issued a resolution on the training of higher education professionals for conducting this work. To implement this resolution, the Division of the Structure of Matter, now the Nuclear Physics Division, was founded at the beginning of 1949 on the basis of the Structure of Matter chair of the MSU Department of Physics. The division comprised five chairs: Physics of the Atomic Nucleus, Accelerators, Neutron Physics and Radioactive Radiation, Nuclear Spectroscopy, and Cosmic Rays.

Academician D V Skobeltsyn became the first Head of the Division. In 1960, he transferred this position to Sergei Nikolaevich Vernov, who occupied it for twenty years, acting at the same time as Head of the Chair of Cosmic Rays and Space Physics. During these decades, the structure of the division was changing, and new chairs were formed.

On the initiative of D V Skobeltsyn, S N Vernov, and the first Director of the Joint Institute for Nuclear Research (JINR) D I Blokhintsev, a branch of MSU RINP with two chairs was organized in Dubna, so the training of the students of these chairs used the facilities of the JINR.

S N Vernov led the way to organizing an efficient educational process at the Nuclear Physics Division, including the work of the Chair of Cosmic Rays and Space Physics. Initially, Sergei Nikolaevich was the lecturer of the main course, Introduction to the Physics of Cosmic Rays, but then passed it on to other teachers. He never ceased to supervise postgraduates working in MSU RINP laboratories.

Students highly valued meetings with Sergei Nikolaevich, at which he discussed the problems of education, science, and their future. Addressing his students, S N Vernov would say: "Forget your free time on Sundays, your free weekday evenings. If you wish to become true scientists, your time must be wholly devoted to science when working, thinking, reading."

The first graduate students of the Chair of Cosmic Rays were future professors L I Sarycheva, I V Rakobolskaya, S A Slavatinskii, and G B Khristiansen. When it was created, the Chair had few staff, which consisted mostly of moonlighting teachers but with time and S N Vernov's effort the number of teachers kept increasing and the scientific interests of the staff grew wider.

Each year the Chair accepts 10 to 15 third-year students and typically has from five to 10 postgraduates. Diploma and PhD theses are mostly prepared in scientific laboratories of MSU RINP and in the laboratories of the P N Lebedev Physical Institute and the Institute for Nuclear Research of the RAS. More than 20 all-department and special courses are presented to students in the Chair, and specialists are trained in the astrophysics of cosmic rays and in space physics.

Sergei Nikolaevich Vernov regarded the practical work of students in research teams as extremely important. Even long before their graduation date, students ought to take part in work on the most pressing problems and apply modern methods. The more initiative a student shows, the earlier he/she should be exposed to modern science and hardware and should meet those who create this science; it is therefore of key importance to involve the leading specialists of research institutes in teaching university courses. Sergei Nikolaevich Vernov wrote: "Teaching allows leading professionals to throw a closer look at their domain as if from outside, to check the completeness of their knowledge and the credibility of the findings." He believed that experts ought to pass on their knowledge to others and to learn from their students. Sergei Nikolaevich himself never hesitated to learn from his students: he learned computerized methods of data processing, admired the results, then wrote in his notes: "Computers should permeate the entire process of education."

Sergei Nikolaevich had a wonderful ability to quickly notice new phenomena in science and introduce new subjects into teaching courses for students at the Chair and in the Nuclear Physics Division. For instance, the creation of first artificial Earth satellites and the discovery of Earth's radiation belts resulted in organizing a whole range of new lecture courses dealing with issues in space physics at the Chair, and was reflected in its title: Chair of Cosmic Rays and Space Physics.

A new area of research — space materials science — started taking shape at the Chair owing to S N Vernov's initiative. The Chair began to train students in this field and worked in close contact with the appropriate division of MSU RINP. S N Vernov also initiated the founding of this new specialization for students at the Moscow Institute of Electronic Engineering, where he gave lectures on space materials science.

Also on S N Vernov's initiative, research on high-energy physics at accelerators and on the physics of ultrahigh energies in cosmic rays intensified and this immediately stimulated adding new special courses to the curricula and to starting the training of students in these new fields. Another new feature was launching at the Chair a special course on neutrino astrophysics in response to new advances in this sphere. Sergei Nikolaevich wrote: "We need to be able to train experts, and fast, in areas which simply did not exist in the past." In fact, almost all research teams of the physics institutes now working in the field of cosmic rays and neutrino astrophysics are former graduates of the Chair of Cosmic Rays and Space Physics.

In parallel with training specialists in narrow problems, Sergei Nikolaevich Vernov also regarded it as necessary and very important to think ahead about training researchers with a very broad span of skills and interests. He himself was a person of this ilk. The MSU Department of Physics highly values everything accomplished by S N Vernov in expanding higher education in cosmic ray physics and space physics along the latest directions.

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Coming of age and development of space physics at Moscow State University. Radiation in space: the legacy of S N Vernov

M I Panasyuk

1. Introduction

This paper presents a brief retrospective review of the main results of a research in the field of space physics obtained at the Lomonosov Moscow State University (MSU) in the

M I Panasyuk D V Skobeltsyn Institute of Nuclear Physics,
M V Lomonosov Moscow State University, Russian Federation
E-mail: panasyuk@sinp.msu.ru

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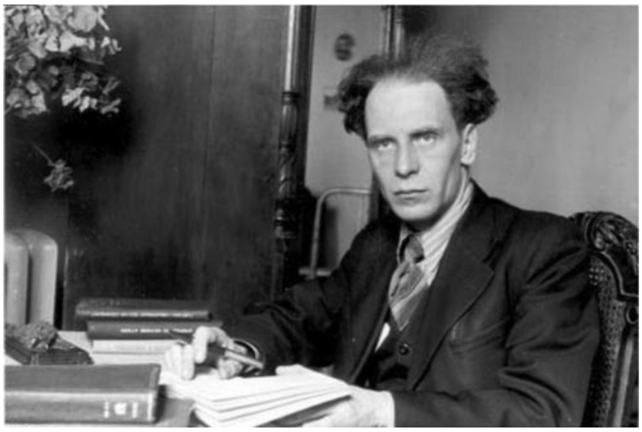


Sergei Nikolaevich Vernov

course of experimental and theoretical studies of radiation, cosmic rays, and magnetic fields in space. At the onset of this work was the outstanding Russian scientist Sergei Nikolaevich Vernov, the Deputy Director and then Director of the MSU Research Institute for Nuclear Physics (RINP); at the beginning of space age he laid the foundation for the establishment of space physics as a science in our country.

Space physics constitutes a science studying electromagnetic and radiation fields in the interplanetary space and nearby planets, space acceleration processes, particle emission and plasma sources in space, and the influence of solar radiation on the circumplanetary space and the physical processes on the planets themselves. Since its research subject includes physical processes in the Universe, space physics can be considered an astrophysical area.

Two outstanding scientists faced the source of space physics — Sergei Nikolaevich Vernov and James A Van Allen — experts in cosmic ray physics. As early as the ‘pre-satellite age’, they conducted experiments to study space particles on Earth, using sounding balloons and rockets. When space experiments became possible, they independently of each other and almost simultaneously suggested that their instruments be set up on the first artificial Earth satellites.

The beginning of space physics as a separate area of scientific research is undoubtedly related to the first satellite launches in the Soviet Union and USA. However, its foundations both here and in the US were laid long before Earth’s first Sputnik was launched in the Soviet Union on 4 October 1957.

Below, the main milestones of space physics development at MSU RINP, directed by Academician S N Vernov from 1960 to 1982, are reviewed.

2. From sounding balloons to first space experiments

In the mid-1930s, S N Vernov suggested using sounding balloons for remote sensing of cosmic rays in the stratosphere (Fig. 1). In our country, these were the first experiments to investigate the interaction processes of primary cosmic rays with Earth’s atmosphere. They were conducted by using ionization chambers installed on sounding balloons. As a result of these experiments, the presence of electron-nuclear showers of secondary cosmic ray particles produced in the atmosphere was proved (S N Vernov et al., 1949) [1].

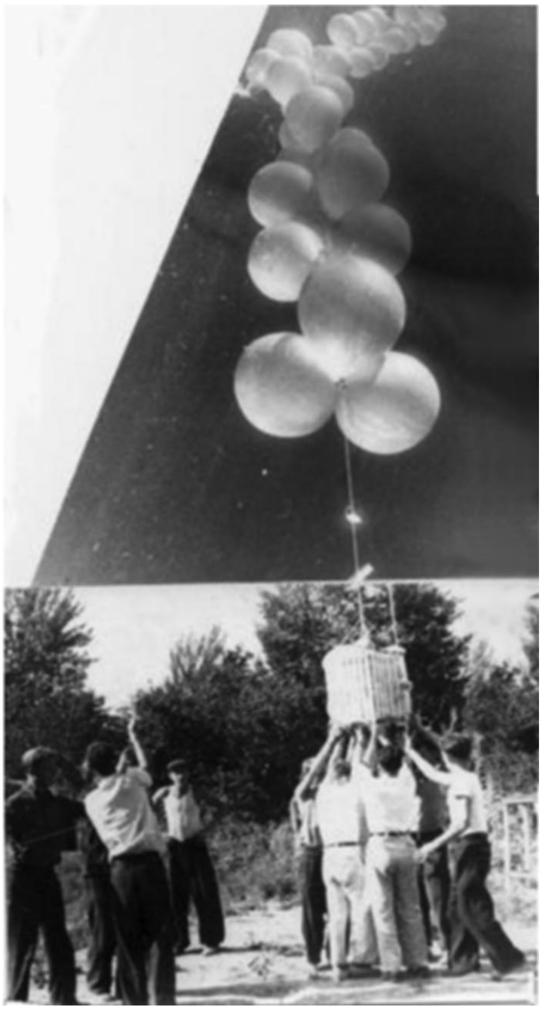


Figure 1. Sounding balloons.

Naum Leonidovich Grigorov and Alla Ivanovna Savel’eva.

However, the nature of primary cosmic radiation was not clear until the end of the 1940s. Here, stratospheric studies of the rays arranged aboard the Vityaz’ research ship played an outstanding role. Using an original device based on Geiger counters that was developed at MSU RINP under the supervision of N L Grigorov, a series of experiments was conducted that helped clarify the nature of primary cosmic radiation. It was discovered that protons form the main cosmic ray component near our planet [2].

Another important issue for primary cosmic ray research during those years was determining cosmic ray energy. The

Dmitry Vladimirovich Skobeltsyn.

idea for a measurement method was hinted of by the process itself — primary particle interaction with the atmosphere and production of the secondary particle cascade, discovered by D V Skobeltsyn in 1936. This idea was realized in the ionization calorimeter constructed by N L Grigorov, V S Murzin, and I D Rapoport in 1958. The calorimeter played a revolutionary role, not only in cosmic ray physics, but subsequently in high-energy accelerator physics, as well.

Implementation of the ionization calorimeter began with national cosmic ray studies in the Caucasus and Pamir mountains. Already the first experiments on Mount Aragats in Armenia provided estimates for a spectrum of single hadrons over the 1–10 TeV energy range and their integral spectrum index. Construction of high-luminosity devices using the ionization calorimeter method opened up wide possibilities of investigating the nature of primary cosmic rays. However, these instruments should have been launched to altitudes where the atmospheric influence had no effect on the change in the primary cosmic ray composition and energy spectrum. The possibilities were realized later, with the beginning of the space age and development of high-altitude balloons and rockets. In 1946, S N Vernov and A E Chudakov began to investigate the cosmic ray composition by using rockets at the Kapustin Yar missile range.

Thus, the 'pre-satellite' phase of cosmic ray research resulted in understanding the nature of the secondary component produced in Earth's atmosphere and determining the primary component of cosmic rays — protons — and the first estimations of the spectral shape of primary cosmic rays. These results were mostly obtained by utilizing ionization chambers, Geiger–Müller counters, photo emulsions, and ionization calorimeters. These were the detectors that made up the experimental research base before the first sputnik launches.

The program of the first satellite launches already presumed on-board scientific experiments. Space physicists, in contrast to other researchers, were perhaps the best equipped at the beginning of space studies. First, they had a well-substantiated research idea — the need to continue cosmic ray research outside Earth's atmosphere aiming to clarify the nature, energy, and composition of particle fluxes. Second, there was experimental equipment developed and proven in terrestrial conditions and stratospheric studies.

The first space experiment was set up on Sputnik-2 launched in November 1957. Weight and space payload restrictions made it possible to place only gas-discharge Geiger–Müller counters aboard. The American scientists did the same: the payload of Explorer-1, the first American satellite, involved similar counters. A larger-scale experiment with various types of detectors was conducted later on the third Soviet sputnik.

Results obtained by the first artificial Earth satellites were unexpected. Already in 1958 they led to the first outstanding discovery in space — detection of Earth's radiation belts. Essentially, it turned out that scientists aiming to continue cosmic ray studies beyond the atmosphere encountered a new natural phenomenon — particle trapping and acceleration in Earth's magnetic field.

3. First discovery in space — Earth's radiation belts

The road to this discovery was short and dramatic. The first instrument to study cosmic radiations — KS-5 — on the basis of a gas-discharge Geiger–Müller counter, developed under the supervision of S N Vernov, was installed on the second Soviet Sputnik-2 (Fig. 2). A similar device was mounted by van Allen on the American satellite Explorer-1. The first research data from circumterrestial orbits were obtained in November 1957 in the Soviet Union, and in January–February 1958 in the USA. Both teams encountered a completely new natural phenomenon — charged particles trapped by Earth's magnetic field. It should be noted, however, that neither S N Vernov nor van Allen or their colleagues could, on the basis of the first experiments, provide a correct physical interpretation of the observed phenomenon. Nevertheless, understanding the physics of the new phenomenon became clearer by mid-1958, i.e., a few months after the experiments in space started.

S N Vernov, A E Chudakov, N L Grigorov, Yu I Logachev, and Yu G Shafer participated in the instrument development and experiment.

Figure 2. (a) Sergei Nikolaevich Vernov, and (b) Research instruments installed on Sputnik-2, the second artificial Earth satellite launched in 1957.

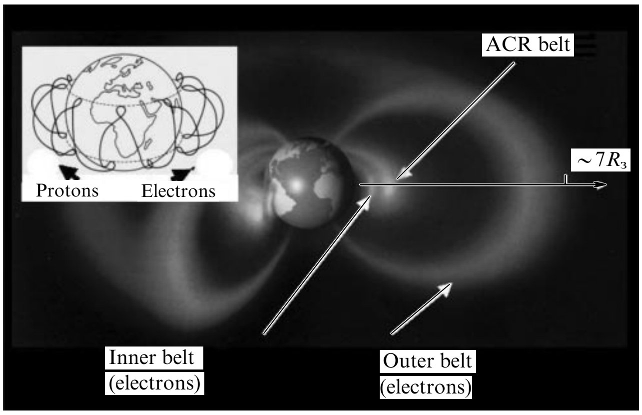


Figure 3. Earth's radiation belts. The inner and outer electron belts are shown, as well as the belt formed by anomalous cosmic ray (ACR) component.

It is the experiment aboard the Soviet Sputnik-3, launched on 15 May 1958, that played a substantial and principal role in clarifying the nature of the discovered phenomenon. Among the various instrumentation designed and manufactured at MSU RINP, a scintillation detector was also mounted on this sputnik. Data from this detector allowed researchers to establish the existence of two spatially separated regions in the circumterrestial space — the outer electron belt filled by electrons with energies $\gtrsim 100$ keV, and the inner proton belt. The energy of the inner belt protons (≈ 100 MeV) was significantly higher than the electron energy in the outer belt. In addition, the altitude dependence of particle fluxes was uncovered, thus indicating particle capture by a magnetic trap (Fig. 3).

The American scientists could not detect the outer radiation belt particles due to characteristics of their satellite orbits. It is now obvious that the first Soviet and American space experiments complemented each other. But, in view of existing international relations, it was impossible to talk about international cooperation at that time, and space physics was developing under conditions of intense competition between scientists of two superpowers.

The essence of the discovery made by the first space vehicles became clear by mid-1958 [3]. It turned out that Earth's radiation belts consist of protons and electrons covering a wide energy range. Calculations demonstrated that the belts are stable formations: particle lifetimes in the inner belt could reach a few dozen years. It was necessary to understand the nature of these particles — their sources and acceleration mechanisms. That took the next 20–30 years. But the first model suggesting the formation mechanism of radiation belts appeared almost immediately after their discovery. This was the production mechanism of secondary energetic protons in albedo neutron decays taking place in interactions of primary cosmic rays with the terrestrial atmosphere. The authors of the model developed at MSU RINP were S N Vernov and A I Lebedinsky (1958) [4]. It is interesting to note that almost simultaneously (and independently) this mechanism of the inner radiation belt formation was suggested by an American, Fred Singer.

The albedo neutron decay mechanism helped to explain the existence of high-energy protons (and, as it turned out later, electrons) in the inner belt near Earth, and over a limited energy range determined by albedo neutron energy. The mechanisms of filling the outer radiation zone with particles were yet to be determined.

Thus, the beginning of space research led to the first outstanding result in the physics of circumterrestrial space — the discovery of radiation belts — and, in essence, to the origin of a new science — space physics.

This period of domestic radiation-belt studies was finished with unmanned spacecraft missions to the Moon. MSU RINP instruments on board these spacecraft helped to obtain the full spatial pattern of radiation belts. In addition, temporal changes in the outer radiation zone were detected that predetermined one of the subsequent vast areas of radiation belt physics — the investigation of their dynamics depending on solar and geomagnetic activities.

The year 1957 can be regarded as a benchmark for space physics as a new research area at MSU RINP. This area later became one of the main ones and gave the Institute a well-deserved high academic reputation.

In that period, a team of space researchers began to form at RINP; at its onset were S N Vernov, A E Chudakov, P V Vakulov, E V Gorchakov, N L Grigorov, A I Lebedinsky, and Yu I Logachev. Already by the beginning of the 1960s, thanks to S N Vernov's efforts, two strong research teams were established at the Institute — the Laboratory of Experimental Designing (OKL in *Russ. abbr.*) headed by A G Nikolaev, and the Space Physics Research Laboratory (LKFI in *Russ. abbr.*) led by I A Savenko.

After the first space experiments, a period of systematic studies of Earth's radiation belts and magnetosphere began.

4. Structure of the radiation belts and radial diffusion model

The first studies of discovered natural phenomenon — radiation belts — showed the presence of temporal and spatial flux variations in them. There were questions: what kind of variations are there, how stable are the radiation belt formations, and how do their characteristics change depending on solar activity? The first experiments were conducted in the maximum of the solar activity cycle; therefore, the question of their stability during the whole cycle was open.

The Elektron series sputniks launched in 1964 with MSU RINP's research instrumentation aboard played a large role in systematizing the knowledge of the structure and dynamics of trapped radiation. Thanks to well-chosen sputnik orbits and composition of payload instruments, almost the whole radiation belt region was investigated for the first time: the proton and electron distributions in energy and space over a wide energy range, as well as their temporal variations. It was these data that were used as the basis for domestic models of the near-Earth radiation that were included in a number of regulatory documents for the space industry and in the first and subsequent editions of the collected papers *Space Model*, published over many years under the supervision of S N Vernov [5]. The results obtained by the Elektron series sputniks represented a significant contribution of the country's space physics to the knowledge of Earth's radiation belts.

The main outcome of the radiation belt studies in the 1960s was perhaps the eventual understanding of the belt's structure: it turned out that the belts are essentially one formation of charged particles (mainly protons and electrons) trapped by the magnetic field and distributed over a very wide energy range — up to a few MeV for electrons, and several hundred MeV for protons. The upper energy bound for trapped protons also coincides with the energy of galactic cosmic rays at their intensity maximum (i.e., on the order of several hundred MeV). The difference between the proton and electron radiation belt structures is essentially in the existence of a gap — a local decrease in particle fluxes at the distance of 2–3 Earth radii in the equatorial plane. From the theoretical modeling viewpoint (see below), the gap is a region of dominant losses for the electron component. However, besides determining the particle loss mechanisms in the belts, the model of their formation should answer the question of how these trapped particles can gain such significant energies.

The first mechanism of radiation belt formation due to cosmic ray albedo neutrons suggested by S N Vernov and A I Lebedinsky could explain only the existence of the inner region of trapped radiation — protons with energies exceeding several dozen MeV, and electrons with energies up to 1 MeV. What the 'accelerator' was for all other particles — essentially the main part of the radiation belts — was an open question.

A theoretical model practically explaining almost the complete space–energy structure of radiation belts was developed by the mid-1960s. It was based on the diffusion mechanism of particle transport in a magnetic field under the action of electric and magnetic field fluctuations in the circumterrestrial space. The approach turned out to be very productive; this can be justified by the fact that even to date radial particle diffusion is considered the basic mechanism in explaining experimentally found space and energy distributions of particles confined inside a magnetic trap.

Radial particle transport is caused by electric and magnetic field fluctuations in the magnetosphere, whereas the fluctuations themselves are caused by solar wind pressure changes. Particles moving inside the trap across magnetic field lines increase their energy due to the betatron acceleration mechanism and conserve the particle magnetic moment — the first adiabatic invariant. Thus, particles from the magnetospheric tail which can serve as a kind of reservoir — solar wind particle storage ring — are taken into the magnetic trap where they are accelerated in the transport process.

The idea of particle diffusion inside a magnetic trap in the presence of magnetic field perturbations was first proposed by E Parker. Later on, this mechanism was developed by several authors. Among these studies, a model elaborated by B A Tverskoy was substantially different from others [6, 7]. This model was in good quantitative agreement with experiments and could explain many space–energy structure characteristics of proton and electron radiation belts. The substantial difference between Tverskoy's model and other models was the statement on predominant realization of the radial diffusion mechanism *only* due to magnetic field fluctuations and the correct estimation of the diffusion coefficient from an analysis of frequency and amplitude of magnetic field perturbations of a sudden pulse type. Tverskoy's first publications were issued in 1964–1965, outstripping publications by foreign authors on quantitative radial diffusion models for radiation belt particles with their statement on the combined effect of large-scale electric field fluctuations inside the magnetosphere and magnetic field fluctuations themselves as the main paradigm.

The Elektron series sputnik data were important experimental proof in favor of Tverskoy's model (see below). The spatial proton distributions for various energies obtained in experiments on those and other satellites agreed well with Tverskoy's model — the model of radial particle diffusion appearing in the presence of magnetic fluctuations. Moreover, the electron diffusion wave parameters (radial electron flux profile displacements to Earth after magnetic storms) observed in the Elektron sputnik experiments agreed with the magnetic diffusion coefficient proposed by B A Tverskoy. Nevertheless, many experimental data in a number of foreign studies published in those years were in agreement with the model of the 'symbiotic' effect of electric and magnetic field fluctuations.

Boris Arkad'evich Tverskoy.

The contradiction was resolved by the mid-1980s, when, after a series of experiments in space aiming to investigate radiation belts exactly, fairly extensive experimental data were obtained not only on protons and electrons, but also on heavier ions.

Here we should mention a long-term program, initiated by S N Vernov, of radiation belt studies on artificial Earth satellites of the Molniya series. The experiments supervised by E N Sosnovets during the 1970s gave a number of new results on both the belt structures and dynamics. The Molniya satellite experiments marked the beginning of setting up a global system of radiation monitoring of the circumterrestrial space at the MSU RINP that subsequently was developed with the use of other satellites: GLONASS (Global Navigation Satellite System), Kosmos, Gorizont, etc. [8].

Besides protons, the solar wind is also composed of helium, carbon, oxygen, and heavier elements. Their relative number densities (concentrations) do not exceed a few percent (for helium) or even less for heavier particles. Despite this, investigation of heavy ions is important for radiation belt physics because it allows in-depth testing of various radiation-belt formation models, as compared with the analyses of proton and electron components only. This is related to the fact that transport coefficients in models can generally depend on both the particle energy and type (i.e., particle mass and charge). In this sense, heavy ions serve as an extremely useful instrument to verify various models. In addition, heavy ions make up original indicators of the particle source. For example, the presence of carbon or multiply charged heavy ions is fairly convincing proof of the concept considering solar wind as a source of trapped particles.

It became possible to conduct such experiments from the mid-1970s. The first experiment to study energetic heavy ions in radiation belts was realized on the Molniya-2 sputnik by this article's author and collaborators. This experiment, along with some others, allowed us to establish the space–energy structure of the equatorial ion belts that was used to test various radial diffusion models. All these experiments, together with foreign ones, composed the data bases concerning the structure of radiation belts and allowed establishing applicability boundaries for various models of particle's radial diffusion.

It turned out that 'magnetic diffusion' (particle transport under the action of magnetic field fluctuations) with the diffusion coefficient proposed by B A Tverskoy indeed describes most of the space–energy structure of radiation belts. However, fluctuations in the magnetospheric electrostatic field also participate in radiation belt formation. Nevertheless, their effective influence is limited only by low particle energies (less than several hundred keV) and, possibly, by the inner radiation zone in the energy range exceeding a few megaelectron-volts (M I Panasyuk, 1984) [9].

Such was our knowledge of radiation belts generally by the mid-1980s; it remains relevant to date. Recall the most important points.

(1) Radiation belts consist of electrons and protons (the main components) with a relatively small heavy ion 'addition'.

(2) Their formation mechanism is radial diffusion under the action of magnetic and electric field fluctuations in the magnetosphere and cosmic ray albedo neutron decay. Magnetic diffusion dominates in radial particle transport. The albedo neutron decay ensures the population of the inner zone of trapped radiation by high-energy protons.

(3) The particle sources for radiation belts are cosmic rays (the inner radiation zone) and solar wind plasma injected from the magnetospheric tail toward the interior of the trapping region.

The substantial advance in understanding the structure of Earth radiation belts was made by S N Kuznetsov and V D Il'in, whose studies contained quantitative estimates of the particle adiabatic motion limit in the geomagnetic field according to the Alfvén criterion [10]. Here, the outer boundary formation mechanism for particles confined in the trap was revealed for both quiet and magnetically disturbed time periods. The quantitative estimate of the adiabaticity limit for particle motion was subsequently decisive in determining the nature of heavy ions trapped in radiation belts. It turned out that the charged states of energetic ions (of MeV energy), such as oxygen, carbon, and iron ions populating the radiation belts, are close to those observed for solar plasma and energetic (i.e., multiply charged) particles. That favors the solar origin of trapped particles.

Studies of heavy ions in radiation belts helped in revealing another mechanism of their formation. It was shown that protons of the inner radiation zone inside the loss cone (in the South Atlantic Anomaly region) produce new secondary particles (e.g., helium) as a result of interaction with atmospheric atoms. These (secondary) particles appearing in the trap form an additional (to the main one formed by radial particle transport to Earth) belt of trapped particles. This effect was first revealed in the low-altitude Interkosmos-17 sputnik experiment (S N Kuznetsov et al., 1981) [11].

The discovery at the beginning of the 1990s of a new radiation belt comprising cosmic ray anomalous component particles was also important for understanding radiation belt physics (N L Grigorov, M I Panasyuk et al.) [12]. It appeared that singly charged oxygen ions (and those of other elements) being constituents of the anomalous component can be trapped in stable orbits after charge exchange in the upper atmospheric layers, thus forming the particle population composed of the substance of the nearby interstellar medium.

5. Ring current and magnetospheric storm model

Solar wind plasma penetrating deep into Earth's magnetosphere was considered the main 'substance' to replenish the belts from the very beginning of radiation belt studies. This hypothesis could be fully approved or refuted only by direct space experiments to measure the particle ion composition in the trapping region. There was another problem closely related to the physics of circumterrestrial plasma and energetic particles — the generation mechanism of magnetic storms. Long before the start of space studies, A Dessler suggested that the ring current is a source of Earth's magnetic field perturbation. But only after direct satellite experiments began has the opportunity to finally solve this problem been realized.

It became clear by the beginning of the 1970s that most of the particle energy in radiation belts is accumulated in the proton component with energies of several dozen keV — the so-called hot plasma region. However, there were no measurements of such low-energy protons. It was also important to conduct an experiment in the equatorial plane where the maximum energy density of the ring current particles should be observed. Such measurements were first done by the Explorer-45 satellite and a bit later by MSU RINP on the Molniya-1 and Molniya-2 satellites (E N Sosnovets, M I Panasyuk, A S Kovtyukh et al.) [13]. These experiments confirmed that protons with energies from a few dozen keV to approximately 200–300 keV are indeed the most important component of Earth's ring current determining its energy characteristics. It turned out that particle density variations of exactly this component of near-Earth radiation correspond to the basic Dessler–Parker–Sckopke formula relating the geomagnetic field change to energy stored by ring current particles.

In contrast to radiation belt particles, ring current particles are more influenced by the magnetospheric electric field. Therefore, detection of longitudinal asymmetry for the ring current injection at the initial stage of a magnetospheric storm (mostly in the evening sector) was not a surprise from the viewpoint of the particle drift (in crossed electric and magnetic fields) model, and completely agreed with previous satellite magnetic field measurements.

The role of magnetospheric electric field variations in particle dynamics inside the trapping region was considered in detail by B A Tverskoy in 1969 [14], and characteristic features of the ring current dynamics during magnetic storms became additional arguments in favor of this model.

The subsequent stage of acquiring knowledge about the ring current as a plasma formation responsible for Earth's magnetic field variation during magnetic storms was related to two newly discovered experimental evidences that did not fit the picture of the proton ring current. First, in 1972 American researchers succeeded in detecting on a low-altitude polar satellite an increase in fluxes of singly ionized oxygen ions in the course of magnetic storms. This was the first indication of the potential existence of a particle source, besides solar wind plasma, in the nearby magnetosphere, namely, in the ring current itself — ionospheric ions. Second, studies of the ring current during strong storms indicated an insufficient particle energy density for the ring current consisting of protons, as compared with the magnetic field energy density in the storm's main phase. It became evident that the ring-current energy 'deficiency' should be looked for in another — ionospheric — source capable of providing the ring current with particles heavier than solar wind protons. Such experiments were simultaneously started up in 1984 in the USSR using the geostationary Gorizont sputnik, and in the USA within the AMPTE (Active Magnetospheric Particle Tracer Explorers) experiment.

These experiments indeed revealed a significant role of ionospheric plasma in ring current formation. Thus, the energy deficiency problem of the ring current was removed in the main and a new particle source — the ionospheric plasma — was ascertained for ring current, as well as for radiation belts. The ionospheric plasma differs from solar particles due to the presence of a significant number of weakly ionized oxygen atoms. Their relative concentration in magnetic storms can reach or even exceed the hydrogen density.

A substantial role in studying solar and ionosphere plasma dynamics was played by experiments conducted in the 1980s–1990s with the geostationary Gorizont sputniks thanks to the long-term successful collaboration (started from the beginning of the 1970s) between RINP and the 'Applied Mechanics' Scientific Production Association (SPA) in Krasnoyarsk. In these experiments, we were able to obtain unique data on solar and ionospheric plasma flux variations (M I Panasyuk, E N Sosnovets, A S Kovtyukh et al.) [15] and extract the adiabatic component of these changes. The adiabatic component is important for identifying the injection mechanism (A S Kovtyukh, 1998) [16]. It was shown that only particles with energies not exceeding a certain limiting value are injected into the magnetic trap during storms. The fluxes of sufficiently high-energy particles vary adiabatically only in the outer regions of the trapping zone. Moreover, it was established that the spectra themselves can be different for injected ions of solar and ionospheric origin.

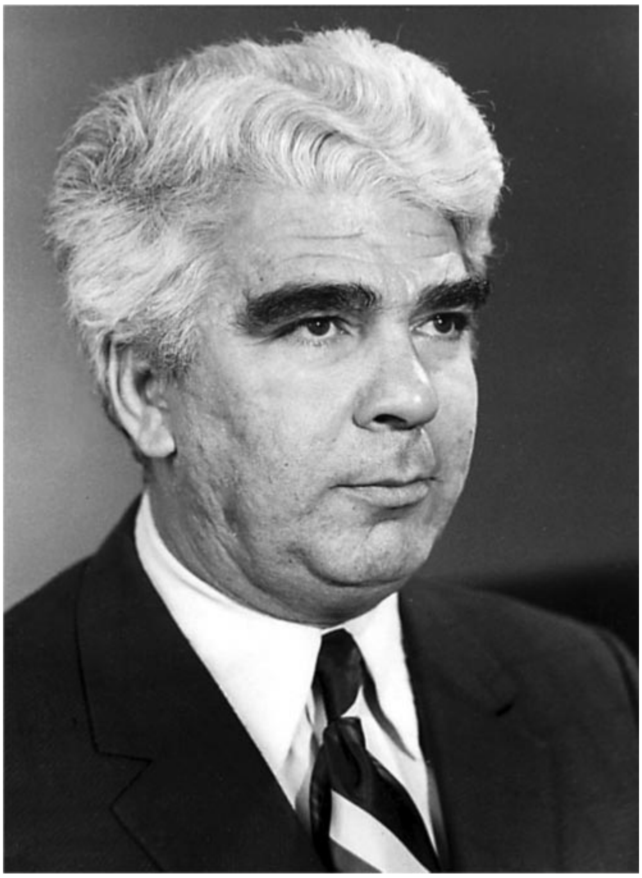
The discovery of ionospheric source for ring current ions made it necessary to theoretically interpret the mechanisms of particle injection from the ionosphere and of particle acceleration. A large contribution to solving this problem was made by E E Antonova, who considered magnetostatically equilibrium longitudinal currents generated by azimuthal pressure gradients [17]. The latters appear due to developing instability of the radial gradient or due to electric field potential distribution over the polar cap, which is imposed from outside. As a result, the following pattern of ionospheric particle injection into the ring current is realized.

The dynamics of the magnetospheric current system are such that substorms and microsubstorms (mostly with the southern direction of the interplanetary magnetic field) occur in the region of transition from dipole lines to magnetic field lines stretched into the tail; the storms are accompanied by an emerging hot plasma bunch or bubble that is not in equilibrium with the surrounding plasma. Some part of the heated plasma is injected into the inner magnetosphere forming the ring current, and another part into the tail forming a plasmoid moving out of Earth.

The heavy ionospheric ion 'contribution', however, has not solved completely the ring-current magnetic effect problem considered according to the Dessler–Parker–Sckopke relation. It appeared that in unique superstorms (with amplitudes $D_{\rm st}$ exceeding 200–300 nT) the energy of the ring current consisting of protons and electrons was not yet sufficient to explain the observed $D_{\rm st}$. It has become evident that contributions to the magnetospheric field variations of ionospheric current systems, Birkeland currents flowing along magnetic field lines, current sheets in the magnetospheric tail and in magnetopause are very important and can even dominate (A S Kovtyukh, 1977) [18].

Problems of the dynamics of magnetospheric current systems were also developed theoretically at MSU RINP. The basics of Earth's magnetospheric field model were laid by V P Shabansky in the 1960s [19].

Later on, in the 1990s, a dynamic ('paraboloid') magnetospheric model was constructed that allowed investigating the dynamics of magnetospheric current systems and their contribution to geomagnetic field variations, and possibly during strong magnetic storms [20]. Magnetospheric magnetic field variations are described in this model by temporal variations of magnetospheric current system parameters that are unambiguously determined from the aggregation of data sets of the near-Earth space measurements. The dynamic model of the magnetospheric magnetic field developed at the Institute is used to analyze interactions of the magnetosphere with coronal ejections causing strong geomagnetic disturbances — magnetic storms and substorms. Currently, the International Standardization Organization (ISO) accepted MSU RINP's dynamic magnetospheric model as the basis for the international standard.



Velior Petrovich Shabansky.

Another conceptual approach to studies of ring current dynamics was developed by B A Tverskoy [21]. This approach is based on the existing difference between plasma pressures in the inner and outer magnetospheric regions during the asymmetric part of geomagnetic disturbances. It was shown that even small plasma pressure at significant geocentric distances can substantially contribute to the ring current energy inside the trap. This approach, however, does not remove the problem of developing strong storms, which is related to 'switching on' strong longitudinal currents and powerful ionospheric ion fluxes directed inward the geomagnetic trap.

The detection of a new — ionospheric — particle source in the inner magnetosphere resulted in the necessity of additionally studying the structure of trapped particles with energies higher than those in the ring current plasma, i.e., radiation belt particles. The ring current plasma consisting of the solar wind and ionospheric particles is undoubtedly the particle source for the radiation belt. In terms of the transport equation, this means that the boundary conditions are defined separately for solar and ionospheric particles.

Thus, the current concept is that the radiation belts and ring current constitute multicomponent particle populations occupying the inner magnetosphere. Apart from solar plasma, solar energetic particles, galactic cosmic rays, and the anomalous component, their sources also include ionospheric plasma as an integral part.

6. Dynamics of radiation belt particles and the injection problem

Studies of variations of Earth's radiation belt particle fluxes began immediately after their discovery. We already mentioned above variations of particle fluxes in the outer radiation belt detected by Sputnik-3. It is now clear that there are many mechanisms responsible for the radiation belt particle variations.

From the viewpoint of the transport equation, changes in the space–energy structure of trapped particles depend on the diffusion coefficient which, in turn, is determined by solar wind parameters in the interstellar medium and depends on the current heliophysical state (e.g., on coronal mass injections in the interplanetary medium), as well as on long-term solar-cycle changes. Therefore, the diffusion coefficient is determined not only by the amplitude of geomagnetic disturbances, but also by their frequency. The 'magnetic' diffusion coefficient determined by B A Tverskoi [22] corresponded to the perturbed-average geomagnetic situation, and therefore defined an 'average' space–energy belt structure.

Measurements made in the mid-1960s with the Elektron series sputniks (S N Kuznetsov, E N Sosnovets, V G Stolpovskii et al.) [23] demonstrated a large variability in the outer electron radiation belt and relative stability of the proton belt. Electron diffusion waves detected in the magnetic storm recovery phase showed agreement between their velocity of travel and the 'perturbed-average' transport coefficient, which confirmed the 'magnetic' diffusion concept for radiation belt particles. In addition, it became obvious that fast changes in electron fluxes can be related to magnetospheric exposure to large-amplitude single pulses of solar plasma pressure, leading to anomalously fast, compared to the transport velocity determined by the perturbed-average diffusion coefficient, particle motion inside the trap.

The characteristic dependence of changes for the electron profile maximum position ($L_{\max}$) on the maximum value of the geomagnetic activity index $|D_{\rm st}|_{\max} \sim L_{\max}^{-4}$ (L V Tverskaya, 1992) [24] obtained on the basis of numerous satellite measurements (Molniya-1, Kosmos-900, Meteor, etc.) leaned toward the mechanism of adiabatic changes for electron fluxes in connection with the injection of the ring-current plasma cloud under a disbalance of inner and outer plasma pressures (B A Tverskoi, 1997) [21].

However, the case that is the most significant in its effects, disturbing the typical space–energy electron belt structure, was the discovery of accelerated electrons with an energy ≈ 15 MeV in the radiation belt core ($L \approx 3.5$) during the recovery phase of a geomagnetic storm by E V Gorchakov (1977) using the Kosmos-900 sputnik [25]. As a matter of fact, the problem of relativistic electron generation inside a geomagnetic trap emerged, which is being investigated to date.

Currently, the mechanism of electron resonant interactions with ultralow frequency (ULF) waves is considered to be the main one leading to electron acceleration up to relativistic energies. This process proceeds faster than regular particle transport due to sudden geomagnetic field pulses; however, it is too slow to explain the effect of electron and proton resonant acceleration in a few seconds at $L = 2.2-2.6$ up to energies of ≈ 15 and 40 MeV, respectively, revealed by CRRES (Combined Release and Radiation Effects Satellite) mission in 1991.

This rather rare event in radiation belts is stimulated by powerful bipolar pulses of the geomagnetic field, as was demonstrated by B A Tverskoy in 1993 [26], and by a number of foreign researchers. Such acceleration effects were subsequently observed by the Granat, Meteor, and some other sputniks. Overall, this kind of electron energy variations corresponds to the model of particle acceleration under the action of sudden pulses, but with an amplitude and shape rarely observed in nature.

Another important aspect of the problem of electron dynamics in radiation belts is related to electron losses. Electrons are more influenced by electromagnetic waves (mostly in the ULF range) than ions. This factor, together with Coulomb scattering, determines their lifetime in the trap. Many studies based on domestic experiments have been performed on this topic. First of all, these are experiments aboard satellites of the Kosmos and Interkosmos series done under the supervision of S N Kuznetsov and Yu V Mineev [27]. The problem is mostly clear now; however, there is an issue that needs further investigation. This is the interrelation between natural and anthropogenic effects on the electron radiation belts. The possibility of electron precipitation from the belts caused by anthropogenic factors (terrestrial radio transmitters, electric power lines) has been indicated in a number of studies based on the investigation of low-energy electrons aboard the Mir orbital station (O R Grigoryan et al., 1985) [28]; recently, this was confirmed by the quantitative model estimates of a Stanford research team. Thus appears a picture of the space–energy structure for the inner part of the electron belt and the gap, where it is precisely the anthropogenic component that is responsible for the structure formation.

Thereby, more than 40 years of studies of the electron radiation belt dynamics have led to a fairly consistent model of describing the belt dynamics as an effect of external (solar wind leading to geomagnetic disturbances) and internal (low-frequency electromagnetic field oscillations, including those caused by anthropogenic attacks) factors influencing its space–energy structure.

Another aspect of the space–energy variations of radiation belt particles is related to the question of particle injection from magnetospheric outer regions. This issue is important because almost all radiation-belt formation mechanisms require particles pre-accelerated to quite significant energies. Indeed, in the quasistationary radial diffusion model, the boundary condition is specified by the experimental energy spectrum at the outer boundary of the radiation belts, which is quite different from that observed in the interplanetary medium. Therefore, injection of sufficiently energetic particles into the trap can occur either after their pre-acceleration in distant regions of the magnetosphere or due to bombardment of sufficiently energetic particles from solar cosmic rays.

As regards investigation of particle acceleration outside radiation belts, a number of studies have been done at MSU RINP using high-apogee sputniks of the Prognoz and Molniya series. In particular, it was shown that there is proton, as well as electron, acceleration in the magnetospheric tail during substorms (the Molniya satellite data; L V Tverskaya, M I Panasyuk, E N Sosnovets, 1971 [29]). It is clear now that such short-time bursts of particle fluxes are determined by particle acceleration in the magnetospheric tail as a result of reconnection and/or development of plasma turbulence.

The second injection scenario is related to penetration of solar energetic particles directly inside the trap. Currently, this mechanism is being well investigated on the basis of numerous experimental data gained by low-altitude satellites (Kosmos-900, Interkosmos-17, CORONAS-I, CORONAS-F, and some others).

The dynamics of solar proton penetration into Earth's magnetosphere in the MeV energy range began to be investigated in detail in the 1970s with the Kosmos series sputniks. Thanks to these studies, a method to diagnose the state of the main magnetospheric structure formations was developed. The north–south asymmetry of solar particle penetration into the polar caps was detected for the first time, and the 'open' character of Earth's magnetosphere was confirmed (E N Sosnovets, L V Tverskaya et al., 1976) [30].

Generally, the particle penetration model is reduced to space variations — latitude displacements of the threshold (depending on the rigidity) of geomagnetic cutoff of the internal boundary for injected particles. The geomagnetic cutoff rigidity itself is 'regulated' by geomagnetic storm and substorm amplitudes, exhibiting complex behavior depending on the local time and geomagnetic activity indices (S N Kuznetsov, L L Lazutin, I N Myagkova, B Yu Yushkov, 2004) [31].

The question of how effective the subsequent trapping of these 'fresh' particles is acquires importance from the viewpoint of radiation belt formation. Whereas for electrons this possibility, according to the Alfvén criterion, should be effectively realized, for energetic solar protons the ratio of the Larmor radius to the magnetic field line curvature makes trapping hardly possible in the region adjacent to the injection inner boundary. Nevertheless, recent results (the CORONAS-F satellite data) show that proton (and heavier particle) trapping actually takes place but is a quite rare event (L L Lazutin, 2007) [32]. To establish what the actual physical trapping model for solar particles is and what their further role in radiation belt formation is constitute the focus of current and future studies.

7. Radiation situation in near-Earth space and the safety issue for space flights

In 1960, the Soviet Union started launching the first sputnik spacecraft for the manned flight program. Despite the low orbits of these spacecraft (under the radiation belts), it turned out that there are regions above the South Atlantic with enhanced radiation at lower altitudes, less than several hundred kilometers. MSU RINP's team supervised by I A Savenko participated in the setup of experiments aboard such sputnik spacecraft. It was established that radiation enhancement in this region coincides with a negative Earth magnetic anomaly — the local decrease in the magnetic field strength compared to that in conjugate regions at the same longitudes in the northern hemisphere. As a result, particles drifting around Earth at these longitudes are reflected at southern hemisphere mirror points at altitudes lower than those in the northern hemisphere. Finally, a radiation anomaly is forming that may undoubtedly constitute a threat to manned space flights (S N Vernov, I A Savenko, P I Shavrin, 1964) [33].

These very data of the first sputnik spacecraft allowed researchers to determine the radiation dose at the manned spacecraft altitudes. It turned out that the dose amounts to ~ 20 mrad per twenty-four hours, under the protection of ~ 3 g cm^{-2} for orbits at altitudes of ~ 400 km and an inclination of less than 65°; that does not pose a threat to cosmonauts' flights. Subsequently, radiation dose measurements were made regularly on all manned spacecraft, and the radiation control R-16 setup constructed at MSU RINP (under the supervision of M V Tel'tsov) on the basis of an ionization chamber has been used for more than three decades, to date, to secure the radiation safety of space flights.

Also, MSU RINP was involved, thanks to Vernov's initiative, in the program of large-scale experimental investigation of radiation fields in space for studying their influence on the operation of on-board satellite systems and degradation of structural materials. Detailed investigations of radiation began with the Kosmos-17 experiments in 1961 and later continued, in the 1960s, with the Elektron series sputniks. Since that time, the Institute has become a leader in radiation studies in the circumterrestrial space.

For many years of space radiation field research, numerous descriptive documents have been drawn up for space industry organizations, allowing them to account for and minimize the influence of radiation — one of the most dangerous space factors — on spacecraft systems.

After many years of studies of the radiation space environment, an understanding was established that all sorts of space radiations — radiation belts, solar energetic particles, galactic cosmic rays, secondary albedo radiation, and particles precipitated from the radiation belts — cause various radiation effects, becoming apparent either in their spatial localization in near-Earth space or in the character of their interaction with matter.

For example, radiation belts are sources for dose effects of irradiation. The magnitude of dose effects depends on the geomagnetic activity (on the temporal scale of geomagnetic storms and substorms), as well as on the phase of the solar cycle.

Relativistic electron variations in the outer zone of the trapping region are a striking example of relatively short-time flux increases capable of disturbing the operation of high-apogee and geostationary artificial Earth satellites. This problem was studied using the Molniya-1 and Molniya-2

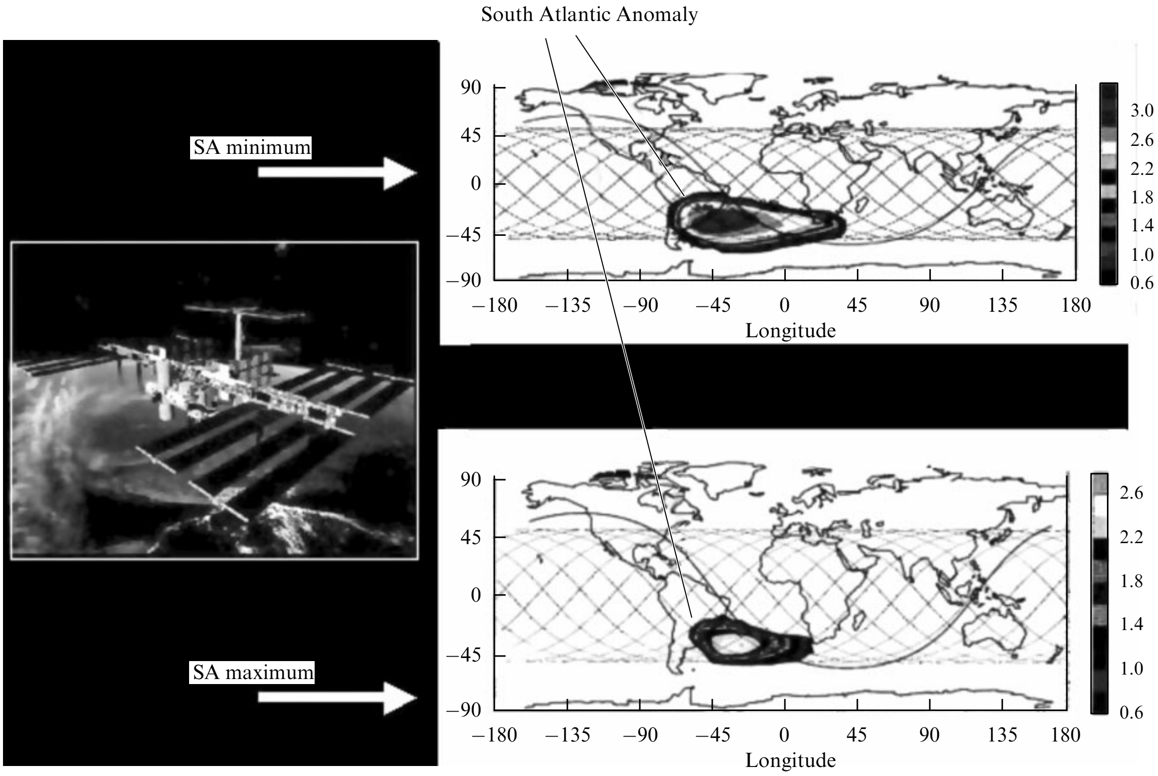


Figure 4. Dynamics of the radiation situation in the South Atlantic Anomaly during the solar activity (SA) cycle: radiation doses in this region increase at the SA minimum, and decrease at the SA maximum.

satellites, Gorizont geostationary satellites, and the Meteor and CORONAS-F polar satellites.

On the other hand, studies of long-term radiation dose variations aboard the Mir station led to the detection of solar-cycle radiation variation at low altitudes in the South Atlantic Anomaly region (Fig. 4), related to the upper atmosphere density and temperature changes (M I Panasyuk, V N Bashkirov, 1997) [34].

In addition to radiation belt particles, solar cosmic rays generated by solar flares and coronal mass ejections are another strong factor increasing radiation risks for space flights. To measure doses of radiation due to galactic cosmic rays and possible solar flares, ionization cameras were installed aboard the Prognoz-1 and Prognoz-2 satellites. During the flares of 4 and 7 August 1972, which were among the ten most powerful registered up to that time, the radiation dose inside the spacecraft exceeded 100 rad.

These results undoubtedly demonstrated the actual radiation hazard for space flights outside Earth's magnetosphere, even within a short time interval.

It should be mentioned that radiation safety of space flights as an area of space physics has a long history of experimental and theoretical studies at the Institute (see Section 8). As concerns the problem of radiation situation changes due to the generation of solar cosmic rays (SCRs), among the most important results in this area are:

- studies of SCR penetration into the inner magnetosphere and, in particular, the low-altitude orbits of manned spacecraft, demonstrated that SCRs are a powerful source of radiation load during strong solar flares that are accompanied by geomagnetic disturbances observed in various orbits, including low ones ($\approx$ 400 km);
- studies of SCR flux variations during solar events in the interplanetary medium demonstrated the close connection between particle fluxes observed near Earth and the localization of active solar regions and shock wave propagation through the interplanetary medium.

A large role in the systematization of information on solar cosmic rays was played by the *Catalogue of Solar Cosmic Rays*, published with the participation of RINP's researchers (Yu I Logachev et al., 1986) [35], and by the probability SCR model (R A Nymmik, 1999) [36].

Among the risk factors of radiation in space, galactic cosmic rays (GCRs) are special. Owing to their extremely low fluxes, GCRs cannot lead to a significant radiation dose load. However, it became evident at the end of the 1970s to the beginning of the 1980s that exactly this space radiation component disturbs the operation of satellite-borne electronic systems, when microvolumes are locally damaged (single malfunction effects) by, first of all, heavy nuclei (e.g., iron nuclei). Currently, these effects are being well studied and a model has been developed to calculate them depending on the parameters of the satellite orbit and heliogeophysical situation (N V Kuznetsov, 2001) [37].

8. Studies of solar energetic particles

The first measurements of solar particles outside Earth's atmosphere were done aboard the Soviet Sputnik-3 in July 1958. These particles appeared after a strong solar flare and created near Earth intensive fluxes of 100-MeV protons with radiation dose of approximately 100 rad. Over all the history of space research, there have been only a few such powerful flares.

Later on, SCR research was done at MSU RINP on all spacecraft launched to Venus, Mars, and the Moon. Interplanetary spacecraft included instruments to detect protons in a wide energy range, starting from $\approx$ 100 keV. Measurements of such low-energy particles demonstrated that solar flares generating low-energy particles occur significantly more often that those with higher-energy particles.

The first SCR studies helped to establish main regularities of particle propagation in the interplanetary space: the presence of diffuse type (slow) events characterized by slow scattering, as well as that of fast, pulse type, events. These data form the basis to make a comparison with results of various theories covering particle propagation processes. Numerous experiments on interplanetary spacecraft have given a unique extensive series of homogeneous data on SCR variations far from Earth. The main conceptions on the structure and dynamics of the interplanetary medium and on the propagation and modulation of cosmic rays have been formulated (G P Lyubimov et al.) [38, 39].

An important role in SCR research was played by experiments aboard the Prognoz series sputniks. From 1972 to 1985, 10 such sputniks were launched. Their payloads included various instruments to study both the energy distributions and the composition of charged solar particles and the neutral (X-ray and gamma) radiation from solar flares. These first complex experiments managed to investigate accelerated particles of solar origin and allowed researchers to draw a series of important physical conclusions (Yu I Logachev, E I Daibog, V G Kurt, M Ya Zel'dovich, V G Stolpovskii) [40, 41], in particular, the following:

(1) a conclusion regarding the geo-effectiveness of flares taking place in the western hemisphere of the Sun's disk as a consequence of particle propagation along the interplanetary magnetic field lines;

(2) proof of the simultaneous ejection of protons (nuclei) and electrons during solar flaring and determination of the electron yield factor from the accelerating region to the interplanetary space;

(3) the existence of several mechanisms of particle propagation in the interplanetary medium: diffusion, without scattering, and coherent, as well as their superposition;

(4) identification of the different natures of background particle fluxes in the interplanetary medium: solar and galactic. It turned out that the solar component correlating with solar activity dominated at energies of less than approximately 15–20 MeV, while the galactic component dominated at higher energies, with characteristic anti-correlation with respect to the solar cycle.

Simultaneously with intensive experimental studies of SCRs in the interplanetary medium, their theoretical investigations were also developed at MSU RINP. First of all, they were related to possible acceleration mechanisms for particles of solar origin. Already in 1961, B A Tverskoy attempted to interpret quantitatively the observed SCR variations on the basis of the turbulent acceleration mechanism, which led to satisfactory agreement with observed spectra of energetic particles. This acceleration mechanism did not compete with, but rather complemented, another one — statistical first-order Fermi acceleration on shock wave fronts — suggested by other authors (G F Krymskii and some others) in the 1970s. It is the combination of simultaneous action of different particle acceleration mechanisms that allows us to comprehend the complex character of distribution function transformations in the process of particle transport in the interplanetary medium. Nevertheless, many questions regarding the problem of solar particle acceleration and, most of all, the localization problem for the acceleration region in the solar atmosphere itself (in its active regions) and/or in the interplanetary medium, as well as the related problem of ultimate energies for particles participating in active processes, remain relevant to date.

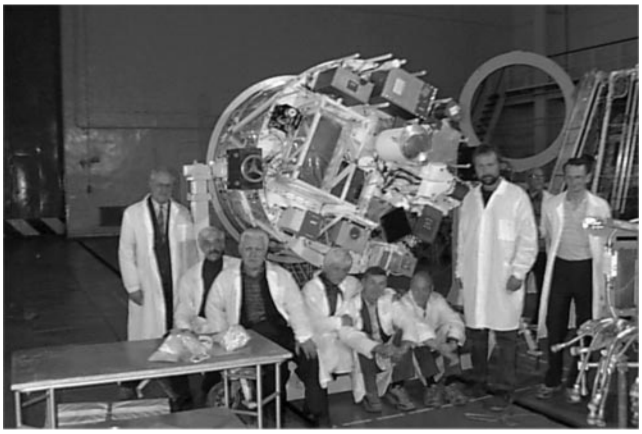


Figure 5. Preparation for CORONAS-I launch (1991).

Recently, investigations of SCR transport and acceleration have been developed on the basis of experiments aboard low-altitude polar satellites of the CORONAS (*Russ. abbr.* for Complex Orbital near-Earth Observations of Solar Activity) series: CORONAS-I, launched in 1991 (Fig. 5), and CORONAS-F, 2001. The last of this series, CORONAS-FOTON, started to operate in January 2009 (Fig. 5).

The CORONAS-F satellite experiment provided a unique opportunity to study solar extreme events in the declining phase of the 23-yr cycle of solar activity, accompanied by powerful coronal plasma ejections and energetic particle production. Investigation of solar states and solar–terrestrial relations during periods of exactly extremely low and extremely high activity can provide material for a better understanding of basic physical processes showing their worth under these conditions. Among the important results are experimental proof of the possibility of two-stage particle acceleration in active regions, detected polarization of X-ray radiation, and observation of asymmetry development for activity distributions over the Sun's disk. They have provided new information on the physics of processes in active regions during flares (I S Veselovsky, S N Kuznetsov, L L Lazutin et al., 2004) [42]. The new facts help to clarify the nature (not yet completely understood) of this phenomenon and point to its close relation with subphotospheric layers and processes in the solar interior, and not only with magnetic field and plasma instabilities in the upper atmosphere — the chromosphere and corona. These facts most probably testify to a preferentially fast supply of excessive free energy from under the Sun's photospheric layers. Thus, new substantial arguments favoring concepts of the nonlocal nature of solar eruptive processes have been obtained.

9. Studies of atmospheric radiation

The beginning of optical observations of Earth's atmospheric radiation in the ultraviolet (UV), infrared (IR), and visible ranges by ground-based and space methods is connected with A I Lebedinsky and O V Khorosheva of MSU RINP.

A I Lebedinsky started active research in this area already in 1948 by creating an original wide-angle photographic camera to shoot auroras. This camera was used on ground-based Arctic and Antarctic stations. The analysis of photographic observations on the global network of stations substantially changed the accepted notions on space distributions of aurora zones. It was established that discrete, sharply outlined aurora formations exist along a zone located asymmetrically relative to the geomagnetic pole.

O V Khorosheva demonstrated that the northern lights appear simultaneously at all longitudes, forming a distinctive oval over both the north and south polar caps. That pioneering result predetermined further studies of the interrelation between this remarkable upper-atmospheric phenomenon and global electrodynamic processes in Earth's magnetosphere for many years ahead. It was established that there is a close connection of the asymmetric aurora oval with the large-scale structure of the geomagnetic field and energetic particle fluxes of magnetospheric origin. The low-latitude polar oval boundary represents a projection onto higher atmospheric layers (ionosphere) of the trapped radiation boundary which coincides with the boundary for closed lines of Earth's magnetic field. Observations of the relative position of the electron and proton auroras together with photographic data allowed researchers to explain the northern lights by direct excitations of atmospheric molecules and atoms caused by penetrating particles.

An important role in studies of the interrelation between the northern lights and magnetospheric processes during geomagnetic disturbances was played by the Oval experiment using the Kosmos-900 satellite that began in 1977. Its supervisors were B A Tverskoy and K I Gringauz (Space Research Institute, RAS). Owing to the experimental measurements of plasma, charged particles, and UV radiation, it was possible to understand many relationships between particle acceleration and transport (including precipitation) processes in remote magnetospheric regions and near space — radiation belts — and northern light generation in the upper atmosphere.

The current explanation of the nature of the northern lights is that they are a manifestation of complex magnetosphere–ionosphere interaction process connecting a chain of numerous physical processes occurring in remote parts of the magnetosphere, such as the tail and plasma sheet, ring current, and radiation belts, as well as in the ionosphere. A large contribution to the advancement of theoretical interpretation of magnetosphere–ionosphere coupling was made by the Institute researchers: B A Tverskoy, V P Shabansky, A P Kropotkin, E E Antonova, I I Alekseeva, and some others.

Space research opened the way for geophysical and astrophysical studies of electromagnetic radiation over a wide wavelength range. Optical measurements beyond the visible spectrum significantly increase the information flow which is carried by the electromagnetic radiation from Earth and other celestial bodies.

The first such experiments aimed at investigating electromagnetic radiation from the Moon, Mars, and Venus were carried out by A I Lebedinsky and collaborators already in the 1960s aboard the Automatic Interplanetary Station (AIS). It was these very experiments that allowed them to reveal previously unknown physical characteristics of the lunar and Venusian surfaces.

Studies of Earth's atmospheric night glow in the UV range also related to the first stage of space research. Just those experiments aboard the Kosmos-45, -65, and -92 satellites conducted by A I Lebedinsky, V I Krasnopol'sky, and V I Tulupov in the 1960s to the beginning of the 1970s gave the first reliable data on the latitude variations of molecular oxygen (O_2) and ozone (O_3) [43]. In these essentially pioneering experiments, important results on latitude and seasonal variations of these atmospheric components were obtained. In particular, the decreasing ozone content during increasing solar activity was demonstrated. Besides the basic significance for space physics, investigation of electromagnetic Earth emissions has applied aspects related to securing the safety of space flights (satellite thermal balance, orientation, etc.). These studies were also initiated by A I Lebedinsky with colleagues at the end of the 1960s using satellites of the Kosmos series.

Investigation of the atmospheric glow in the UV range was recently continued aboard the Universitetskii-Tatiyana polar satellite launched in January 2005. The main result was the detection of UV radiation bursts with a huge energy reaching several hundred MJ and even a few GJ (10^9 J) in a pulse for separate events [44]. These phenomena, called 'transient light phenomena', are observed near the equator. It is clear now that these interesting atmospheric phenomena, observed as glow in the UV range and close to the red light range, are also accompanied by gamma radiation and electromagnetic radiation of the low-frequency radio wave range. Generation of fast neutrons is not precluded either, since the energy of gamma quanta reaches approximately 10–20 MeV in the transients. Therefore, we have a completely new class of physical phenomena in the upper atmosphere; recently, their investigation has received great attention in various space research centers. The nature of these phenomena, i.e., the physical generation mechanisms, is not completely clear to date. However, one of the models (Gurevich, 2001) suggests that 'runaway' relativistic electrons appearing in strong electric fields of lightning discharges and propagating upward along magnetic field lines can be responsible for them. Only future experiments can clarify whether these 'runaway' electrons of circumterrestrial lightning phenomena indeed trigger transient light effects in the upper atmosphere.

The next experiment aboard MSU's Universitetskii-Tatiyana-2 satellite launched on 17 September 2009 is exactly to study the nature of atmospheric transients. The sputnik's payload includes a more advanced set of instruments, which allows expanding our knowledge of this new atmospheric phenomenon.

10. Conclusion

Space physics is more than 50 years old. Over that time, scientists of MSU's largest institution — the Skobeltsyn Institute of Nuclear Physics — working in this area have come a long way marked by significant advances in experimental, as well as theoretical, research in space physics. Important fundamental and applied results were obtained. The results of many investigations were successfully realized in the projects of the cosmic branches of industry. A strong team was established — a scientific school capable of continuing studies in this area, thus ensuring progress in space research. There are good prospects for space physics, and the numerous results of recent studies that need further research confirm that. We will always remember the outstanding role that Sergei Nikolaevich Vernov played in establishing this science and creating a research team that achieved significant results.

At the origin of these studies and this scientific school was the distinguished Soviet physicist, one of pioneers of space research — Academician Sergei Nikolaevich Vernov.

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S N Vernov and space physics: Apatity–Leningrad, 1968–1983

V A Dergachev

1. From the biography of S N Vernov (Leningrad period)

Sergei Nikolaevich Vernov (11.07.1910–26.09.1982), an outstanding Soviet physicist, was the first to initiate programs for studying cosmic rays and cosmic radiation with the aid of the first Soviet satellites.

Sergei Nikolaevich was born in the city of Sestroretsk near St. Petersburg. His father was a post office employee and his mother was a mathematics teacher. After graduating from a unified labor high school in 1926, as 'the best graduate of the class' he joined a mechanical technical school and already after one year became a student in the Physicomechanical Department of the Leningrad Polytechnical Institute (LPI) (at present, the St. Petersburg State Polytechnical University), from which he graduated in 1931 with a diploma in engineering physics. The Physicomechanical Department at the LPI, which was founded in 1919 on the initiative of A F Ioffe, was for a long time an incubator for engineers–physicists. Beginning from 1930, being a fourth classman at the LPI, S N Vernov started to work as a temporal researcher at the Radium Institute and then became a postgraduate at this institute. Sergei Nikolaevich recalls that he chose the theme of his doctoral thesis after meeting D V Skobeltsyn at the LPI, whom he considered his teacher and who discovered charged particles in cosmic rays as early as 1927. His choice was naturally related to the study of cosmic rays which became the main field of his research till the end of his life.

Sergei Nikolaevich worked at the Radium Institute from 1930 to 1936. His doctoral thesis was devoted to the study of cosmic rays using Geiger–Müller counters. He wrote an abstract, "Newest data in the study of cosmic rays," where he showed that small-volume gas-discharge counters can be successfully used for both terrestrial and balloon investigations of cosmic rays. Already in 1934, S N Vernov presented a report at the All-Union Conference on Stratosphere Studies, devoted to the issue of cosmic rays.

During the same period, S N Vernov was sent to the Main Geophysical Observatory (Leningrad) to study cosmic rays in

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V A Dergachev Ioffe Physical-Technical Institute,
Russian Academy of Sciences, St. Petersburg, Russian Federation
E-mail: dergach@mail.ioffe.ru

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