrons in electron-positron component of cosmic rays with increase of energy, ratio $J_+/(J_+ + J_-)$, was discovered [34]. This might be a signature for the existence of dark matter. Or, alternatively, another additional source of positrons may exist producing them with efficiency increasing with the energy. The data on the positron component are reliable thanks to the high statistical accuracy of the measurements. The spectrometer has a permanent magnet and separation of electrons and positrons is reliable. The energy of particles is measured sufficiently accurately with the help of the calorimeter. The excess of positron fraction and its increase with energy has been confirmed recently in the Fermi mission [35].

2.2. Solar and Galactic Cosmic Rays at Lower Energies. One of the admirable properties of galactic cosmic rays is the relative stability of their intensity in time. Above this "background" sudden strong increases of cosmic ray intensity related to powerful processes on the Sun were observed. It became clear that from time to time the Sun generates strong fluxes of energetic particles; they received the name solar cosmic rays (SCR). Powerful solar energetic particle (SEP) events appear relatively rarely, while less powerful ones are observed more frequently, as it is usual for nature.

The first observations of SCRs have been carried out with the help of instruments on the ground sensitive only to higher primary energies (>1 GeV). Experiments on balloons in the stratosphere could observe particles with a lower energy threshold (>100 MeV). Measurements at high altitudes utilizing satellites and other space vehicles allowed to observe less powerful effects, and until now more than 1000 SEP events with energetic particle emissions connected to solar flares have been registered. While the first observed events of energetic particles have been related to effects of very high power and still those could only be detected with

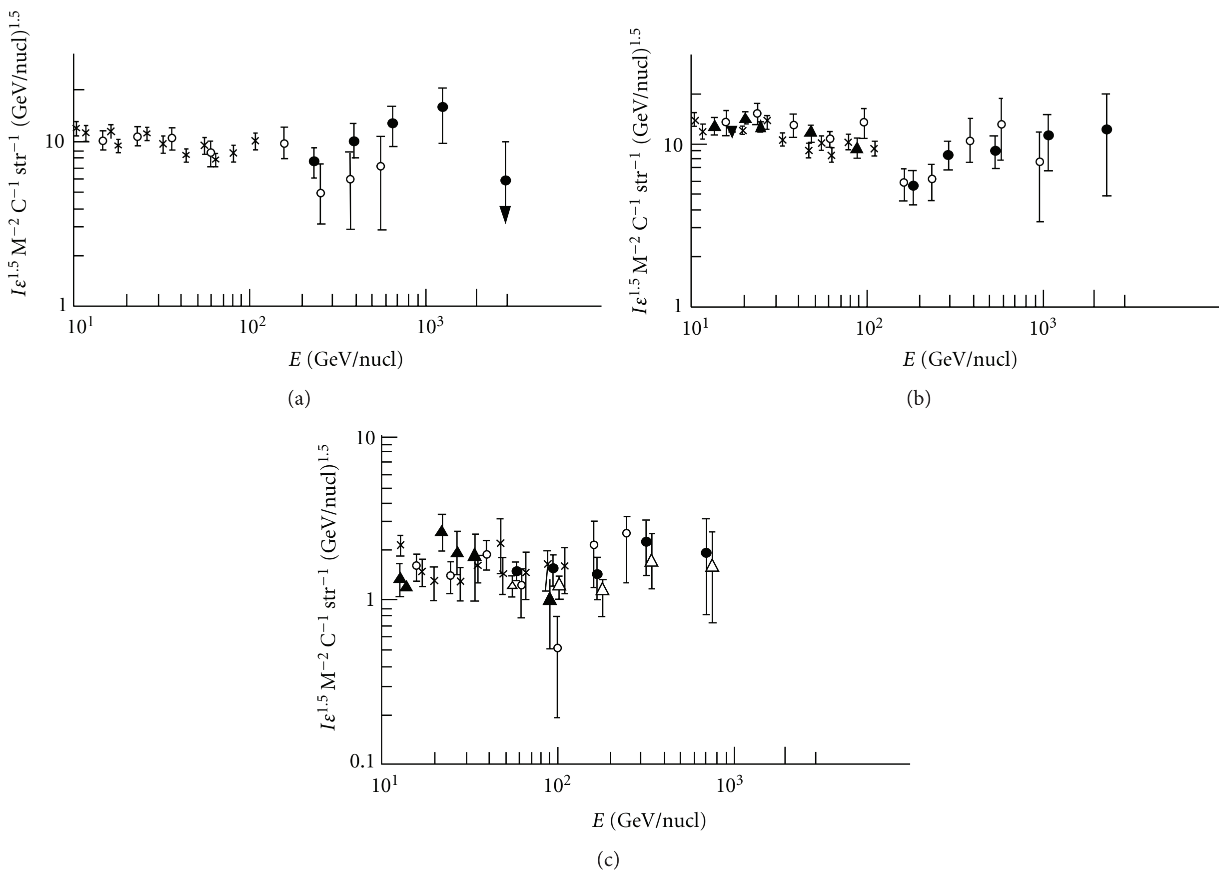

Figure 7: Energy spectra of carbon C (a), oxygen O (b), and iron Fe (c) nuclei at high energies according to the results of flights equipped with the complex device SOKOL.

ground-based devices, nowadays instruments on satellites and space probes allow observing practically all increases of SCR flux reaching the vicinity of Earth. At present they remain unnoticed only in a few cases of small SEP events on the reverse hemisphere of Sun, from which energetic charged particles cannot reach the Earth's orbit or an interplanetary probe. To exclude these gaps it is proposed to "patrol" the space around the Sun at various heliolongitudes including the reverse hemisphere of the Sun. The solar mission STEREO is already fulfilling this programme.

Usually, the energy of accelerated solar particles does not exceed 10 MeV/nucl (1 MeV for electrons). Such SEP events during the solar activity maximum occur about once per week. The associated particles are observed beyond the magnetospheric boundaries, within its peripheral regions or in the polar cap. Less frequently, typically once a month flares accelerating particles up to energies ~100 MeV/nucl and higher are observed. Such particles penetrate into the atmosphere of Earth in the polar latitudes and can be observed during the flights of high-altitude balloons. In even more rare events, observed typically once per year, particles are accelerated to 1 GeV. Extremely powerful SEP events, occurring 2-3 times per 11-year cycle of solar activity, are characterized by very high fluxes of accelerated particles with a maximum energy 10 GeV or even more. Most frequently they are observed by neutron monitors distributed all over the world.

2.2.1. Ground-Based Observations of CR Variability and SCR. The interplanetary magnetic field (IMF) is partly screening the flux of galactic cosmic rays. This shielding effect, especially at lower energies, is varying in time and thus the cosmic ray intensity observed near the Earth is temporary variable. Both regular and quasiperiodic (e.g., diurnal, ~27 day, ~11 year) variations are connected with solar activity and provide information about the structure of interplanetary magnetic field and on the solar wind in the heliosphere. More detailed reviews on cosmic ray variations can be found in [36, 37] and in monographs [38, 39]. The research of cosmic ray variations requires long-time series of homogeneous measurements. The first instrument devoted to this task was the ionization chamber developed and constructed by A. Compton in 1934. In USSR the measurements of cosmic ray flux with purpose to study its variations started in 1936 by Yu. G. Shafer in the Yakutsk Pedagogical Institute with an independently constructed ionization chamber—electrometer. These works have been broken by the World War, in which Shafer went through the fighting course from Stalingrad to Berlin, and he recovered the measurement of cosmic rays in 1947 in the Yakutsk Institute of Space Physics and Aeronomy by building

Figure 8: Neutron monitor in Yakutsk.

the ionization chamber named ASK. By this instrument the network of stations over the whole territory of USSR was equipped.

Before and during the International Geophysical Year (1957) the whole world network of cosmic ray stations was equipped by neutron monitors (NMs) developed by J. Simpson in 1948. Such equipments were installed also in USSR, for example, in IZMIRAN (Troitsk, near Moscow), at Apatity (Polar Geophysical Institute), where the measurement is continuous until present. One of NMs operating in Russia until now is seen in Figure 8.

A neutron monitor consists of the group of proportional counters. Two types of counters are used, namely, those filled with gas having a high concentration of the isotope ^{10}B or ^{3}He. The counters are surrounded by the moderator serving to slow down the neutrons before entering the counter and also to reflect low-energy neutrons. The moderator is inserted into the lead producer surrounded by the outer moderator-reflector. This rejects unwanted low-energy external evaporation neutrons produced in the local environment. During the years the neutron monitor design has been changed. First the IGY monitors were used and in some places they are still in use. For that the moderator and reflector material is paraffin. In 1964, the network of neutron monitors with larger counting rate, named supermonitors (NM64), replaced the original IGY NMs in many places.

The network of NM64 in the USSR was created under the leadership of Vernov while the main role in the construction work was done by I. N. Kapustin, the engineer in Polar Geophysical Institute. The NM64 monitor has a low-density polyethylene moderator and reflector. The differences are also in geometry and tubes. More information about neutron monitors can be found, for example, in [39].

High mountain NMs having higher statistics play an important role. One of them was constructed at Lomnický štít (2634 m above sea level, High Tatra mountains, run by IEP SAS, one of the authors—K. Kudela—is the PI of it since 1982) during IGY as a contribution of Czechoslovak physicists to IGY activity. It is operating until now (data are available at http://neutronmonitor.ta3.sk/). Let us mention just one result: since 1950s it was assumed that solar protons accelerated to high energies and interacting with residual solar atmosphere can produce neutrons which can be detected even at the Earth's orbit. After 30 years, during the solar flare on June 3, 1982, the increase corresponding to solar neutrons at two high altitude NMs in central Europe, namely, at Jungfraujoch and at Lomnický štít, been observed in coincidence with satellite measurements of increased flux of high-energy gamma rays reported by E. L. Chupp. The high statistical accuracy of the measurements (5 min resolution at that time) at Lomnický štít contributed to that finding [40, 41]. Selected results obtained with use of that NM are presented in [42].

2.2.2. SCRs Observed on Balloons. The measurements of SCRs on balloons are filling the energy gap of 100–1000 MeV between those observed by ground-based devices and on satellites and space probes. The first SCRs in the stratosphere were registered independently in the US, Minneapolis, Fort Churchill, and in USSR, Murmansk, in 1958. Regular measurements in the stratosphere in USSR started in 1957 by the group of A. N. Charakhchyan in Moscow (Dolgoprudnyj), in the vicinity of Murmansk and episodically in Yakutsk and Tixie (Yu. G. Shafer, V. D. Sokolov, and A. N. Novikov) as well as in Simeiz, Crimea (Stepanyan). Later on, from 1962, regular flights of radiosondes began in Apatity (L. L. Lazutin, one of the authors). The measurements have been conducted during short-time flights on rubber balloons by radiosondes with the use of two Geiger counters; a short pulse was transmitted to the Earth in the case of single detector count; longer pulse meant the coincidence of two counters. A metallic shield was placed between the counters to register charged particles in two energy channels. The needle of the barograph interrupted the transmission on seven contacts—serving for the measurement of residual pressure of air above the balloon. Figure 9 shows the scheme of radiosonde RK-2 by A. N. Charakhchyan using valves, which were replaced later by semiconductors in all devices of regular measurements in Moscow, Mirnyj, and Apatity. Figure 10 shows the results of measurement—the altitude profile in the coincidence channel during four solar flares with SCR emission. Figure 11 shows the moment before the launch of radiosonde of cosmic rays in Apatity observatory.

Along with the measurements of SCRs described shortly above, regular stratospheric measurements of cosmic rays are running with the purpose to check cosmic ray variations at different depths in the atmosphere by the group at the Lebedev Physical Institute of Russian Academy of Sciences, Moscow (G. V. Bazilevskaya and Yu. I. Stozhkov). Figure 12 exhibits such registrations [44, 45].

2.2.3. SCR Observed on Satellites and Space Probes. In the USSR, Vernov established the service of continuous monitoring of cosmic rays in the upper layers of the atmosphere—daily launches of the same type of device in Moscow, Apatity, and sometimes also in the southern part of the country (region of Alma-Ata). Along with that, during each flight of the satellites where it was possible to put the scientific device measuring cosmic rays, such device was installed on board. By this way the detection of solar and galactic cosmic rays

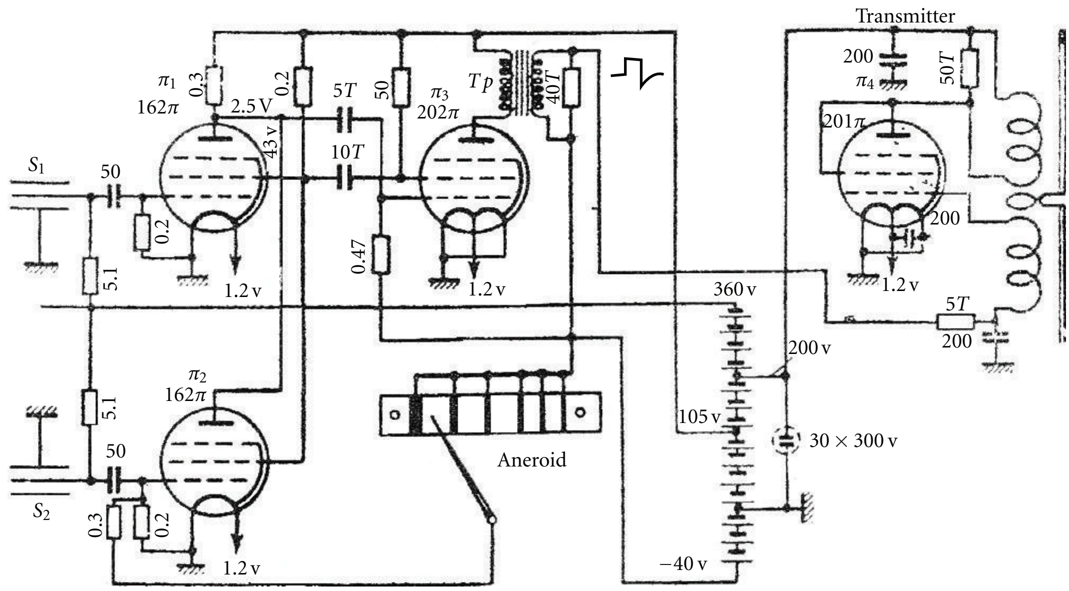

Figure 9: Electronic block diagram of the experiment measuring cosmic rays on a radiosonde.

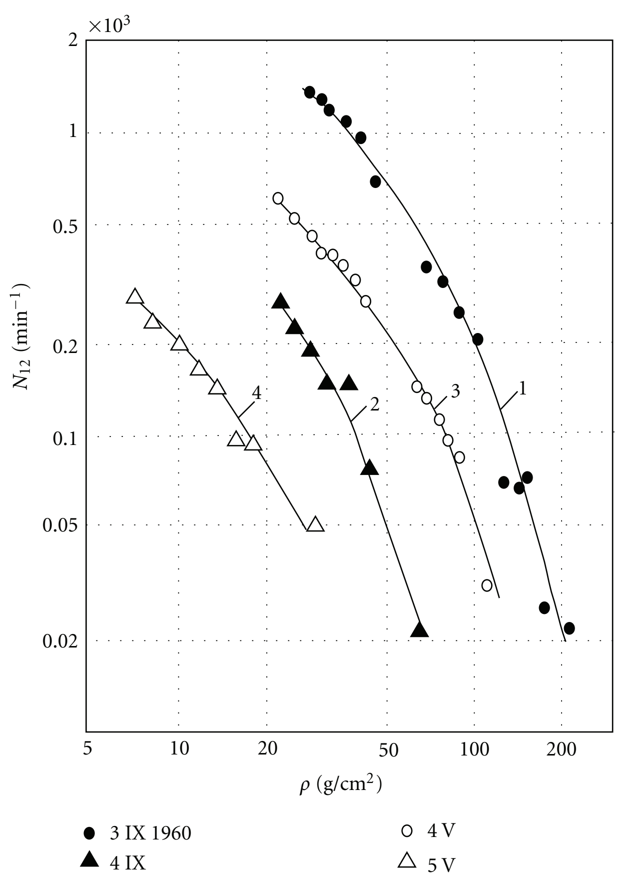

Figure 10: The counting rates (per min) of coincidence pulses versus altitude (in atmosphere pressure) of two GM tubes on radiosondes during four different SEP events [43].

was conducted during all flights to Venus and Mars as well as during the flights of several Zond interplanetary stations.

Figure 11: Academician B. M. Pontecorvo visiting the launch site of radiosondes in Apatity before one of the launches.

Particularly successful was the flight of Venera-4, where the measurement of cosmic rays was performed over the whole route. This was a period of enhanced solar activity (1967) and the devices observed a large number of solar energetic particle events. During the subsequent flights to Venus many measurements were carried out; however, the flight of Venera-4 was the most impressive because it was the first really successful and interesting information that was obtained over a long-time period including the landing on Venus.

In the majority of events the particle increases at relatively low energies were not intense. Thus, they were observable only outside the magnetosphere. In particular, low inclination satellites could not see them because of geomagnetic field filtering. Aboard Venera-4 protons and heavier nuclei were detected using two identical semiconductor detectors that looked into opposite directions and thus allowed to observe partial spatial anisotropy. If the particles are emitted by

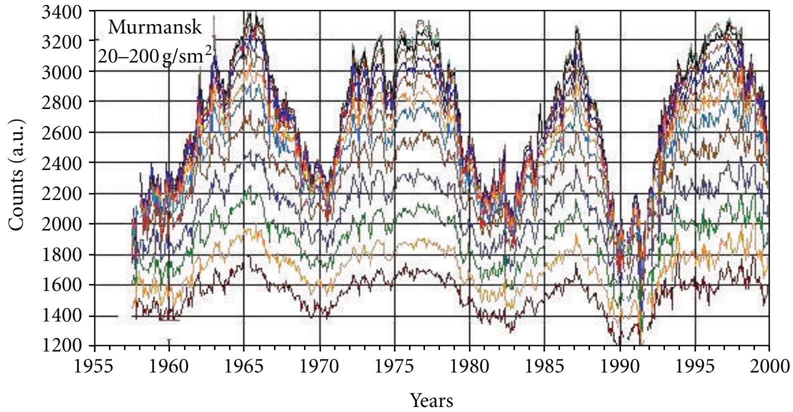

Figure 12: Temporal profile of cosmic ray intensity measured over Murmansk since 1957 at different depths of the atmosphere [44, 45].

Sun, their motion is directed by the field lines of IMF approximated by an Archimedean spiral (with an angle of about 45° to the sunward direction at 1 AU). These field lines are not smooth—irregularities of various dimensions are superimposed on them, and charged particles are scattering on the irregularities, sometimes changing direction of velocity to the opposite. Due to such scattering during their lengthy stay in the IMF, particles "forget" their initial direction of motion, and their angular distribution becomes nearly isotropic. Thus, in such cases the anisotropy is equal to zero. The flight of the space probe Venera-4 has shown that such situation is found relatively frequently; however, at the same time the devices looking toward the Sun observed much higher particle fluxes over several hours in comparison with those looking in the opposite direction (Figure 13). This means that in the given events the Sun emitted rather large fluxes of particles over an extended time period, sometimes up one day, and the lines of IMF controlling their motion were sufficiently smooth. This way these particles propagated without scattering, so that there was low number of particles flowing from the opposite direction. Such picture corresponds to a high positive anisotropy of particle fluxes from solar flares. Such type of events was later observed quite often; they obtained the name of SEP events without scattering; however, Venera-4 was the first space probe which observed these phenomena. Now it has became clear that the anisotropy of solar flare particles in the interplanetary space is developing in general quite regularly. First the anisotropy is sufficiently high and it is directed from the Sun along the interplanetary field lines, later it is decreasing and becomes radial, and finally, the angular distribution takes a form with maximum flux perpendicular to the field lines, which is connected with the drift of charged particles in the crossed electric and magnetic field (the electric field arises due to motion of the magnetic field line together with the solar wind plasma).

The previous flights around Venus did not give a reply to the question about existence of the trapped radiation in its vicinity. Venera-4 has shown that near Venus there is no trapped radiation even at the smallest distances to its surface: when the device was approaching the surface the radiation was not increasing but even decreasing in accordance with geometry (because of the screening by the solid body of Venus). This important result is in agreement with the lack of noticeable magnetic field of Venus measured by the team of IZMIRAN during the same mission.

Data from Venera-4 have shown that while the Sun produces charged particles with large diversity, it also creates conditions in the interplanetary space that control the motion of the particles in the heliosphere. Those particle fluxes which are observed along the Earth's orbit or in another point of space are determined by both the conditions of the source (solar flares) as well as by the properties of interplanetary medium, which they pass through on their way from the Sun to the periphery of heliosphere. The propagation of particles brings significant "corrections" into their fluxes: at the Earth's orbit we do not observe identical temporal profiles of the fluxes of accelerated particles, the energy spectra formed at the site of their generation changes, part of the accelerated particles is not escaping from the Sun, and so forth. Let us treat, for example, the instant generation and outflow of particles from the solar surface. In the simplest case of diffusive propagation of particles, an extended time profile will be observed on the Earth's orbit (so-called diffusional wave, Figure 14): high-energy (high velocity) particles arrive first, later followed by lower energy particles, and so forth. The comparison of observed temporal profiles of particle fluxes with computed ones assuming diffusion indicates that sometimes particles are released really instantaneously on the Sun and propagate further diffusively, as it is, for example, in the flare on November 22, 1977, and in the couple of other cases.

The Prognoz satellites started to be launched in 1972, constructed to study SCRs and in particular to develop a method for forecasting powerful solar flares, representing estimates of radiation hazard during space flights. Table 2 gives basic information about the satellites Prognoz launched in USSR.

We must admit that the primary task of the Prognoz project—to obtain reply on the question about the causes of solar flares and to elaborate the method of the prediction of solar flares with potential of radiation hazards—was not

Table 2: Dates of launch and orbits of the satellites Prognoz—measurements out of the magnetosphere.

Satellite	Date of launch	Initial apogee altitude (10^3 km)	Orbital period (days)	Time of active operation (months)
Prognoz-1	14.04.1972	≈200	≈4	4,4
Prognoz-2	29.06.1972	≈200	≈4	5,5
Prognoz-3	15.02.1973	≈200	≈4	12,5
Prognoz-4	22.12.1975	≈200	≈4	2,5
Prognoz-5	25.11.1976	≈200	≈4	7,8
Prognoz-6	22.09.1977	≈200	≈4	5,3
Prognoz-7	30.10.1978	≈200	≈4	6,8
Prognoz-8	25.12.1980	≈200	≈4	8,8
Prognoz-9	01.07.1983	≈720	≈27	8,0
Prognoz-10	26.04.1985	≈200	≈4	9,3

achieved. However, it gave an opportunity to step forward in the understanding of some acceleration processes and especially of propagation of accelerated particles in the interplanetary medium, in the research of recurrent particle fluxes, and other phenomena. A summary of the results of the experiments can be found in proceedings [46, 47]. Below we list some important results obtained with the help of satellites Prognoz.

Protons Are Accelerated in All Flares. It was shown that in all solar flares both accelerated electrons of relatively low energy (>40 keV) and protons appear (on satellites Prognoz protons with >1 MeV were measured). This fact enabled to exclude the term "electron flares" from the terminology which supposed that flares accelerate electrons exclusively. Until the flight of the Prognoz satellites this opinion was widely accepted and it was assumed that particle acceleration in such flares is due to betatron mechanism which has a low efficiency for the acceleration of heavy particles. It was shown that for all flares detected on Prognoz satellites, including the weakest events, electrons were accompanied by protons [48]. Further research showed that the energy spectra of electrons and protons are similar if represented as dependence on kinetic energy of particles and this requires a mechanism completely different from betatron acceleration.

Coherent Propagation of Particles. An unusual mode of fast propagation of particles was discovered: in a narrow angular interval near the magnetic field line connected to the region of flare, electrons are propagating practically without scattering, that is, conserving their angular distribution along most of their path from the Sun to the Earth. This assures high velocity of their motion through space. During propagation such a "bubble" of particles generates radiowave emission of type III, for which the frequency depends on the density of medium where the propagation takes place. This mode of propagation was named coherent. On Prognoz satellites the coherent propagation was observed also for protons [49, 50].

Detecting the coherent propagation of particles is difficult, since to cross a narrow beam of the particles has low probability. Such an event on the Earth's surface takes place just for 10–20 min, and subsequently, the beam flowing over the space vehicle is stretched along the field line only at 0.5-1 AU. Near the Sun the beam has even smaller dimensions, because due to propagation in space it is broadening. Furthermore, for the existence of energetic particle "huddles" there are necessary specific conditions in space, sufficient smoothness of the magnetic field and its focusing in the ecliptic plane.

Energy Spectra of Protons in the Interplanetary Space during Quiet Sun. In the absence of intensive particle fluxes accelerated at the Sun, that is, in periods of quiet Sun, there are low fluxes of energetic particles in interplanetary space still exist. The origin of such particle fluxes has not been identified for a long time. Before the launch of Prognoz satellites the energy spectra of protons and other particles was known only above 500 keV/nucl. If one artificially extrapolates energy spectra of protons from 500 keV towards lower energies (Figure 15), such spectra will coincide with the solar wind one. Thus, it was natural to assume that the observed spectra of protons and heavier particles are just the continuation—a tail—of the solar wind particles. The nonthermal character of this tail was assumed because with using the Gaussian distribution of solar wind protons with measured temperature (10^4 K) the proton flux would decrease so sharply with energy that it is impossible to speak about any agreement with the observed proton flux at energies 0.5–1 MeV—the difference would be several orders of magnitude. In this case the energy spectra of particles during quiet time another minimum should appear in the energy range about 30–100 keV. It would be interesting to find such a minimum its existence would have principal implication because it would separate populations of different nature, that is, having different origin.

The Interplanetary Medium during Periods of Quiet Sun. Studies of variations of solar particle flux suggested that the interplanetary space in each given period of time is in a certain dominant (characteristic) state, to which it tends to recover after various disturbances. Such a dominant state is controlled by the magnetic field of the Sun and by solar wind, which in general are not changing very frequently. On the average one can assume that during low solar activity the structure of the interplanetary medium remains stable for 1-2 or more solar rotations. The structure of interplanetary medium is closely associated with various active regions on the Sun, thus affecting the properties of the interplanetary medium in the solid angle formed by the magnetic field lines flowing out from active regions. The structure near the Sun

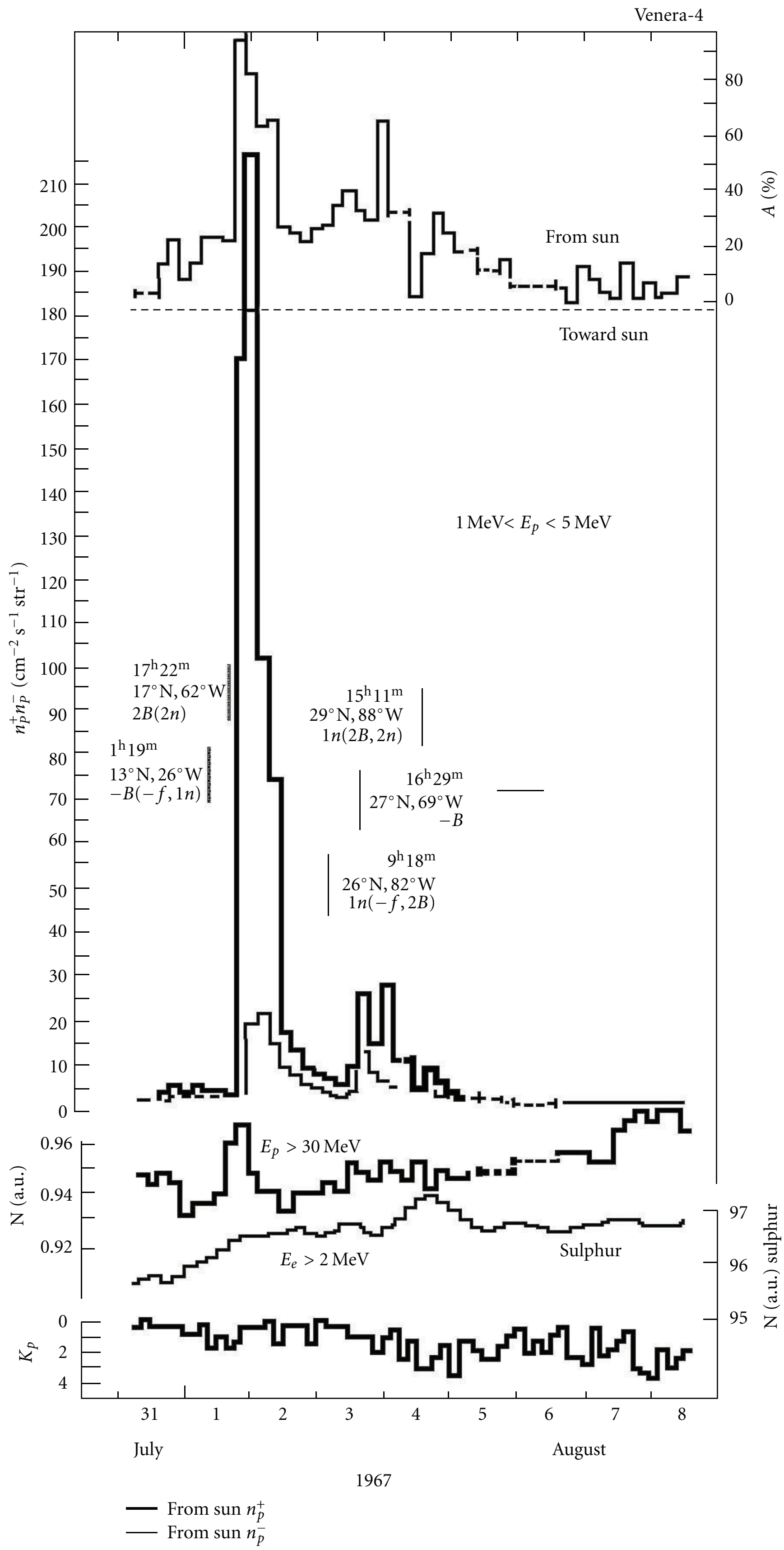

FIGURE 13: Fluxes of particles from a couple of solar flares during July-August 1967, according to the measurement of instrument AMS aboard Venera-4. Upper curves indicate the anisotropy of protons with Ep > 1 MeV. The thick line represents the proton flux from the Sun; the thin one is toward the Sun.

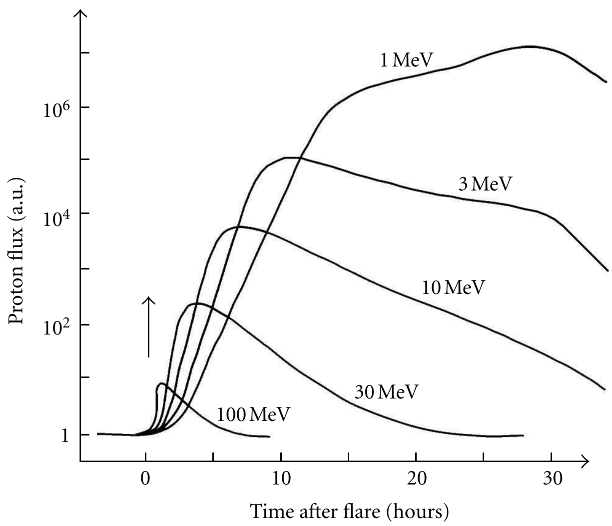

Figure 14: Sketch of the diffusional wave of solar protons—temporal profiles of various energy proton fluxes at 1 AU for impulsive acceleration at the Sun at 1 AU.

is bound to its surface and is rotating together with that. This is clearly observed in the solar particle fluxes at various time scales. In the Prognoz 1 and 2 data the fine structure of interplanetary medium was clearly demonstrated. The Prognoz satellites registered the long-lasting quasi-stationary structure of interplanetary medium as well. This emerges from the rate of decay of solar particle fluxes in events associated with flares after reaching the diffusive maximum. The decay rate is an independent feature of the extent of disturbance of the IMF and solar wind velocity. It was found out that for the majority of solar particle increases (>1 MeV) during the year 1972 the decay followed the exponential law with the same characteristic time of about 16 hours [51]. Even after the largest solar flares in 1972 when the interplanetary space was disturbed due to passage of strong shock waves, just after a few days all characteristics recovered to their original state and the characteristic time of decay rate was again about 16 hours (Figure 16).

The decay phase of the SEP event after the maximum contains information about solar wind velocity, turbulence of the IMF, and other parameters of the interplanetary medium. The level of disturbance of IMF is one of the main factors of the state of interplanetary medium characterized by the diffusion coefficient of particles in the medium, and the solar wind velocity determines the form of temporal profile of particle flux, the rate of its increase, and decay after maximum.

Various models of particle propagation predicted various shapes of the decay profile during the late stage of the event. The temporal profile of particle flux in solar events usually has a characteristic form. At 1 AU for a SEP event connected with a single flare, the particle flux has a rather fast onset, reaching the maximum and subsequently decreasing to the level before the event. Events with a picture adequately described by diffusion approximation are frequently observed. In such cases, assuming an impulsive injection of particles (the time of generation is much shorter than the transit time to the site of observation), the temporal profile $J(t)$ in the decay phase has a power-law profile and the flux is proportional to $t^{-3/2}$. For prolonged injection, one has to assume an injection function of particle source leading thus to the prolongation of the event; however, it is negligibly reflected on the late stage of the event.

If the influence of the solar wind is essential, the convective outflow of particles and their adiabatic cooling may be important. Then the decay form can be approximated by $J(t) \sim e^{-t/\tau}$ [52–55]. Power law works sufficiently well for high-energy particles (>100 MeV). For lower energy particles of (<10 MeV), however, the convective outflow process begins to play much more important role, and the decay becomes exponential. It turns out that in the majority of solar energetic particle events, lower energy (<10 MeV) proton fluxes decay exponentially, while at 30–60 MeV the convective outflow, although less pronounced, is observed too. Often the particle propagation is accompanied by various processes of additional acceleration which leads to the modification of the "smooth" temporal profile so that decay cannot be described by any single functional form. Apart from sufficiently frequent observations of events with exponential decays, in many studies until now no adequate attention has been paid to that form of intensity decrease.

If in the decay phase of the SEP event convective outflow of particles and adiabatic cooling dominate over the diffusion, for the characteristic time of decay the following relation was found [52]:

$$\tau = \frac{3r}{2V\left(2+\alpha\gamma\right)}, \tag{1}$$

where V is solar wind speed, γ is the index of energy spectra of particles, r stands for the distance of the site of observation to the Sun, and $\alpha \approx 2$ for nonrelativistic particles. The analysis performed indicates that in a considerable fraction of events (up to 50%), when V remained constant during the whole decay phase, τ is satisfactorily well described by the above expression.

Due to rotation of the Sun, real measurements carried out near the Earth take place in different flux tubes, where the magnetic conditions are usually different. In some cases the stability of particle fluxes along the longitudes is observed only over a short-time period. In such cases two devices located within a small angular distance (sometimes $\leq 10^\circ$) observe entirely different fluxes. At the same time, relatively frequently, same conditions for particle propagation appear over a wide latitudinal extent, what is confirmed by simultaneous measurements of different space devices. In such cases the particle fluxes are constant over the large angular extents (even up to >100°) [56].

Long-term studies, including almost three full solar activity cycles, have shown that for a remarkable fraction (almost half of the solar energetic particles events), the value τ for energies 1–10 MeV is 16–20 hours, in agreement with the above formula for the typical values of the parameters involved. This means that the interplanetary medium remains in the state corresponding to the same value of τ during these

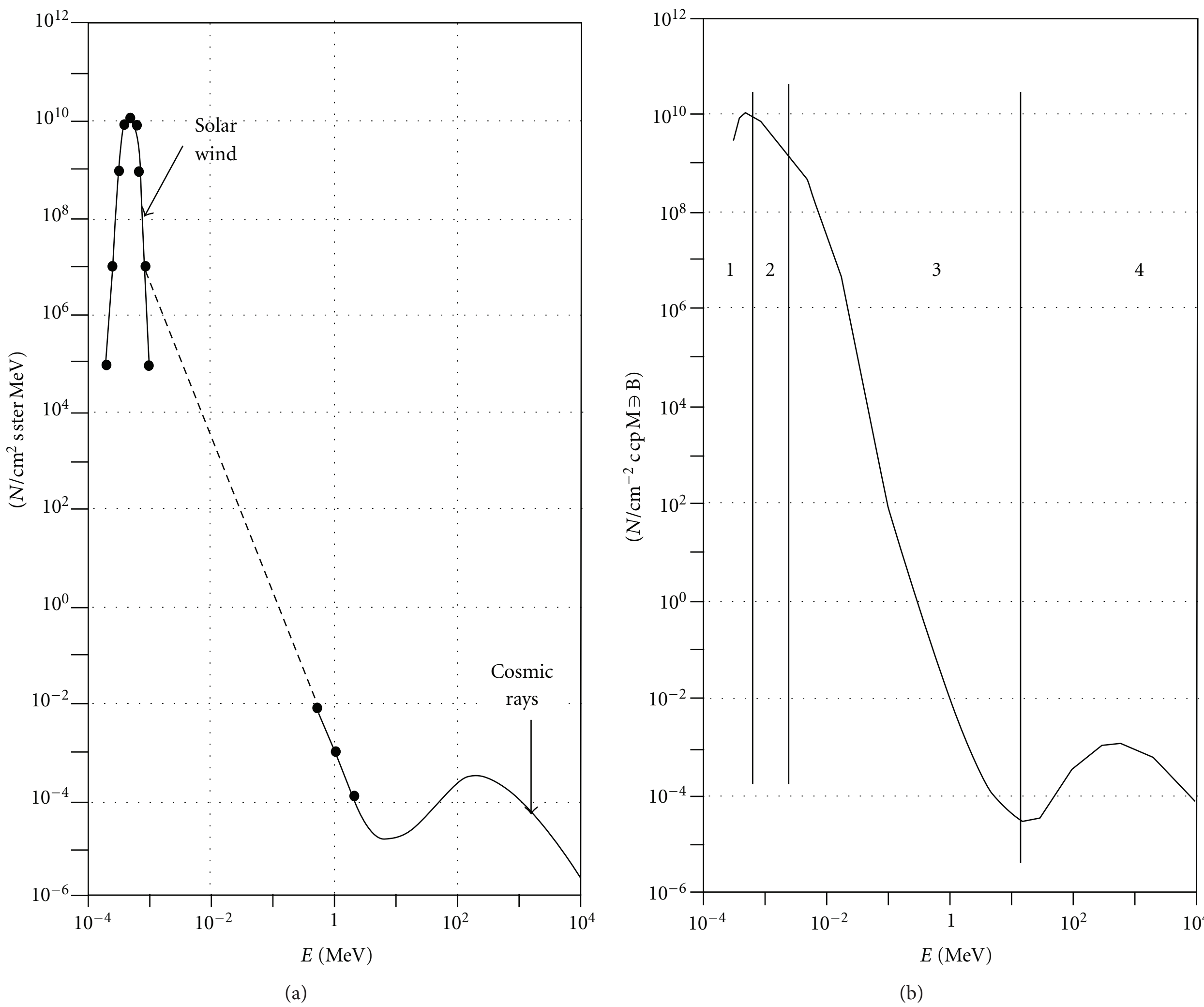

Figure 15: Energy spectra of protons at 1 AU during quiet Sun according to understanding in 1970s (a) and at present (b). 1: solar wind, 2: suprathermal particles, 3: energetic particles of solar origin, 4: galactic cosmic rays. One of the tasks of the Prognoz-3 satellite consisted of measurements of particle flux at energies as close as possible to the energies of solar wind particles. The experiment conducted allowed to measure spectra during the quietest periods within the active interval of Prognoz-3. Energy spectra were measured down to 30 keV and the minimum of the proton flux was found. Presently it is clearly confirmed that there are no peculiarities in the energy spectra of particles in the energy range between energetic particles (<1 MeV) and solar wind. The energy spectra of protons measured in quiet time period of the Sun according to recent observations are shown in (b).

time periods. Around 20% of events have larger values of τ reaching sometimes 50 hours or more [57].

Recurrent Solar Particle Fluxes. The flights of the first two Prognoz satellites took place in the period of decreasing solar activity, and the devices on board often observed recurrent fluxes of particles in the interplanetary space, that is, fluxes persisting over long-time periods, which were rotating together with the Sun. Several different series of such type of fluxes were observed, their characteristics obtained, and it was shown that a part of them was connected with the Sun. The most interesting was the conclusion that if an active region emits recurrent fluxes of particles, the energy is not accumulated within the region, and consequently there is no need to release superfluous energy by an explosive manner. This means that no solar flares are taking place there [58]. A further study of recurrent fluxes has shown that they are most frequently connected with the so-called coronal holes—regions with lower level of emission in soft X rays, which are also the sites of origin of high-speed solar wind.

Long intervals of stationary conditions in the interplanetary space can be found during the periods of low solar activity due to recurrent fluxes of low-energy particles having the spatial structure saved over the extended period of time. Recurrent fluxes sometimes exist over several rotations of the Sun, which was observed several times on Prognoz satellites as well [59]. The longest one comprised 26 solar rotations in the declining phase of the solar cycle 21 [60].

In addition, it turns out that not only recurrent increases of fluxes are observed, but recurrent minima corotating along with the Sun as well. We named these deep decreases of

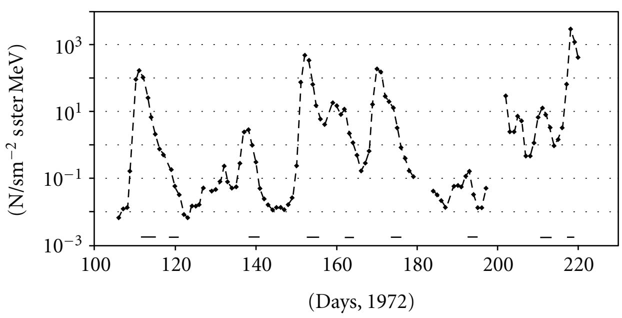

Figure 16: Fluxes of solar protons observed on Prognoz-1. Within 70 days eight increases of SCRs were observed with exponential decay profiles (energy Ep ≈ 1 MeV) of nearly identical characteristic times $\tau = 16.5$ hours. This provides an evidence of long-term (more than two solar rotations) stationary state of the interplanetary medium in the inner heliosphere.

particle intensity as "canyons" (due to the similarity of the spatial structure of fluxes with those in the ground canyons). Figure 17, constructed using IMP-8, Pioneer-11, and Voyager-1 and -2 space probe data, is illustrating that [61].

Such regions of minimum fluxes corotating with the Sun arise due to the existence of constant background fluxes of particles at some minimum level in the heliosphere. During periods of high solar activity the background fluxes are overlapped and they can only be observed during quiet Sun periods, but even that is limited to the observations in some of the sectors of space surrounding the Sun.

Radiation Dose from Solar Flares. For two powerful solar flares, namely, August 4 and 7, 1972, the radiation dose was determined in the interplanetary space from Prognoz satellite measurements [62]. The dose obtained outside of the Earth's magnetosphere was significantly higher than that observed on Earth's orbiting satellites. This is important for the interplanetary missions as well as missions towards the Moon.

High-Energy Gamma Rays and Neutrons from Solar Flares. IEP SAS, Kosice, started satellite measurements of cosmic rays and energetic particles in the cooperation with SINP Moscow and with other institutes in the frame of the Intercosmos programme in 1977. Before that period IEP SAS participated in magnetospheric energetic particle studies by data analysis since the flight of low-altitude satellite IK-3 in 1971, with the instrument constructed at Charles University in Prague. This scientific direction later continued also experimentally and included measurements aboard Prognoz-type satellites too (Intershock, Interball). It has contributed to the understanding of mechanisms important for the identification of sources, transport, and losses of particles within the magnetosphere as well as in the vicinity of its boundary regions like the magnetopause and bow shock as well as in the geomagnetic tail. These scientific tasks are out of scope of this paper. A short summary before 2003 can be found, for example, in [63], and a later review is in [64].

Around 1975, a small experimental group was established at IEP SAS developing electronics and later also completing devices for the measurement of energetic particles in the interval of energies well above those of solar wind but below the typical energies of cosmic rays. Important works in electronics were done by J. Rojko († 2011). One of the authors (K. Kudela), along with organizing measurements on satellites, was dealing with data analysis and its physical interpretation, together with other colleagues (L. Just † 2008, M. Slivka, and others), in cooperation with colleagues in the institutes of the former USSR/Russia and in other countries. This cooperation, based on data obtained from Russian satellites, was significantly enhanced after 1989, by the possibility to collaborate also with colleagues in the US, west Europe, Japan, and so forth.

The first device for measurement in space with participation of IEP SAS was the SK-1 developed jointly with Ioffe Physico-Technical Institute in Leningrad and launched in 1977 aboard the IK-17 satellite. The task was to detect neutrons of solar origin in the vicinity of Earth. Although solar neutrons were not detected, this experiment measured the flux of cosmic ray albedo neutrons and gamma rays at different latitudes in detail [65]. In collaboration with SINP MSU the devices SONGs were constructed (IEP SAS was responsible for the electronic box) for the detection of high-energy neutrons and gamma rays [66]. These devices were in operation onboard the low-altitude polar orbiting CORONAS-I (1994) and CORONAS-F (2001–2005) satellites. CORONAS-F mission: was Especially productive several solar flares with high-energy gamma ray emissions were detected with energy spectra up to >100 MeV as well as with solar neutrons (e.g., [66, 67]), indicating the acceleration of protons in these flares up to very high energies. They also provided information about the interaction of accelerated protons with the residual solar atmosphere (the production of neutral pions with their subsequent decay into two gamma quanta of high energies) as well as showing the timing of acceleration which is in some cases seen as a precursor before the onset of GLE (ground level events) observed by neutron monitors [68, 69].

3. Conclusion

In the conclusion we emphasize that the past 100 years of cosmic ray research allowed to move substantially in understanding the nature of cosmic rays, in clarifying the crucial moments of its generation and propagation in the heliosphere and in Galaxy as well as in understanding the role of the Sun and of the planets in the formation of radiation conditions in the vicinity of the Sun. Apart from the fact that substantial progress in space physics and cosmic ray physics was achieved, there are a number of questions which are not clarified yet. Some of the main open problems are as follows:

(i) the form of the energy spectrum of cosmic rays at very high energies (>10^{20} eV/nucl);

(ii) the change of composition with energy above 10^{17} eV/nucl;

(iii) the determination of the composition of nonmodulated cosmic rays at relatively low energies (<10 GeV),

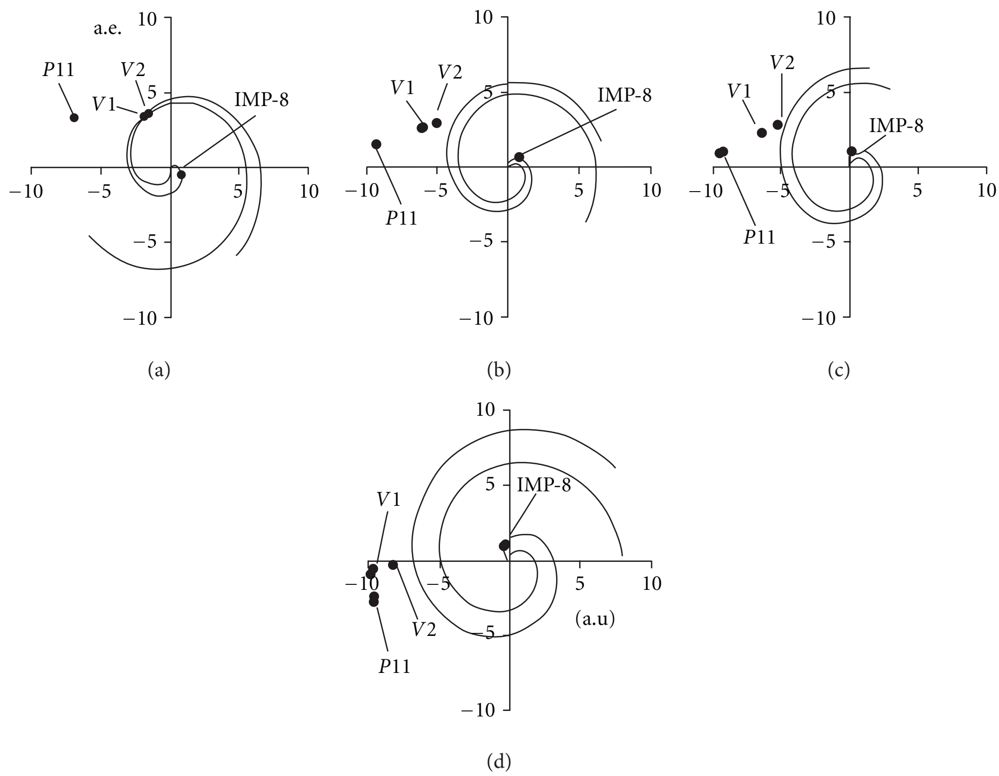

Figure 17: Spatial structures, bordered by spirals of IMF and comprising decreased fluxes of low-energy protons (Ep~1 MeV), projected onto the ecliptic plane. Time periods from left to right: August 22–September 04, 1978; October 29–November 09, 1979; December 06–23, 1979; January 05–23, 1981. The spirals were calculated from solar wind velocities measured on IMP-8 at the beginning and at the end of intervals with "caverns"—intervals with low fluxes of protons.

that is, in the interstellar medium beyond the heliospheric border;

(iv) the influence of cosmic rays on the weather and climate on Earth;

(v) Forecasting radiation hazardous flares with high flux of SCRs putting obstacles for interplanetary propagation of space technology and living organisms.

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