

CONFERENCES AND SYMPOSIA

PACS numbers: 01.10.Fv; **01.60.+q**, **01.65.+g**, **07.87.+v**, **94.20.−y**, 94.20.wq, 96.50.Vg, 96.50.Wx; 96.50.S−

Commemoration of the centenary of the birth of Academician S N Vernov (Joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences and the Department of Physics of M V Lomonosov Moscow State University, 16 June 2010)

DOI: 10.3367/UFNe.0181.201102e.0187

On 16 June 2010, a joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS), Joint Physical Society of the Russian Federation, Scientific Council of the Department of Physics of Moscow State University (MSU), Scientific Council of the MSU SINP, RAS Council on Space Research, Coordination Scientific and Technical Council of the Federal Space Agency, RAS Scientific Council on the Integrated Problem of Cosmic Rays and RAS Scientific Council on Physics of Solar–Terrestrial Relations took place at the R V Khokhlov central physics auditorium of the MSU Department of Physics. The session was devoted to the 100th anniversary of the birth of Academician Sergei Nikolaevich Vernov.

The agenda of the session announced on the website www.gpad.ac.ru of the RAS Physical Sciences Division listed the following reports:

Ryazhskaya O G (RAS Institute for Nuclear Research, Moscow) "Opening address";

(1) **Matveev V A** (RAS Physical Sciences Division, Moscow) "A few words about S N Vernov";

(2) **Sadovnichy V A** (M V Lomonosov Moscow State University, Moscow) "S N Vernov as a scientist at Moscow State University";

(3) **Trukhin V I** (M V Lomonosov Moscow State University, Moscow) "S N Vernov as a professor in the MSU Department of Physics";

(4) **Panasyuk M I** (D V Skobeltsyn Institute of Nuclear Physics of M V Lomonosov Moscow State University, Moscow) "Cosmic ray astrophysics before and after 1957";

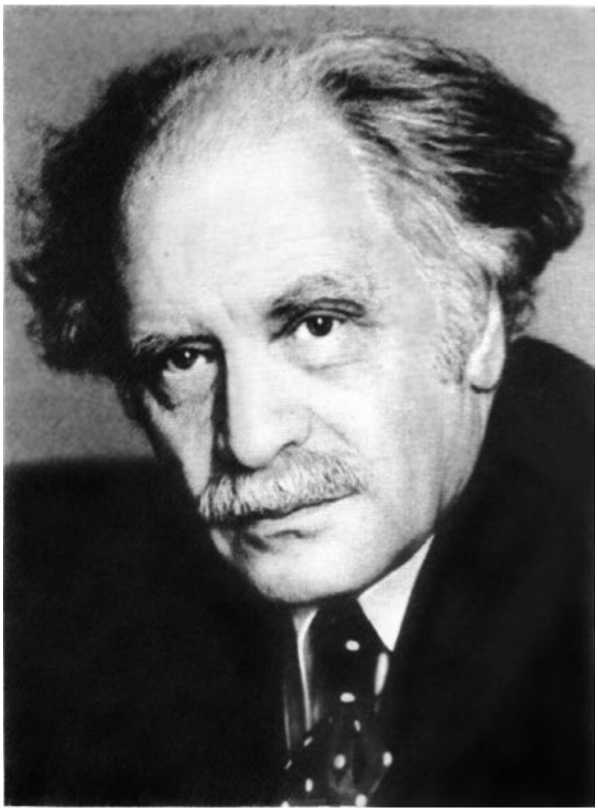
(5) **Dergachev V A** (RAS A F Ioffe Physical-Technical Institute, St. Petersburg) "S N Vernov and space physics: Apatity–Leningrad, 1968–1983";

(6) **Stozhkov Yu I** (P N Lebedev Physical Institute, RAS, Moscow) "S N Vernov and ground-breaking studies of cosmic rays in the stratosphere";

(7) **Berezhko E G, Krymsky G F** (Yu G Shafer Institute of Cosmophysical Research and Aeronomy of the SB RAS Yakutsk Scientific Center, Yakutsk) "S N Vernov and cosmic ray research in Yakutia".

Texts of the articles based on the reports presented are printed below.

Uspekhi Fizicheskikh Nauk **181** (2) 187 – 229 (2011)
DOI: 10.3367/UFNr.0181.201102e.0187
Translated by V I Kisin, S V Vladimirov, M N Sapozhnikov, and V V Lobzin; edited by A Radzig



Sergei Nikolaevich Vernov
(11.07.1910–26.09.1982)

PACS numbers: **01.60.+q**, **01.65.+g**
DOI: 10.3367/UFNe.0181.201102f.0187

Opening address

O G Ryazhskaya

The date 11 July 2010 marks the 100th anniversary of the birth of the outstanding Russian scientist, Academician Sergei Nikolaevich Vernov.

O G Ryazhskaya Institute for Nuclear Research, RAS, Russian Federation
E-mail: ryazhskaya@vaxmw.tower.ras.ru

Uspekhi Fizicheskikh Nauk **181** (2) 187 – 188 (2011)
DOI: 10.3367/UFNr.0181.201102f.0187
Translated by V I Kisin; edited by A Radzig

S N Vernov was one of those who stood at the origins of space physics. His name is inseparable from the breakthroughs and important achievements of space research in the USSR. His work started with cosmic ray physics. The physics of cosmic rays is the field having organic links to other fields of science. The origin of cosmic rays and the processes in which they acquire enormous energies are questions whose solutions can only be found in close contact with astrophysics, radio astronomy, and cosmology. The energy spectrum of cosmic rays extends from 0.1 to 10^{11} GeV, i.e., there exist particles whose energies exceed that of particles generated in modern accelerators by a factor of several tens and hundreds of millions. The study of the interaction between such particles and nuclei led to the creation of elementary particle physics and high-energy physics, with whom the cosmic ray physics continues to maintain a very close link. Cosmic rays throw a bridge between the space and the microcosm.

S N Vernov's span of interests in science was very broad. He carried out a number of fundamental studies in cosmic ray physics and in fields related to them, like elementary particle physics, plasma phenomena, astrophysics, and geophysics, and he was one of the founding fathers who established the foothold in space studies and exploration. Sergei Nikolaevich was the first in the world to develop the methodology of high-altitude automatic studies of cosmic rays using stratospheric radiosondes. With this technique, he measured the flux of cosmic rays in the stratosphere as a function of geomagnetic latitude and proved that most of the energy of cosmic rays is associated with charged particles. Sergei Nikolaevich studied in detail the electron–photon, muon, and nuclear-active components of cosmic rays in the stratosphere, measured the east–west asymmetry in the fluxes of primary cosmic rays, proved that the primary component consists mainly of protons, established the mechanism of production of secondary particles, and obtained indications that the π meson existed. In the 1950s, a unique facility was built under S N Vernov's guidance at MSU for studying ultrahigh-energy cosmic rays, and the energy spectrum of cosmic rays with energies up to 10^{17} eV was obtained. An inflection point was found experimentally at about 10^{15} eV in the energy spectrum of cosmic rays. The establishment of this phenomenon was recorded as a discovery. Its authors were S N Vernov, G B Khristiansen, G V Kulikov, V I Solov'eva, A T Abrosimov, and B A Khrenov.

Many important experiments, first on geophysical rockets and then on artificial Earth satellites and interplanetary probes, were conducted since the late 1940s under S N Vernov's leadership. Using instruments on the first artificial Earth satellites, S N Vernov, A E Chudakov, Yu I Logachev, E V Gorchakov, and P V Vakulov discovered Earth's outer radiation belt and found an explanation for the nature of the inner belt. Detailed studies performed under the guidance of S N Vernov on the sputniks (the Elektron and Kosmos series) led to understanding the structure and dynamics of the Earth radiation belts and to the development of the theory of the belts' origin. Further progress in these studies under S N Vernov's scientific leadership resulted in establishing a number of fundamental laws of solar physics, physics of interplanetary medium, and Earth's magnetosphere and ionosphere. S N Vernov was one of the creators of space materials science and of the study of problems related to radiation safety in the course of piloted space flights.

S N Vernov was an outstanding science administrator. Our ancestors used to say: "For obtaining a good result it is necessary to find the right person at the right time." Sergei Nikolaevich possessed this gift. Owing to his leadership, various research avenues created in space physics continue to produce valuable results.

PACS numbers: **01.60.+q**, **01.65.+g**, 94.20.wq
DOI: 10.3367/UFNe.0181.201102g.0188

A tribute to S N Vernov

V A Matveev

1. Introduction

We have gathered here today to give credit to the memory of an outstanding Soviet scientist, a science and physics education organizer, and Full Member of the USSR Academy of Sciences, Sergei Nikolaevich Vernov.

S N Vernov's name is inseparable from the era of the inception and maturation of the physics of cosmic rays, nuclear physics, and space research.

We pay tribute to the memory of a Russian scientist who built a world-famous scientific school, whose students and followers work actively in many areas of modern fundamental and applied physics, both in this country and abroad.

Sergei Nikolaevich chose which direction to pursue in his research at the beginning of the 1930s when, as a postgraduate at the Radium Institute, he began to study cosmic rays. Only very few people could have foreseen that the study of cosmic rays would become fundamentally important for science and turn new pages in elementary particle physics, as well as in the physics of interplanetary space and interstellar-matter physics. From the very first years of S N Vernov's life in science he was guided in his work by Academician D V Skobeltsyn and worked in close contact with him; time showed that S N Vernov was one of D V Skobeltsyn's most talented disciples.

2. Study of cosmic rays in the stratosphere

The area that S N Vernov started to attack with all his energy was the study of cosmic rays at high altitudes. This meant that experiments inevitably excluded human presence and hence any active participation of the experimentalist in the operation of the equipment. In 1935, S N Vernov realized for the first time in world practice the transmission of information on cosmic rays by radio from balloon probes. This opened a future full of promise for stratospheric, and later for still higher altitude rocket studies [1].

In 1935, S N Vernov went to work for a Doctor's degree at the P N Lebedev Physical Institute (FIAN in *Russ. abbr.*), where his style of research was much influenced by S I Vavilov and D V Skobeltsyn: a combination of daring experiment and profound theoretical analysis.

In 1945 and later S N Vernov launched large-scale stratospheric studies, having set up FIAN's stratospheric station and a special research team at Moscow State

V A Matveev Institute for Nuclear Research, RAS, Russian Federation
E-mail: matveev@inr.ac.ru

Uspekhi Fizicheskikh Nauk **181** (2) 188–191 (2011)
DOI: 10.3367/UFNr.0181.201102g.0188
Translated by V I Kisin; edited by A Radzig

University. This project was aimed at clarifying the nature of cosmic rays and the mechanism of their interaction with matter. New instruments — unique and having no analogs at the time were then designed — which made it possible to draw the conclusion that protons constituted the main component of primary cosmic rays. Many years of devoted work by S N Vernov and his students led to successfully uncovering the nature and mechanism of the generation of secondary components. The results received wide international recognition and numerous confirmations.

Sergei Nikolaevich Vernov's extraordinary success in studying cosmic rays in the stratosphere brought him in 1949 the First-Class State Prize, and in 1953 he was elected Corresponding Member of the USSR Academy of Sciences.

S N Vernov took an active part in building in the USSR a network of stations for continuously monitoring cosmic rays, thus performing an extensive research program. Beginning in 1958, regular daily releases of balloon probes were carried out in a number of locations in the USSR, and after 1963 also in Antarctica. Unique data collected in this way made it possible to identify giant spikes of cosmic ray intensity in the stratosphere caused by solar flares and to form a detailed picture of the effect of the 11- and 22-year cycles of solar activity on galactic cosmic rays [2–4]. In 1976, a group of S N Vernov's collaborators were awarded the Lenin Prize for a series of papers and results on cosmic rays in the stratosphere.

3. Building facilities for studying extensive air showers

S N Vernov was not only an outstanding scientist with a broad outlook, but also an important science organizer who knew how to form a closely knit research team and point it to solving problems in the principal fields of cosmic ray physics.

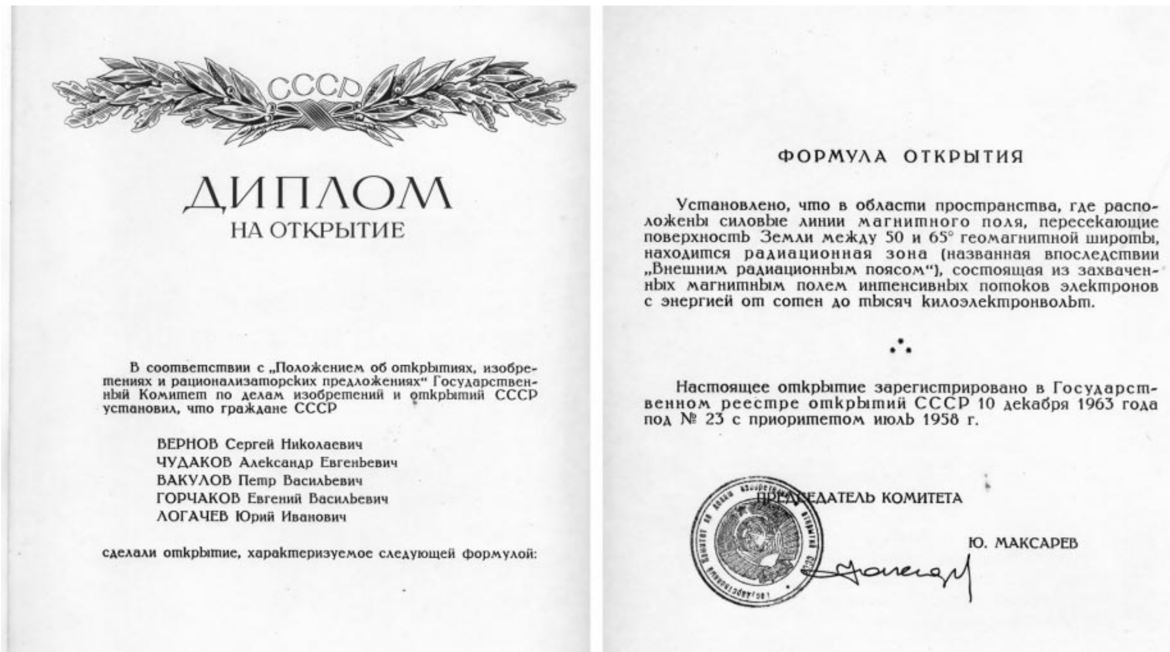
In the late 1950s, a special laboratory building equipped with unique apparatus was erected at MSU under S N Vernov's supervision, designed to study the interaction of particles at ultrahigh energies ($10^{14}-10^{17}$ eV) with matter. The most fundamental observation was the change in the slope of the energy spectrum of cosmic rays in the range of $10^{15}-10^{16}$ eV [5]. This result was certified as a discovery; its significance for profound understanding of astrophysical processes proceeding in the deep space remains great.

In the 1970s, S N Vernov supervised the creation in Yakutia of a new giant facility (covering an area of about 20 km^2) for recording the data on extensive air showers, which makes it possible to study particles with ultimately high energies (10^{17}– 10^{20} eV) [6]. In 1982, a group of researchers closely collaborating with Vernov was awarded the Lenin Prize for their investigation of primary ultrahigh-energy cosmic radiation.

4. Study of cosmic rays using Soviet sputniks and interplanetary probes

S N Vernov's talents as an extraordinary scientist and organizer manifested themselves especially in the work on cosmic rays using Soviet artificial satellites and interplanetary probes. A discovery of momentous significance was made already with the first Soviet sputniks — the discovery of Earth's outer radiation belt [7]. The investigation of Earth's radiation belts is of major significance not only for studying the physical properties of interplanetary space but equally for a number of theoretical and practical issues of modern geophysics. In 1960, S N Vernov was awarded the Lenin Prize for the discovery of Earth's outer radiation belt and the investigation of its properties.

In subsequent years S N Vernov headed the program of implementation of detailed studies of Earth's radiation belts and magnetosphere on Soviet satellites of the Elektron series. Already by 1968 this project allowed the team of researchers to clarify the complete structure and dynamics of radiation belts and to develop the theory of their origin. The study of Earth's radiation belts, supervised by S N Vernov, became an outstanding achievement of Soviet science. In 1968, S N Vernov was elected Full Member of the USSR Academy of Sciences.



СССР

ДИПЛОМ
НА ОТКРЫТИЕ

В соответствии с „Положением об открытиях, изобретениях и рационализаторских предложениях" Государственный Комитет по делам изобретений и открытий СССР установил, что граждане СССР

ВЕРНОВ Сергей Николаевич
ЧУДАКОВ Александр Евгеньевич
ВАКУЛОВ Петр Васильевич
ГОРЧАКОВ Евгений Васильевич
ЛОГАЧЕВ Юрий Иванович

сделали открытие, характеризуемое следующей формулой:

ФОРМУЛА ОТКРЫТИЯ

Установлено, что в области пространства, где расположены силовые линии магнитного поля, пересекающие поверхность Земли между 50 и 65° геомагнитной широты, находится радиационная зона (названная впоследствии „Внешним радиационным поясом"), состоящая из захваченных магнитным полем интенсивных потоков электронов с энергией от сотен до тысяч килоэлектронвольт.

Настоящее открытие зарегистрировано в Государственном реестре открытий СССР 10 декабря 1963 года под № 23 с приоритетом июль 1958 г.

ПРЕДСЕДАТЕЛЬ КОМИТЕТА
Ю. МАКСАРЕВ

Certificate for the discovery of Earth's outer radiation belt.

5. Progress in high-energy physics

S N Vernov possessed an amazing feel for new physics.

In the late 1970s, M A Markov and A A Logunov supported the project of construction of a new building for the MSU Research Institute for Nuclear Physics (RINP) — the High Energy building. S N Vernov felt certain that this new stage in the advancement of physics demanded the creation of new accelerators and large-scale machines, and that these would lead to fundamental results at particle energies above 10^{15} eV. The processing of these results called for special equipment and highly skilled personnel. S N Vernov proved his ability to bring a project to life, and currently we have at the MSU RINP a team of researchers, experimentalists and theoreticians — around 150 people — who take active part in experiments on the biggest accelerators in the world, including the Large Hadron Collider at CERN [8].

6. Conclusion

S N Vernov devoted much energy and effort to science management and social functions. He served as MSU RINP Director, Chair of the Cosmic Ray Division at the MSU Department of Physics, Deputy Academician-Secretary of the Nuclear Physics Division of the USSR Academy of Sciences, Chair of the Scientific Council on the Problem of Cosmic Rays, Head of the Commission on Nuclear Physics and Cosmic Rays of the Research and Technology Council of the USSR Ministry of Higher and Medium Special Education, Chair of the Moscow Peace Defense Committee, etc.

Celebrating now the centenary since the day Sergei Nikolaevich was born, we recall the illustrious pages of our history, the history of academic science and its close links to university science: this is precisely the collaboration that resulted in rich output — outstanding scientific results. These close links survive today in the latest experimental projects in which the personnel of MSU and RAS work side by side.

S N Vernov enjoyed the highest reputation both among his research fellows and among his colleagues in the USSR Academy of Sciences. His standing was based not only on his impeccable professionalism, but also on his human qualities. Many outstanding scientists were among his friends: S N Vavilov, D V Skobeltsyn, M A Markov, N I Bogoliubov, M V Keldysh, B M Pontecorvo, A A Logunov, N A Dobrotin, A E Chudakov, and G T Zatsepin.

I happened to be present when S N Vernov met N N Bogoliubov, M A Markov, A M Baldin, D I Blokhintsev, and others. I was profoundly impressed by their deepest mutual respect, and at the same time their warm friendly relations. They all belonged to the same era — the era of great scientific discoveries against the background of the hard and multifaceted, at times tragic, history of the country and its people and the trials and tribulations that fate brought to them. At the same time, they belonged to that category of people for whom serving their science was inseparable from serving their country.

S N Vernov's work at each phase of his creative activities was of primary importance for the progress of cosmic ray physics and space physics. It is not surprising that his name is widely known not only in this country, but also beyond its borders, and that it everywhere enjoys a well-deserved high reputation. In the 50 years of S N Vernov's life in science, he built a large and actively working scientific school of several dozen PhD and DSc physicists in every section of cosmic ray physics. At the conclusion of each stage in his research career, teams of researchers would spring up whose subsequent work would open a number of new avenues of inquiry and solve many important problems. The achievements of the scientists of this school have twice been rewarded with the Lenin Prize, four times with the USSR State Prize. As for Sergei Nikolaevich Vernov himself, he was awarded the high distinction of Hero of Socialist Labor.

S N Vernov (left) with Academician A A Logunov (MSU chancellor) and Professor I M Ternov (1980).

S N Vernov (right) with Academicians N N Bogoliubov, A N Tavkhelidze, and V G Kadyshevskii.

S N Vernov (right) with Academician M A Markov.

S N Vernov (left) with Academician G B Khristiansen.

S N Vernov (left) with Academician B M Pontecorvo.

S N Vernov's name belongs to the pantheon of scientists who symbolize the pride and glory of the physical science in this country and of the Russian Academy of Sciences and its Physical Sciences Division.

Studying the heritage of the research work of S N Vernov and his students is a good school for young generations of scientists who seek to leave their mark on modern science as it strives to achieve understanding of the fundamental laws of the Universe.

Included in this article are photographs taken by Yu A Tumanov, D V Bobkov, and A T Abrosimov, and also photographs received from the family archive of E S Vernova.

References

1. Vernoff S *Phys. Rev.* **46** 822 (1934); *Nature* **135** 1072 (1935)
2. Vernov S N et al., in *Proc. of the 9th Intern. Cosmic Ray Conf.: ICRC, London* Vol. 1 (1965) p. 517
3. Vernov S N et al. *Izv. Akad. Nauk SSSR Ser. Fiz.* **39** 316 (1975) [*Bull. Acad. USSR, Phys. Ser.* **39** (2) 63 (1975)]
4. Vernov S N et al., in *VII Leningradskii Mezhdunar. Seminar "Korpuckulyarnye Potoki Solntsa i Radiatsionnye Poyasa Zemli i Yupitera". Leningrad, 25–28 Maya 1975 g.* (VII Leningrad Intern. Seminar "Solar Corpuscular Fluxes and Earth's and Jupiter's Radiation belts", Leningrad, May 25–28, 1975) (Leningrad, 1975) p. 389
5. Kulikov G V, Khristiansen G B *Zh. Eksp. Teor. Fiz.* **35** 635 (1958) [*Sov. Phys. JETP* **8** 441 (1959)]
6. Efimov N N et al. *Problemy Fiziki Kosmicheskikh Luchei* (Problems in Cosmic Ray Physics), (Comp. E V Gorchakov) (Moscow: Nauka, 1987)
7. Vernov S N et al. "Vneshnii radiatsionnyi poyas Zemli" ("Earth's outer radiation belt"), Diploma of Discovery No 23, Priority as of June 1958, the date of the talk at the Vth Assembly of the International Geophysics Year
8. *V Glub' Materii. Fizika XXI Veka Glazami Sozdatelei Eksperimental'nogo Kompleksa na Bol'shom Adronnom Kollaidere v Zheneve* (Going Deep into Matter. Physics of the XXIst Century Through the Eyes of the Creators of the Experimental Facility for the Large Hadron Collider in Geneva) (Moscow: Eterna, 2009) p. 576

PACS numbers: **01.60.+q**, **07.87.+v**, **94.20.–y**
DOI: 10.3367/UFNe.0181.201102h.0191

S N Vernov as a Moscow University scientist

V A Sadovnichy

The date 11 July 2010 marks the 100th anniversary of the birth of Academician Sergei Nikolaevich Vernov — the scientist of world renown, Hero of Socialist Labor, recipient of the USSR Lenin and State Prizes, one of the founders of the Research Institute for Nuclear Physics (RINP) [now renamed as D V Skobeltsyn Institute of Nuclear Physics (SINP)] of Moscow State University and then its Director from 1960 till 1982, and Head of the Nuclear Physics Division at the Department of Physics of the M V Lomonosov Moscow State University. The name of S N Vernov marks grandiose achievements of this country in the implementation of the Soviet Atomic project, in space exploration, in gaining knowledge of the fundamental properties of matter.

In the second half of the 20th century, nuclear physics, space physics, and high-energy physics took a giant jump to an enormously higher qualitative level. This was reflected in the birth of many other scientific and technological fields. It was a renaissance of fundamental and applied research throughout the world, especially in this country. Sergei Nikolaevich Vernov proved to be just the person that the State and Moscow State University needed at that very moment. To quote a metaphoric comparison made by Georgii Borisovich Khristiansen, he acted for more than 25 years as an outstanding conductor of research on the structure of matter and space physics. It was to a large extent owing to S N Vernov that Moscow State University continues to show great achievements in these fields of science.

S N Vernov, in his capacity of RINP Deputy Director from 1946 till 1960, and RINP Director from 1960 till 1982, made a huge contribution, alongside D V Skobeltsyn, to the creation and further evolution of this Institute and of the Nuclear Physics Division at the MSU Department of Physics and to training the personnel for the Soviet Atomic project and for space research.

It was in the years of S N Vernov's work at Moscow State University that space research using artificial satellites (sputniks) and space rockets was born and then grew in volume and stature. Direct contacts between S N Vernov

V A Sadovnichy M V Lomonosov Moscow State University, Moscow, Russian Federation. E-mail: info@rector.msu.ru

Uspekhi Fizicheskikh Nauk **181** (2) 191 – 195 (2011)
DOI: 10.3367/UFNr.0181.201102h.0191
Translated by V I Kisin; edited by A Radzig

and S P Korolev, Chief Designer of Soviet missiles, were established already in 1947, and in 1956 MSU RINP was added to the list of research institutes invited to take part in scientific experiments on sputniks. S N Vernov became a scientific leader of the program of cosmic ray research on artificial Earth satellites.

The first meeting with the designers of the future satellite finalized the specification data for our instruments (gas-discharge counters were supposed to be used as radiation detectors): weight of the instrument — not more than 2.5 kg; energy consumption — 2 W and telemetry through a single 'dry' channel with a frequency 50 Hz.

Gas-discharge counters in the instruments were coupled to recording electronics, for which one of the following three options was available at the time: low-power electron tubes, thyratrons with unheated cathodes, or semiconductor elements. Electron tubes were rejected immediately because of their high power consumption. Huge effort was spent on developing thyratrons with unheated cathodes: even a prototype device with acceptable weight and power consumption was assembled, but it proved absolutely impractical because of the unstable operation of thyratrons. The only way out was to use semiconductor elements.

It should be noted that semiconductor technology, which at that time (1957) was only emerging, was almost unknown to experimentalists. This only intensified Sergei Nikolaevich's insistence that thyratrons be replaced with semiconductor diodes and triodes. His expectations were fully justified: the semiconductor circuits were stable and operated reliably in a wide range of temperatures and withstood vibrations excellently. The Fizpribor plant manufactured the instruments and they were ready to travel into space. The only operation to conduct now was to test them for the length of service life. Suffice it to mention that the radiation recording instrument designed in 1957 at RINP was then used on sputniks for more than 25 years and earned very high reputation. Even today, one can find the circuits assembled for that launch and discover that they are perfectly functional.

On 4 October 1957, the world learnt that the USSR had launched the first-ever artificial Earth satellite. As the date of the launch of the first sputnik was kept top secret, the launch-ready instruments designed and built under Vernov's supervision were not installed and stayed behind. Just imagine what Sergei Nikolaevich would have felt: the sputnik carried 50 kilos of batteries but was only capable of sending the 'I am alive' signal — 'beep-beep-beep' — while RINP had on the table a ready instrument weighing only 2.5 kg left unused on the ground!

The situation changed drastically after 4 October. Already the second sputnik launched on 3 November 1957 carried two gas-discharge counters with semiconductor electronics, built at MSU RINP and intended for recording cosmic radiation. Cosmic-ray intensity was measured for the first time at altitudes never reached before, and a significant increase in the intensity of the detected particles was observed at high latitudes (Fig. 1). On 15 May 1958, the third Soviet sputnik was launched, and it also had instruments built at MSU RINP. As a result, S N Vernov and his team finally established the existence of two Earth's radiation belts: the inner belt, discovered by American scientists in February–March 1958 utilizing the equipment installed on the Explorer satellite, and an outer belt discovered by MSU scientists in July 1958. In 1960, S N Vernov and A E Chudakov were awarded the Lenin Prize for the discovery of Earth's outer radiation belt.

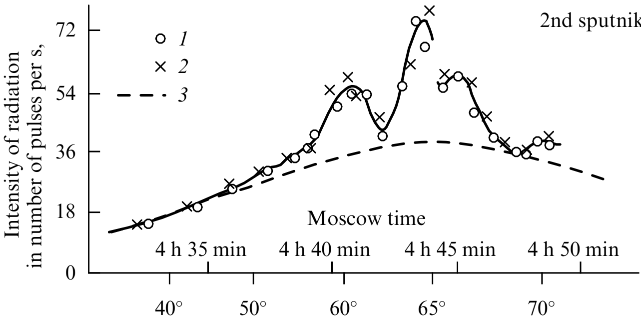


Figure 1. Data on cosmic radiation recorded on the 2nd sputnik during one of the passages over northern areas of the USSR: dashed curve — the mean values, circles — readings of instrument No. *1*, × — readings of instrument No. *2*.

The investigation of radiation belts was unfolding in an atmosphere of very intense competition against American scientists, and within a very short time interval — the interval between the launches of the second and third artificial Earth satellites was a mere six months! This made the recognition of the scientific merits of MSU RINP and S N Vernov for the discovery and interpretation of radiation belts all the more commendable. In summer 1959, an International Conference on Cosmic Ray Physics was convened at Moscow State University. The audience included many foreign scientists, among them a representative American delegation. The scientific achievements of Soviet scientists were reported to this conference by S N Vernov. The report that caused maximum interest was S N Vernov's talk on the mission of automatic space station Luna-1, which realized the world's first contact of a recording instrument (again built at RINP) with the lunar surface.

In 1957–1982, S N Vernov supervised at MSU RINP the design, manufacturing, and launching of instruments which were installed on 140 sputniks and space rockets. By now this number has risen to 400. As a result, S N Vernov and the staff of the Institute were able to make an important contribution to studying various phenomena in extraterrestrial space (radiation belts, magnetospheres of Earth and other planets, auroras, galactic and solar cosmic rays, anomalous component of cosmic rays, active processes on the Sun and in the heliosphere, etc.).

Diploma of the Lenin Prize Laureate delivered to S N Vernov.

S N Vernov (4th from the left) with participants in the International Conference on Cosmic Rays at Moscow State University (1959).

A man of boundless energy, enthusiastic about all science, faithful to science without limits, S N Vernov possessed a keen sense of the new in science, having the rare ability of never letting the goal drift out of his sight. His talent and his assertive, determined character helped to launch projects on many fronts, not directly connected with research on the artificial Earth satellites: stratospheric research; the study of extensive air showers (EAS); dosimetric measurements in space which founded a new branch of science — space radiometry, and work on space materials and high-energy physics research. We wish to highlight his efforts to expand high-energy physics research at MSU RINP: a new building for the Institute, the creation of a unique photographic-plate-viewing center in it, the promotion of scientific links with the largest research centers abroad possessing high-energy accelerators and providing viewing material to MSU RINP. As a result, Moscow State University has obtained important scientific results in high-energy physics, including the recent discovery of the top quark. These results are recognized by the world's scientific community and define the key positions occupied by the University in the study of the fundamental properties of matter on prestigious international projects carried out in such scientific centers as CERN (Geneva, Switzerland), KEK (Tsukuba, Japan), Fermi National Accelerator Laboratory (FNAL) (Chicago, USA), Thomas Jefferson National Accelerator Facility (TJNAF) (Newport News, USA), as well as research centers in Germany, namely DESY (Hamburg) and FAIR (Darmstadt), at the National Institute of Nuclear Physics (INFN) (Genoa, Italy), Joint Institute for Nuclear Research (JINR) (Dubna, Russia), Institute of High Energy Physics (Protvino, Russia), and other very large research centers (Fig. 2). In 2009, the Large Hadron Collider (LHC) started operating at CERN. This is the grandest integrated research facility in the world. MSU — one of the leading universities in the world — is participating in this unique scientific project of the 21st century in three key experiments: CMS (Compact Muon Solenoid), ATLAS (A Toroidal LHC ApparatuS), and LHCb (Large Hadron Collider beauty experiment).

Sergei Nikolaevich was an exceptionally bright person: this was obvious in everything he undertook. He was a master of conjuring a creative atmosphere around himself, and of mobilizing large teams of researchers for addressing the most important tasks. We, his colleagues, were always in awe of his ability to concentrate spiritual and physical efforts on the most important task. This approach never failed to bear fruit. Many programs that he initiated and supervised would result in discoveries of new phenomena and new physical laws.

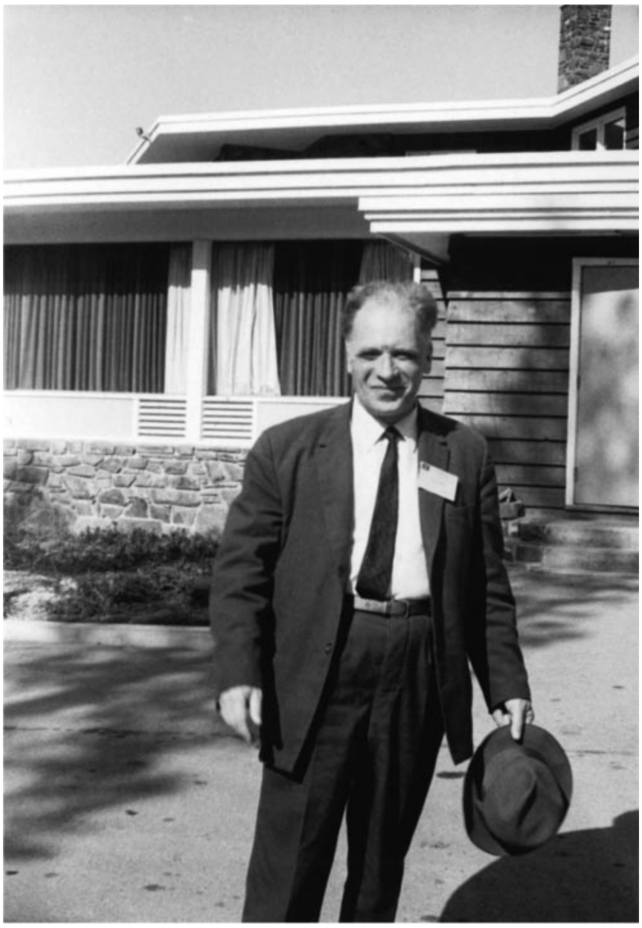
One of Sergei Nikolaevich's main characteristics was his insistent wish to closely link the solution of fundamental problems of science and urgent practical tasks. Priority discoveries made by S N Vernov and his students allowed MSU RINP to obtain most important methodological and technological results. Many of these results are now employed as domestic and international standards for describing the space environment and its effects on space vehicles. This is very important for developing criteria for radiation safety of space flights.

Instruments for monitoring radiation in Earth's neighborhood which were designed and then mass-produced at RINP were installed on the International Space Station, many satellites of the GLONASS (Global Navigation Satellite System), and on special-purpose satellites.

The laboratories of MSU RINP designed and manufactured flight kits of scientific instruments for the Russian–Indian University sputnik YouthSat, for the experimental programs TUS (Treck Facility), RELEK, and NUKLON included in the Russian Federal Space Program and aimed at studying the precipitation of magnetospheric electrons, and ultrahigh-energy cosmic rays.

S N Vernov's students and followers built unique world-class ground-based facilities to study the highest-energy cosmic rays (Tunka-133, MSU EAS). They created a new field of research: space materials science. Fundamental knowledge was obtained about the behavior of materials under space conditions, methods of their protection against

Figure 2. International relations of MSU RINP in high-energy physics research.



Sergei Nikolaevich Vernov at the International Conference on Cosmic Rays (Dhampur, India, 1963).

adverse effects of the space environment, and technologies for developing advanced materials for space applications, including nanomaterials.

These days MSU is accomplishing a breakthrough to the future by implementing the development program undertaken on the instructions of the President and the Government of the Russian Federation for 2010–2020. One of the most important breakthrough directions of this program is the integrated research named as the 'Investigation of the structure of matter and space, and application of space technologies.'

Now, nearly fifty years after our first steps into space, the first Universitetskii-Tatiyana sputnik was built at RINP with the assistance of the MSU Department of Mechanics and Mathematics. Its launch on 21 January 2005 marked the 250th anniversary of the founding of Moscow State University. Unique information on the physics of transient airglow in Earth's upper atmosphere (Fig. 3) has been collected over the two years of the satellite's time in orbit in the course of observation of solar activity. The next satellite, Universitetskii-Tatiyana-2, was launched on 17 September 2009. The separation of the third stage of the booster rocket was for the first time observable in real time by the robot telescope of the MASTER system (Mobile Automated System of TElescope Robots) developed by scientists of the MSU P K Shternberg State Astronomical Institute and the Moscow association Optika; the unique characteristics of MASTER robots exceed those of western analogs (Fig. 4).

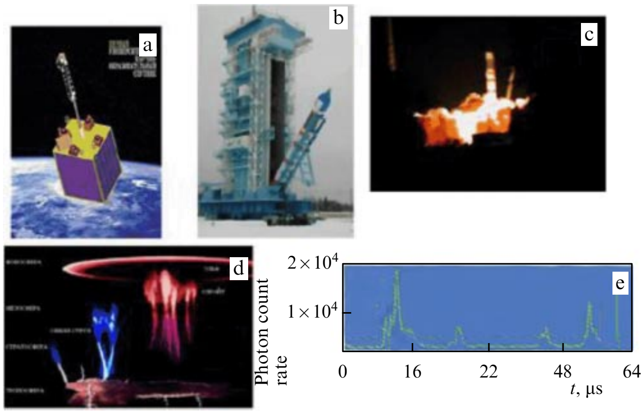


Figure 3. The first Moscow State University sputnik, Universitetskii-Tatiyana, launched on 21 January 2005 from the Plesetsk launch pad: (a) general view, (b) booster rocket being prepared for the start, (c) launch, (d) possible transient emission in the stratosphere of Earth, and (e) flashes of radiation recorded by the satellite's instruments.

The next to fly will be the satellite Mikhailo Lomonosov, on the date marking the 300th anniversary of the birthday of the famous Russian scientist, the founder of Moscow State University. In fact, these two launches are precursors of a whole fleet of Moscow State University sputniks. These achievements are an additional indicator of the high-quality foundation of space research built by S N Vernov and his disciples.

Sergei Nikolaevich was not only an outstanding and highly talented scholar, but also a teacher in the highest and noblest sense of the word. S N Vernov organized within the framework of the Nuclear Physics Division a training program at the MSU Department of Physics for space explorers and assembled a large scientific school which continues to work fruitfully and produce results. Hundreds of specialists feel completely justified in regarding themselves as his students: they learned their profession through his lectures, in joint work, and at seminars, to which he always paid maximum attention. The notion of 'Vernov's school' is considerably wider than the circle of his students at MSU. Nevertheless, even this smaller circle counts among its members some illustrious scientists — true space explorers.

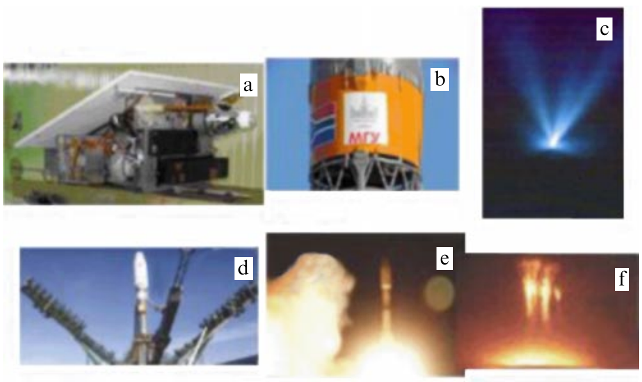


Figure 4. The Moscow State University sputnik Universitetskii-Tatiyana-2, launched on 17 September 2009 from the Baikonur Cosmodrom launching pad: (a) general view, (b) booster rocket with MSU logotype, (c) several hours before the launch, (d) launch, (e) separation of booster stages (robot telescope MASTER), and (f) transient flashes registered by instruments aboard the sputnik Universitetskii-Tatiyana-2.

Among them we find three Academicians (G T Zatsepin, G B Khristiansen, A E Chudakov), and 45 DSc and 225 PhD scientists.

S N Vernov successfully combined productive research with science administration in his capacities of Deputy Academician-Secretary of the Nuclear Physics Division of the USSR Academy of Sciences, Chair of the Scientific Council on the Cosmic Rays integrated program, Chair of the Nuclear Physics Section of the Scientific and Technical Council of the USSR Ministry of Higher and Medium Special Education, member of the editorial boards of the journals *Nuclear Physics*, *Proceedings of the Academy of Sciences: Physics Series*, *Geomagnetism and Aeronomy*, *Vestnik of Moscow State University* (Physics Series), and member of a number of learned and scientific councils.

The characterization of S N Vernov would be incomplete if we failed to mention his massive activities in popularizing science as such, and the achievements of scientists of Moscow State University in particular. His lectures and popular science articles appeared in many central newspapers and popular science magazines.

Sergei Nikolaevich Vernov was a cheerful and charming man. His innate kindness and responsiveness and his desire to help in times of difficulties earned him general respect and love. As luck would have it, I lived near him for several years in the main MSU building: his apartment was on the fifth floor, mine was on the fourth. Great friendship bound me to his first deputy at RINP, Professor I B Teplov, with whom we often discussed the problems of the Institute, and Sergei Nikolaevich's opinion was always offered on any subject in these discussions. On the other hand, Sergei Nikolaevich would never make a decision on an important issue without first working out a version taking into account I B Teplov's point of view.

Sergei Nikolaevich Vernov died on 26 September 1982 and was buried in Novodevichy Cemetery.

To perpetuate the memory of S N Vernov, a plaque has been mounted at the entrance to the RINP building at Vorobievy Gory, where he worked from 1953 to 1982, the auditorium 5–18 of the Department of Physics became the S N Vernov auditorium, outstanding students of the MSU Department of Physics are awarded the Vernov scholarship, and the S N Vernov contest for best research paper by a young scientist is regularly conducted at MSU RINP. One of the streets in Dubna in the Moscow region and a street in the town of Sestroretsk in the Leningrad region, where S N Vernov was born, bear his name.

Moscow State University is a leading research center in the country, contributing in important ways to progress in fundamental science and to strengthening of most needed scientific university education. Sergei Nikolaevich Vernov belongs to the constellation of scientists who are the pride of MSU. His path through science and life offers a brilliant example for the new generations of young researchers ready to do good for their Fatherland.

PACS numbers: **01.60.+q**, **01.65.+g**
DOI: 10.3367/UFNe.0181.201102i.0195

S N Vernov centenary talk

V I Trukhin

The date 11 July 2010 marks the 100th anniversary of the birth of Academician Sergei Nikolaevich Vernov, the scientist of world renown, one of the founders of the Research Institute for Nuclear Physics (RINP) [now renamed as D V Skobeltsyn Institute of Nuclear Physics (SINP)] of MSU and of the Nuclear Physics Division (NPD) of the MSU Department of Physics.

Let us look at the brief history of the creation of the Research Institute of Nuclear Physics (RINP) and NPD. In 1940, a chair, Atomic Nucleus and Radioactivity, was set up in the Department of Physics of MSU on the initiative of Academician S I Vavilov and Corresponding Member D V Skobeltsyn. It was headed by D V Skobeltsyn, while S N Vernov and I M Frank became chair professors. In 1943, S N Vernov change his principal position to professorship in the Department of Physics of MSU, namely D V Skobeltsyn's chair, so that Vernov's pedagogical activities and his research were connected with Moscow State University until the last days of his life.

In 1940 and in 1943–1945, S N Vernov gave lecture courses on cosmic ray physics for students of the Atomic Nucleus and Radioactivity chair, and since 1944 he headed the chair's laboratory of the atomic nucleus — the first laboratory of nuclear physics at MSU. It was in this laboratory that S N Vernov launched his study of cosmic rays in the stratosphere, while Professor L V Groshev and Assistant Professor V S Shpinel were the first in the USSR to begin work on the study of the structure of atomic nuclei by β- and γ-spectroscopy. Students of the chair began to take active part in this research work.

In 1946, a Special Resolution of the USSR Council of People's Commissars created at MSU, on the basis of the chair and the chair laboratory, a Scientific and Research Center for training specialists for the Soviet Atomic project — the Institute of the Atomic Nucleus — mentioned in declassified documents as MSU NIFI-2; in 1956, this was changed to the current title MSU RINP (SINP). For two years, from 1946 till 1948, all the main organizational work of the institute and the chair (renamed Structure of Matter) became the responsibility of S N Vernov as deputy Director of the institute because Director of the Institute D V Skobeltsyn was sent to the USA as the USSR representative in the UN.

In this period, D V Skobeltsyn and S N Vernov tackled the task of creating an institute operating as large-scale university type nuclear physics center for conducting fundamental nuclear physics research and training of young researchers.

Work for the Soviet Atomic project demanded a sharp increase in the number of graduates specializing in nuclear physics. In December 1948, the USSR Council of Ministers

V I Trukhin M V Lomonosov Moscow State University, Russian Federation. E-mail: trukhin@phys.msu.ru

Uspekhi Fizicheskikh Nauk **181** (2) 195 – 197 (2011)
DOI: 10.3367/UFNr.0181.201102i.0195
Translated by V Kisin; edited by A Radzig

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.

PACS numbers: **01.65.+g**, **07.87.+v**, 94.20.wq
DOI: 10.3367/UFNe.0181.201102j.0197

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

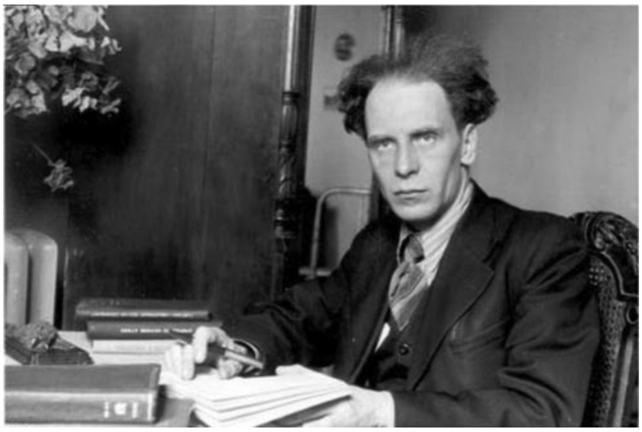
M I Panasyuk

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

Uspekhi Fizicheskikh Nauk **181** (2) 197 – 210 (2011)
DOI: 10.3367/UFNr.0181.201102j.0197
Translated by S V Vladimirov; edited by A Radzig



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].

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

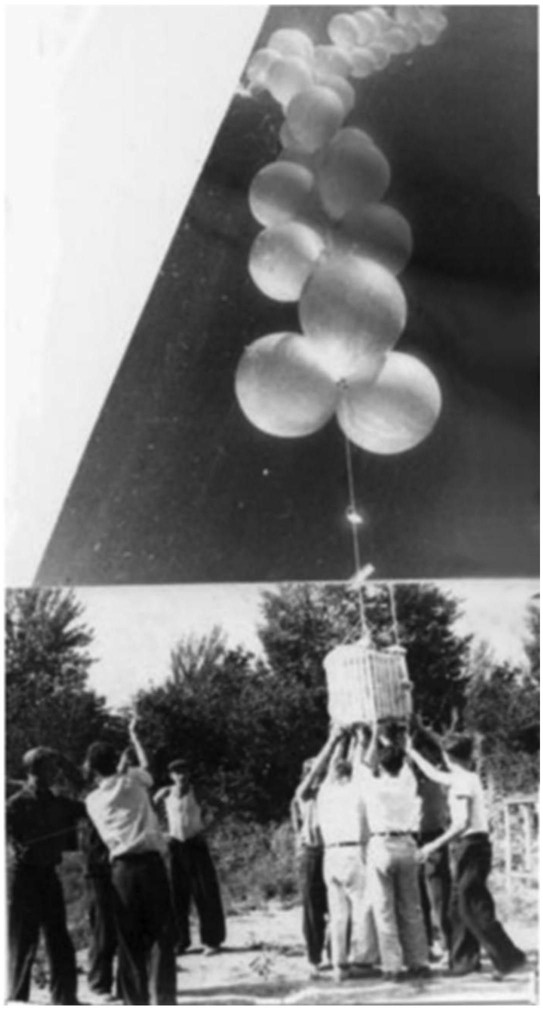


Figure 1. Sounding balloons.

Naum Leonidovich Grigorov and Alla Ivanovna Savel'eva.

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.

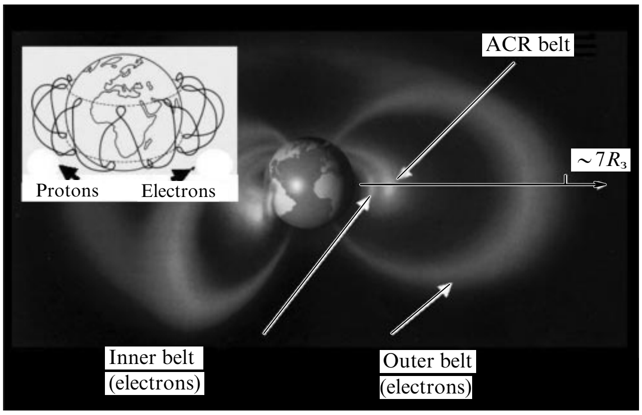


Figure 3. Earth's radiation belts. The inner and outer electron belts are shown, as well as the belt formed by anomalous cosmic ray (ACR) component.

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.

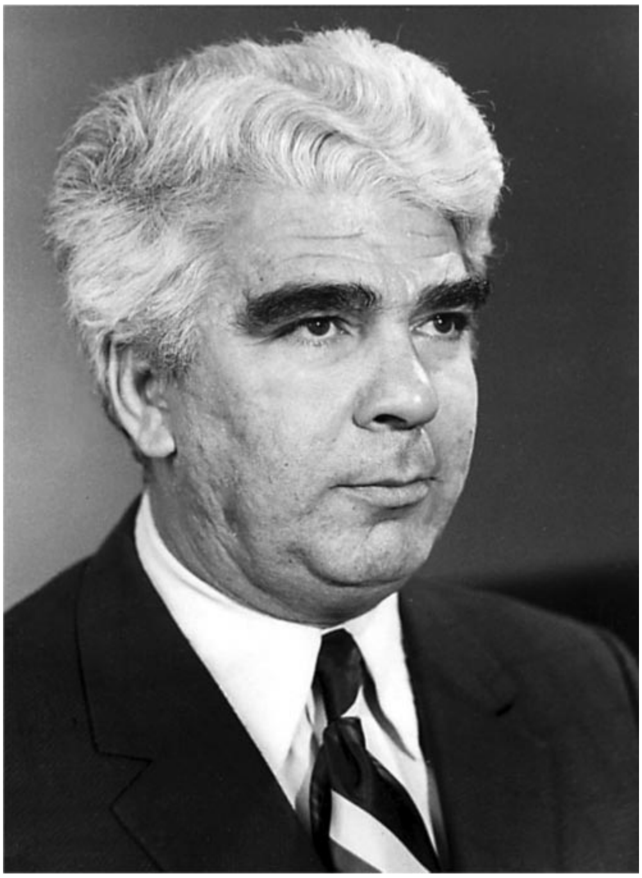
The discovery of ionospheric source for ring current ions made it necessary to theoretically interpret the mechanisms of particle injection from the ionosphere and of particle acceleration. A large contribution to solving this problem was made by E E Antonova, who considered magnetostatically equilibrium 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_{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_{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

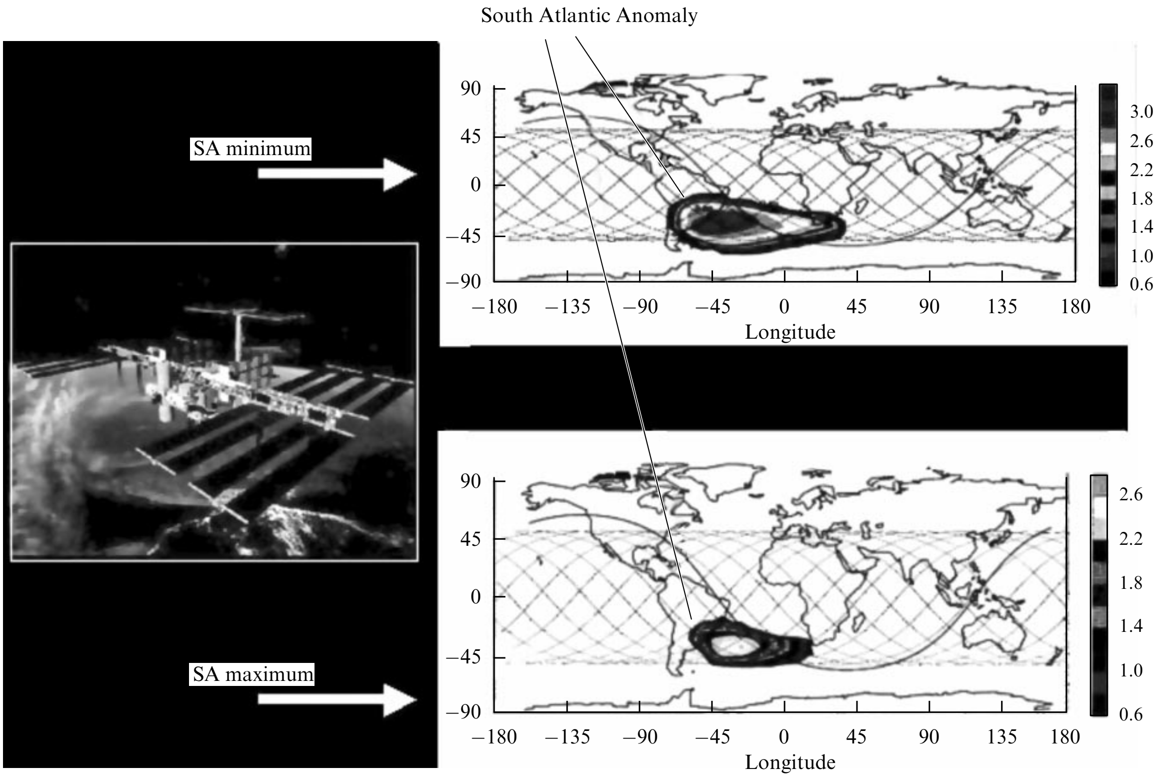


Figure 4. Dynamics of the radiation situation in the South Atlantic Anomaly during the solar activity (SA) cycle: radiation doses in this region increase at the SA minimum, and decrease at the SA maximum.

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 anticorrelation 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.

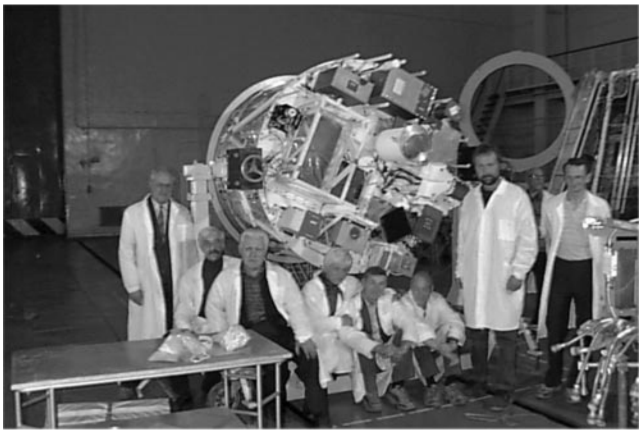


Figure 5. Preparation for CORONAS-I launch (1991).

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.

References

1. Vernov S N *Zh. Eksp. Teor. Fiz.* **19** 622 (1949)
2. Vernov S N et al. *Dokl. Akad. Nauk SSSR* **68** 253 (1949)
3. Vernov S N et al. "Vneshnii radiatsionnyi poyas Zemli" ("Outer radiation belt of the Earth"), Discovery Diploma (Patent) No. 23, priority date from June 1958
4. Vernov S N et al. *Dokl. Akad. Nauk SSSR* **124** 1022 (1959) [*Sov. Phys. Dokl.* **4** 154 (1959)]
5. Panasyuk M I (Ed.) *Model' Kosmosa* Vol. 1 *Fizicheskie Usloviya v Kosmicheskom Prostranstve* 1 (Space Model Vol. 1: Physical Conditions in Space) (Moscow: KDU, 2007)
6. Tverskoi B A *Dinamika Radiatsionnykh Poyasov Zemli* (Dynamics of Radiation Belts of the Earth) (Moscow: Nauka, 1968)
7. Tverskoi B A *Osnovy Teoreticheskoi Kosmofiziki* (Basics of Theoretical Space Physics) (Moscow: URSS, 2004)
8. Balashov S V et al. *Kosmonavtika Raketostroenie* (1) 95 (2003)
9. Panasyuk M I *Kosmicheskie Issled.* **22** 572 (1984) [*USSR Rep. Space* (85-003) 29 (1985)]
10. Il'in V D, Kuznetsov S N, in *VII Leningradskii Mezhdynar. Seminar "Korpuskulyarnye Potoki Solntsa i Radiatsionnye Poyasa Zemli i Yupitera", Leningrad, 25–28 Maya, 1975 g.* (VII Leningrad Intern. Seminar "Solar Corpuscular Fluxes and Earth's and Jupiter's Radiation Belts", Leningrad, May 25–28, 1975 (Leningrad, 1975) p. 269
11. Popeliavska B et al. *Kosmicheskie Issled.* **19** 401 (1981) [*Cosmic Res.* **19** 280 (1981)]
12. Grigorov N L et al. *Geophys. Res. Lett.* **18** 1959 (1991)
13. Kovtyukh A S, Panasyuk M I, Sosnovets E N *Izv. Akad. Nauk SSSR Ser. Fiz.* **40** 496 (1976)
14. Tverskoy B A, in *Solar-Terrestrial Physics 1970* (Astrophysics and Space Science Library, Vol. 29) (Dordrecht: Reidel, 1972) p. 297
15. Panasyuk M I et al. *Issled. Geomagn. Aeron. Fiz. Solntsa* **86** 99 (1989)
16. Kovtyukh A S *Geomagn. Aeron.* **39** (2) 24 (1999) [*Geomagn. Aeron.* **39** 155 (1999)]
17. Antonova E E, Tverskoy B A *Geomagn. Aeron.* **36** (2) 1 (1996) [*Geomagn. Aeron.* **36** 145 (1996)]
18. Kovtyukh A S, Panasyuk M I, Sosnovets E N *Kosmicheskie Issled.* **15** 559 (1977) [*Cosmic Res.* **15** 484 (1978)]
19. Shabansky V P *Yavleniya v Okolozemnom Prostranstve* (Phenomena in Near-Earth Space) (Moscow: Nauka, 1972)
20. Alexeev I I et al. *Space Sci. Rev.* **107** 7 (2003)
21. Tverskoi B A *Geomagn. Aeron.* **37** (5) 29 (1997) [*Geomagn. Aeron.* **37** 555 (1997)]
22. Tverskoi B A *Geomagn. Aeron.* **5** 793 (1965)
23. Kuznetsov S N, Stolpovskii V G, Sosnovets E N, in *Issledovaniya Kosmicheskogo Prostranstva*: *Trudy Vsesoyuz. Konf., Moskva, 10–16 iyunya 1965 g.* [in Russian] (Exec. Ed. G A Skuridin) (Moscow: Nauka, 1965) p. 420
24. Tverskaya L V *Geomagn. Aeron.* **38** (5) 22 (1998) [*Geomagn. Aeron.* **38** 571 (1998)]
25. Gorchakov E V et al. *Kosmicheskie Issled.* **19** 571 (1981)
26. Pavlov N N et al. *Geomagn. Aeron.* **33** (6) 41 (1993)
27. Glukhov G A et al. *Geomagn. Aeron.* **24** 821 (1984)
28. Grigoryan O R et al. *Inzhenernaya Ekologiya* (4) 25 (1996)
29. Vernov S N et al. *Geomagn. Aeron.* **12** 785 (1972)
30. Ivanova T A et al. *Kosmicheskie Issled.* **14** 235 (1976)
31. Panasyuk M I *Kosmicheskie Issled.* **42** 509 (2004) [*Cosmic Res.* **42** 489 (2004)]
32. Lazutin L L, Kuznetsov S N, Podorol'skii A N *Geomagn. Aeron.* **47** 187 (2007) [*Geomagn. Aeron.* **47** 175 (2007)]
33. Vernov S N et al. *Kosmicheskie Issled.* **2** 136 (1964)
34. Bashkirov V F, Panasyuk M I, Teltsov M V *Kosmicheskie Issled.* **36** 359 (1998) [*Cosmic Res.* **36** 336 (1998)]
35. Logachev Yu I (Exec. Ed.) *Katalog Energeticheskikh Spektrov Solnechnykh Protonnykh Sobytii 1970–1979 gg.* (Moscow: IZMIR-AN,1986)
36. Nymmik R A *Radiation Measurements* **30** 287 (1999)
37. Kuznetsov N V, Panasyuk M I *Voprosy At. Nauki Tekh., Ser. Fizika Radiatsionnogo Vozdeistviya na Radioelektron. Apparaturu* (1–2) 3 (2001)
38. Lyubimov G P *Kosmicheskie Issled.* **40** 610 (2002) [*Cosmic Res.* **40** 565 (2002)]
39. Lyubimov G P *Izv. Ross. Akad. Nauk Ser. Fiz.* **67** 353 (2003)
40. Daibog E I et al. *Kosmicheskie Issled.* **21** 476 (1983)
41. Daibog E I et al. *Izv. Akad. Nauk SSSR Ser. Fiz.* **51** 1825 (1987)
42. Veselovsky I S et al. *Kosmicheskie Issled.* **42** 453 (2004) [*Cosmic Res.* **42** 435 (2004)]
43. Lebedinsky A I et al. *Izv. Akad. Nauk SSSR Ser. Fiz. Atmos. Okeana* **5** 149 (1969)
44. Sadovnichy V A et al. *Kosmicheskie Issled.* **45** 291 (2007) [*Cosmic Res.* **45** 273 (2007)]

PACS numbers: **01.60.+q**, **01.65.+g**, 94.20.wq
DOI: 10.3367/UFNe.0181.201102k.0210

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

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

Uspekhi Fizicheskikh Nauk **181** (2) 210 – 218 (2011)
DOI: 10.3367/UFNr.0181.201102k.0210
Translated by M N Sapozhnikov; edited by A Radzig


АКАДЕМИЯ НАУК СССР

БИЛЕТ

для входа на заседание
Всесоюзной Конференции
по изучению стратосферы,
посвященное вопросу
„КОСМИЧЕСКИЕ ЛУЧИ"

Заседание состоится в Большом Конференц-зале
Академии Наук СССР (Университетская наб., 5,
вход с набережной, главный подъезд)

3 апреля 1934 г. в 10 ч. утра


ПОВЕСТКА ДНЯ

Космические лучи

1. *Акад. А. Ф. Иоффе* — Вступительное слово.
2. *Л. В. Мысовский* — „Исторический обзор развития учения о космических лучах в связи с исследованием на больших высотах".
3. *Д. В. Скобельцын* — „Физические свойства космических лучей".
4. *А. Б. Вериго* — „Ионизационный метод исследования космических лучей и аппаратура для измерения космических лучей на больших высотах".
5. *С. Н. Вернов* — „Применение счетчиков Гейгера-Мюллера для исследования космических лучей в стратосфере".
6. *М. П. Бронштейн* — „Гипотезы о происхождении космических лучей".
7. *М. С. Эйгенсон* — „Космические лучи и астрономия".

Ticket for a session of the All-Union Conference on Cosmic Rays and the agenda with the S N Vernov report (Leningrad, 1934).

the stratosphere. In 1934, he was included in the crew of the Osoviakhim stratostat, but came down with tonsillitis and could not take part in the flight. He was replaced by his peer Il'ya Usyskin who tragically perished in this flight. Fate saved the life of Sergei Nikolaevich to give him the opportunity to accomplish many scientific cosmic feats in the future.

In 1935, S N Vernov was accepted into the doctoral program at the Lebedev Physical Institute, USSR Academy of Sciences (FIAN in *Russ. abbr.*) and, supervised by S I Vavilov and D V Skobeltsyn, finally formed his scientific style combining adventurous experiments with deep theoretical analysis. However, the connection between Sergei Nikolaevich and the Radium Institute continued for many years.

The maximum creative and scientific–organizational activity of S N Vernov was manifested in the 1950–70s. The scope of his scientific interests in the field of cosmic rays had considerably expanded. He used cosmic rays as a tool for studying the interplanetary medium, solar activity, and other objects.

A memorial tablet mounted on a wall of the first building of the Radium Institute on Roentgen Street, 1 in St. Petersburg names academicians and corresponding members of the USSR Academy of Sciences, who worked at the institute in different years, Academician Sergei Nikolaevich Vernov being among them.

In the year of the 100th anniversary of Sergei Nikolaevich's birthday, we cannot help remembering those brilliant pages that he wrote on the history of studying cosmic rays and of space exploration.

2. How fate brought Sergei Nikolaevich and me together

I have had the luck to meet many brilliant people in my life, but Sergei Nikolaevich Vernov occupies a special place among them. I was fortunate to associate with him beginning from 1968 almost until his death.

In 1964, when I was in my fifth year at the Physicomechanical Department of the LPI, where Sergei Nikolaevich had studied earlier, I was lucky, along with a few of the students, to take part in the IV-th Conference on Cosmic Rays, which was held in the small town Apatity, Murmansk region, from 24 to 29 August. On the beautiful day of 22 August 1964, I flew for the first time in my life to a scientific conference together with scientists of the Ioffe Physical-Technical Institute (PTI), USSR Academy of Sciences. (This episode and my further contacts with S N Vernov are described in more detail in my paper, "Sergei Nikolaevich Vernov, as I remember him" [1]).

The conference was set up by the Scientific Council of the USSR Academy of Sciences within the framework of the complex issue of Cosmic Rays chaired by S N Vernov.

Being a third-year student at the Physicomechanical Department of the Chair of Experimental Nuclear Physics at the Kalinin LPI, I joined G E Kocharov's group at the PTI. Early in 1968, G E Kocharov asked me to help in organizing the Fifth All-Union School on Cosmophysics in Apatity, Murmansk region. At the request of Sergei Nikolaevich he went to Apatity and met Sergei Ivanovich Isaev, the Director of the Polar Geophysical Institute, and after meetings with E K Kozlov, the Chairman of the Kol'sk Branch of the USSR Academy of Sciences, and the Secretary of the CPSU town Committee of Apatity, the question about the organization of a Winter School on Cosmophysics in Apatity, which had already become traditional at the Academy of Sciences, was resolved. We began to make trips to Sergei Nikolaevich in Moscow to coordinate the organizing committee of the school and its program, the list of participants, and other organizational questions. After that, being the scientific secretary of schools, a number of seminars, symposia, and conferences on cosmic rays, and the scientific secretary of the Scientific Council on Cosmic Rays, for many years I often visited Sergei Nikolaevich at the Research Institute for Nuclear Physics (RINP) of Moscow State University, who was Director of this institute, and at the Nuclear Physics Division of the Presidium of the USSR Academy of Sciences, where Sergei Nikolaevich was the Deputy Academician-Secretary of the Division.

3. Apatity stage of cosmophysics schools (1968–1969)

I would like to emphasize at once the special role of S N Vernov in the development of cosmic ray science and the organization of many scientific meetings on cosmic rays. He continuously organized these meetings, not only in Moscow, but also in Apatity, Irkutsk, Yakutsk, Alma-Ata, Erevan, and other places. This undoubtedly facilitated the advancement of science in these cities and attracted the attention to cosmic rays of not only young scientists but also the local administration on which the development of the infrastructure of scientific studies considerably depended.

Cosmophysics schools held in our country had a specific feature distinguishing them from meetings, conferences and symposia. The main task of these schools was to give new knowledge on different lines of investigation in cosmic ray physics to participants working in different fields of physics, to present a clear picture of the general state and prospects of cosmic physics, and to establish interrelations between different natural processes. Sergei Nikolaevich believed that the participants in the school should discuss the state of the art and prospects of the main avenues in cosmic physics and receive information on advances in related scientific fields covering neutrino astrophysics, cosmological objects, the role of relict radiation in the evolution of the Universe, and solar physics, etc. This required the invitation of well-known scientists as lecturers at the school. Sergei Nikolaevich paid close attention to the choice of reports and review lectures of interest for a wide circle of participants. Of course, the duration of such schools was quite long and their regulation differed from that accepted in the Academy of Sciences for meetings and seminars.

By the time I was included on the committee for organizing and carrying out the Winter Cosmophysics School in Apatity in 1968, already four such schools supported by the resolution of the Section of Cosmic Rays and Radiation Belts had been held in previous years in different cities. Thus, we could use the experience of these schools for organizing the V-th Winter Cosmophysics School.

The V-th and VI-th Winter Cosmophysics Schools chaired by S N Vernov were supported by the resolution of the Presidium of the USSR Academy of Sciences and were held at the Polar Geophysical Institute (PGI) in Apatity from 21 March to 5 April 1968 (the V-th school) and from 18 March to 1 April 1969 (the VI-th school). 150 scientists presenting 57 reports attended the fifth school, and 300 scientists presenting 116 reports attended the sixth school. The PGI had well-equipped laboratories in which the ionosphere, aurora, Earth's magnetic field, and cosmic rays were investigated. I was lucky to collaborate with Sergei Nikolaevich and his colleagues for a long time after these schools during the organization of other meetings on cosmic physics.

The organizing committees of the V-th and VI-th Schools usually prepared the program of sessions at least 3–4 months prior to their beginning, and asked well-known scientists to give lectures. For example, the organizing committee of the V-th School invited our leading scientists V L Ginzburg, Ya B Zel'dovich, B M Pontecorvo, E P Mustel', E L Feinberg, L E Gurevich, A Z Dolginov, G T Zatsepin, L I Dorman, S I Syrovatskii, and some others.

Opening of the Sixth Cosmophysics School: (from left to right) Yu A Volkov, Scientific Secretary of the Polar Geophysical Institute, S I Isaev, Director of the Polar Geophysical Institute, S N Vernov, Chair of the School's Organizing Committee, E K Kozlov, Chairman of the Kol'sk Branch of the USSR Academy of Sciences, G E Kocharov, Deputy Chair of the School's Organizing Committee, P V Prokoshin, Secretary of the CPSU town Committee, and V A Dergachev, Scientific Secretary of the School's Organizing Committee (Apatity, Murmansk region, 1969).

Visit to the I A Kuz'min laboratory: (from left to right) L I Miroshnichenko (Pushkov Institute of Earth Magnetism, the Ionosphere and Propagation of Radiowaves, RAS (IZMIRAN in *Russ. abbr.*), G E Kocharov, S N Vernov, and I A Kuz'min (Apatity, PGI, 1969).

During a lecture: (from right to left) E K Kozlov, S N Vernov, L L Lazutin (PGI), and A E Chudakov (Apatity, PGI, 1969).

S N Vernov during a break between sessions among participants in the school. V A Dergachev is instructed about changes in the program of the Sixth Cosmophysics School (Apatity, PGI, 1969).

The task of organizing the V-th and VI-th Cosmophysics Schools was mainly performed by researchers of the PTI, and, of course, Sergei Nikolaevich, with me and G E Kocharov, considered all the questions, including the accommodations of the participants (which was rather difficult to do in a small town). In addition, Sergei Nikolaevich emphasized the importance of publishing the proceedings of the school and proposed attempting to publish them (the proceedings of previous schools were not published). Because the next school was to be held the next year, it was necessary to publish the proceedings as fast as possible. We took on this task not understanding on the whole all the problems that awaited us. We accepted papers till the end of May 1968 and then carefully edited them by enlisting the services of scientific and style editors, and finally printed them on an offset duplicator. As a result, I had to be in Apatity for more than three summer months in 1968. Eventually, the proceedings of the V-th school were published within four months after the end of the school. Sergei Nikolaevich was very glad and emphasized the importance of this work, showing a copy of proceedings at each convenient opportunity.

However, this wide publicity of the school played a malicious jest on us when we organized the next school, the VI-th one. The number of proposed reports and lectures was so large that all of them could not be accepted. And the number of researchers willing to attend the school was too large (300 people). I will not describe here the problems concerning the accommodations of participants in the school and how Sergei Nikolaevich organized a visit to a Secretary of a CPSU town Committee, who understood our situation and asked local inhabitants who had already received apartments in a new building not to occupy flats in one part of one of the building for two weeks during the work of the School. Such was the authority of science at that time!

By the time of the VI-th Cosmophysics School, we had become friendly with the scientific community in Apatity and regularly discussed with Sergei Nikolaevich many questions at the Kol'sk Branch of the USSR Academy of Sciences with A N Voronkov, the Deputy Chairman of the Presidium of the Kol'sk Branch of the Academy of Sciences and Yu A Shashmurin, the Scientific Secretary of the Branch, who significantly helped us to organize the printing of the proceedings on an offset duplicator. S I Isaev, the Director of the PGI, and Yu A Volkov, the Scientific Secretary, helped us to solve all the problems encountered during the work of the school and organized leisure hours. We visited some laboratories at the PGI. Yu A Volkov, L L Lazutin, I N Kapustin, and others invited us to their homes and we appreciated their northern hospitality.

One day during a break between sessions we walked about the lobby and discussed the possibility of including an additional report in the evening session. Sergei Nikolaevich saw one of the participants standing stock-still near the stand displaying the program and said: "Pay attention to this young man, he will go far." This young man was Mikhail Igorevich Panasyuk, who was then only a postgraduate student. And Sergei Nikolaevich was not mistaken!

Due to the huge number of reports, the Organizing Committee of the Sixth School decided to publish mainly lectures of invited scientists and review papers of interest to a wide circle of researchers. During the session of the Scientific Council on the complex problem of cosmic rays on the last day of the school, Sergei Nikolaevich highly praised the activity of the school organizers. Of course, it was necessary to publish the proceedings of the Sixth School, like those of the Fifth School, in a short time, which was accomplished (the proceedings were published in two volumes).

Unfortunately, this was the end of the Apatity stage of these schools. One of the reasons, as pointed out in the discussion of the next schools, was that we could not maintain the high level of conducting the schools and could not provide the rapid publishing of proceedings. Nevertheless, these cosmophysics schools were exceptional in a certain sense, and they considerably expressed and even determined in some aspects the development of the cosmophysics community. However, another format for these schools was required.

4. Leningrad stage of cosmophysics at international seminars, conferences on cosmic rays, the European symposium (1969–1983).

Sergei Nikolaevich loved Leningrad and cosmic ray physics very much. This love led to the resolution of the Nuclear Physics Division of the Presidium of the USSR Academy of Sciences to organize annual international seminars in Leningrad, beginning from 1969. These seminars were devoted to the discussion of separate problems of cosmic physics, with the participation of foreign scientists.

The First Leningrad International Seminar on the Physics of Interplanetary Space was held at the Ioffe PTI in Leningrad from 3 to 7 June 1969. One should not forget about the difficulties of organizing scientific meetings during the white nights period in Leningrad, when the number of unoccupied apartments in hotels is lacking. All the problems encountered in the organization of seminars had to be agreed with the local administration at the highest level. Reports were mainly presented by invited scientists. Reports by foreign participants were synchronously translated and discussed in detail.

Conversation with S N Vernov near the Ioffe PTI building in Leningrad during a meeting on 3–7 June 1969. From left to right: G E Kocharov, V I Chesnokov (PTI), K I Gringauz (Space Research Institute, RAS (IKI in *Russ. abbr.*)), J R Winkler (USA), I M Podgorny (IKI), D J Williams (USA), S N Vernov, S M Krimiges (USA), K G McCracken (Australia) (photograph from the S M Krimiges paper, "Decades of great accomplishments" in book [2]) (Leningrad, 1969).

In opening the seminar, B P Konstantinov, Vice President of the USSR Academy of Sciences (Director of the PTI for a long time) highly valued the idea of organizing such seminars and considered some of the urgent problems of modern physics. In conclusion, he thanked foreign colleagues who took part in the seminar: H Alfvén (Sweden), D J Williams, J R Winkler, and S M Krimiges (USA), W R Webber (England), A Somogyi (Hungary), K G McCracken (Australia), P Velinov (Bulgaria), and Knut (German Democratic Republic).

It was natural to publish seminar proceedings in the current year. And here Sergei Nikolaevich had our support. Of course, the organization of these meetings took much time. The publishing of proceedings on the offset duplicator required a lot of routine work, which was performed by our small group. Nevertheless, the seminar proceedings were published at the PTI in 1969.

As a whole, the year 1969 was very arduous, and we in fact had no time for research.

Sergei Nikolaevich saw this and proposed that the proceedings of the next seminars be published at the Research Institute for Nuclear Physics of Moscow State University, because they had better equipment and could use a greater number of staff members for this work. So, the proceedings of the second and third Leningrad seminars were published at the MSU RINP, although they failed to do it in the same year as the seminar.

Sergei Nikolaevich believed that seminar proceedings should be published as fast as possible and asked G E Kocharov to estimate the possibilities. I remember that Grant Egorovich said that everything depended on V A Dergachev. Of course, I could not refuse Sergei Nikolaevich! And I toiled at this generous task in fact until the last seminar which was headed by Sergei Nikolaevich. And while Sergei Nikolaevich was alive, 12 Leningrad seminars were held in which scientists from other countries participated with pleasure and presented review papers containing the newest information. Seminars were devoted each year to different problems of cosmophysics, which was rapidly developing in the 1970s–1980s.

S M Krimiges, a leading researcher in several NASA's projects in the USA and a participant in the first Leningrad seminar, visited Russia in 2007 in connection with the 50th anniversary of the launching of the first sputnik in the USSR and pointed out in his talk: "*I remember well my first visit to the USSR in 1969 at the invitation of Academician S N Vernov to participate in the conference at the Ioffe Physical-Technical Institute in the then Leningrad. Several Western scientists (H Alfvén, K G McCracken, W R Webber, J R Winkler, D J Williams) also took part in the conference and we had a magnificent series of discussions and compared for the first time the data on solar high-energy particles obtained by means of satellites in the USA and USSR*" [2].

The Sixth Leningrad International Cosmophysics Seminar: during a lecture. First row (from left to right): S N Vernov, G E Kocharov, A Somogyi (Hungary), A Z Dolginov (Ioffe PTI), V A Krat (Pulkovo Observatory); second row (from right to left): S I Syrovatskii (FIAN), V A Dergachev (Leningrad, 1974).

The topics of the next seminars were as follows.

The Second International Seminar on the problem 'Generation of Cosmic Rays in the Sun' (Leningrad, 8–12 December 1970). In opening the seminar, S N Vernov pointed out the importance of studying solar cosmic rays and indicated the main areas of these studies. He said that the accumulated experimental data and theoretical hypotheses could be used to analyze in detail the physical processes governing the generation of cosmic rays in the Sun and their acceleration in outer space, and to work out recommendations for further theoretical and experimental investigations in this field. The seminar proceedings were published at the MSU RINP in 1971 [3].

The Third International Seminar on the problem 'Acceleration of Particles in Space (Circumterrestrial and Interpanetary Space), the Galaxy and the Metagalaxy' (Leningrad, 13–15 July 1971) [4].

The Fourth Leningrad International Seminar on 'The Uniformity of the Particle Acceleration on Different Space Scales' (Leningrad, 16–18 August, 1972) [5].

The Fifth Leningrad International Seminar on 'Solar Cosmic Rays and Their Penetration into Earth's Magnetosphere' (Leningrad, 26–29 June 1973) [6].

The Sixth Leningrad International Seminar on 'Particle Acceleration and Nuclear Reactions in Space' (Leningrad, 19–21 August 1974) [7].

The Seventh Leningrad International Seminar on 'Corpuscular Solar Fluxes and Earth and Jupiter Radiation Belts' (Leningrad, 25–28 May 1975) [8].

The Eighth Leningrad International Seminar on 'Active Processes in the Sun and the Problem of Solar Neutrinos' (Leningrad, 25–27 September 1976) [9].

The Ninth Leningrad Cosmophysics Seminar on 'Solar Cosmic Rays: Their Generation and Interaction with Matter from the Source to Earth' (Leningrad, 23–25 December 1977) [10].

The Tenth Leningrad Cosmophysics Seminar on 'Nuclear Cosmic Physics' (Leningrad, 6–8 October 1978) [11].

The Eleventh Leningrad Cosmophysics Seminar on 'The Interaction of Cosmic Rays with a Medium' (Leningrad, 30 November–2 December 1979) [12].

The Seventh European Cosmic Ray Symposium (Leningrad, 15–19 September 1980) [13].

The Twelfth Leningrad Cosmophysics Seminar on 'Complex Studies of the Sun' (Leningrad, 6–8 February 1982) [14].

The Thirteenth Leningrad Cosmophysics Seminar on 'The Intensity of Cosmic Rays and Cosmogenic Isotopes' (Leningrad, 19–21 November 1982) [15].

The world's best-known scientists in cosmophysics felt-honored to be invited to participate in the Leningrad seminars. These seminars attracted great attention of outstanding foreign and Russian scientists because they could discuss here in detail the most urgent scientific problems.

Seminar opening: A Somogyi (Hungary) addresses the meeting. Seated are (from left to right): V Kuchovich (Poland), S N Vernov, G E Kocharov, J Simpson (USA), V A Dergachev, E Bagge (FRG), P Povinec (Czechoslovakia) (Leningrad, 1976).

During a banquet after seminar's closing (from right to left): S N Vernov with his wife, I M Podgorny (IKI) with his wife, G E Kocharov, V A Dergachev, T N Charakhch'yan (FIAN) (Leningrad, 1976).

As an example, we can consider the Eighth Leningrad International Seminar on 'Active Processes in the Sun and the Problem of Solar Neutrinos', which was held at the Ioffe PTI from 25 to 27 September 1976. S N Vernov opened the seminar. Many known scientists presented reports. Among them were: G E Kocharov, G V Domogatskii, N N Stepanyan, B V Somov, B I Luchkov, M I Pudovkin, V A Krat, T N Charakhch'yan, A Z Dolginov, A K Lavrukhina, L I Dorman, I M Podgorny, B M Vladimirskii, and some others (USSR); A Somogyi, D Benko, G Erdesh (Hungary); Z Kobylinsky, V Kuchovich (Poland); J Vorpal and J Simpson (USA); K Kudela, S Pinter, P Povinec (Czechoslovakia), and E Bagge (Federal Republic of Germany). L E Gurevich and B M Pontecorvo also actively participated in discussions.

The seminar opened with a speech by S N Vernov, the Chair of the Organizing Committee, who said that the Leningrad seminars had already been of much benefit, especially concerning cosmophysics. S N Vernov demonstrated in his talk that he knew in detail many problems of current interest in cosmophysics. He presented a number of problems related to processes proceeding in the Sun, which had to be studied theoretically. A A Somogyi (Chair of the Commission on Cosmic Rays of the International Union of Pure and Applied Physics) pointed out that interest in the seminar arose not only due to scientific problems, but also due to the beauty of Leningrad and the warm friendly atmosphere at the seminar. John A Simpson, Director of the Enrico Fermi Institute, University of Chicago and a world-renowned scientist, said that the seminar was important due to representative scientific discussions and reports concerning the latest studies and the opportunity of visiting the USSR to meet many Soviet scientists, especially young scientists, studying cosmic rays. He also pointed out that the Leningrad seminars actively facilitated collaboration between the two countries and exchange programs developed by the Academy of Sciences in the USA and USSR. The seminar closed with speeches by E Bagge, Director of the Institute for Nuclear Physics, Kiel University, S Pinter, Director of the Geophysical Observatory (Hurbanovo, Czechoslovakia), and G E Kocharov, Deputy Chair of the Organizing Committee.

The jubilee seminar, the tenth, opened with a speech by S N Vernov, who pointed out that the idea of such international seminars devoted to some problems of cosmophysics belonged to Moisei Aleksandrovich Markov, Academician-Secretary of the Nuclear Physics Division of the USSR AS.

S N Vernov said that the different aspects of cosmophysics in space and time were discussed at previous seminars: "*And we have managed to relate the different aspects of these complex and interconnected phenomena by bridging them. And we expanded the topic from seminar to seminar, increasing the number of organizations and the number of researchers who more and more became the enthusiasts of our seminars. And in the meantime, our science developed very successfully. We worked and are still working in the field where the flights of satellites and cosmic rockets provide a great amount of new information. Therefore, it is natural that our seminars are always of current interest. They are devoted to very new and very interesting questions that appeared only recently and require active discussions of different aspects and rapid solution*" [11].

Along with seminars, we also organized together Conferences on Cosmic Rays in Leningrad and the Seventh European Cosmic Ray Symposium (ECRS).

I would like to emphasize how deeply S N Vernov understood the scale of cosmic ray physics. He said: "*In fact we are divided into two parts, some of us gravitating to astronomy, having practically no relation to nuclear physics, while others gravitate to nuclear physics and are clearly far from astronomy. However, there are people among us who can be cut in half because one part of them belongs to nuclear physics, while the other to astronomy*" [13].

D N Skobeltsyn called the astronomical aspect of cosmic rays cosmophysical. From this point on, cosmic ray physics was divided into the cosmophysical and nuclear–physical fields, and cosmic ray conferences were held and are being held in these two fields. It is pertinent here to cite S N Vernov again: "*What will we have if we break cosmic ray physics into cosmic ray physics studying astronomical problems, and cosmic ray physics investigating nuclear problems? This will lead to a parcel of rubbish, comrades*" [13]. Such conferences were held in Leningrad: in 1969, the cosmic ray conference was chaired by Sergei Nikolaevich, and the 30th Jubilee Conference was held in 2008 without him, and we remembered him again.

During the conference opening in 1969, K P Seleznev, Rector of the Leningrad Polytechnical Institute, gave Sergei Nikolaevich a memorial medal in connection with the 50th anniversary of the Physicomechanical Department where Sergei Nikolaevich had studied.

A speech by S N Vernov during the opening of the Seventh European Cosmic Ray Symposium at the LPI on 15 September 1980 was very profound. He talked with feeling about Dmitrii Vladimirovich Skobeltsyn, his teacher, whom he met at the LPI in 1932 and to whom, according to S N Vernov's words, we were indebted not only because of cosmic ray physics but also due to high-energy physics. Although D V Skobeltsyn was 88 in 1980, he was the leader of the Cosmic-Ray Physics School in the Soviet Union.

The Seventh European Cosmic Ray Symposium opened with greeting speeches by A Wolfendale (England), Secretary and future Chair of the IUPAP Cosmic Ray Commission, A Somogyi (Hungary), ex-Chair of this Commission, and G N Aleksandrov, prorector of the LPI.

S N Vernov emphasized in his talk at the Symposium that many cosmophysical problems had been considered at Leningrad seminars (by this time, 11 seminars had already been held) and, giving these seminars credit, he said: "*I even misspoke, calling the symposium a seminar because we have already simply become accustomed to meet together each year at traditional Leningrad seminars*" [13].

At the end of his talk, S N Vernov called on participants not to stop at the achieved results. He said: "*What do we need now from cosmic rays? The Academician M A Markov, Head of the Nuclear Physics Division, thinks that we work poorly because we have not followed the way of researchers in the field of accelerators and have not created industrialization in cosmic rays. We should build boldly large facilities, use computers instead of manual calculations and we should not be afraid of large scales, as are researchers who are now building giant accelerators that cost hundreds of millions of rubles*" [13]. How this is also relevant now!

On the behalf of the LPI staff, G N Aleksandrov extended his best wishes to S N Vernov on his 70th birthday and on awarding the high rank of Hero of Socialist Labor for outstanding merits in scientific, pedagogical, and communal activities.

In his concluding speech, S N Vernov highly praised the Symposium in which more that 300 scientists had participated. The total number of reports, including plenary talks, amounted to 445; 22 invited speakers presented lectures. S N Vernov pointed out that, unlike the proceedings of the previous symposia, the proceedings of this symposium would be published. And they were published in 1980.

S N Vernov also said: "*I think that the field of studying cosmic rays is so diversified and our science is developing so quickly that we should meet together each year, i.e., international conferences should be held every two years and European symposia in the year between them; one year is a large enough time period*" [13]. As a whole, the symposia changed the structure of Leningrad International Seminars.

Cosmic physics suffered an irrecoverable loss after the death of Sergei Nikolaevich. He lived a very meaningful life, did much for people, and left the memory of himself in the hearts of his numerous pupils, collaborators, and all those who were lucky enough to associate with him, listening to his interesting reports. We will always remember Sergei Nikolaevich and will try to ensure that his living image influences our deeds.

5. S N Vernov as a man

I have met in my life two brilliant scientists and organizers of science, Academicians B P Konstantinov and S N Vernov. The 100th anniversary of their births is celebrated in this year. They greatly influenced me in the choice of my scientific path and, which may be even more important, in the wish to be and remain a man in any situation.

I worked with Sergei Nikolaevich for more than 12 years as a scientific secretary of his seminars, all-union conferences, and schools. He was distinguished among others by his great talent in physics, exceptional creativity, and extraordinary capacity for work.

I often visited the MSU RINP at that time and saw how he cared about his collaborators and how he was easily accessible to them all, from the heads of departments to simple staff members. Sergei Nikolaevich never pretended, never was didactic, but, I would say, rather preferred to teach. And all the staff members of the Institute had the greatest and warmest respect for him. Sergei Ivanovich treated everyone equally and respectfully. Overall, he appreciated in people good manners and the ability to behave properly.

Sergei Nikolaevich was a rather mild-tempered man. But in the cause of science, his mildness could instantly evaporate. And I saw it two times.

I still remember the special, elated, and even joyful mood that I experienced during each visit to Sergei Nikolaevich at the MSU RINP or at the Nuclear Physics Division of the Academy of Sciences or in Leningrad at the home of his daughter on Grazhdanskii prospect. Now, after almost 40 years, it is very difficult to recall in detail the content of our conversations. Because I also lived on Grazhdanskii prospect at that time, Sergei Nikolaevich called me almost every time he came to Leningrad and asked which questions remained unsolved and which help was required. Of course, we always discussed both the preliminary and final programs of planned meetings. I remember how I sometimes visited Sergei Nikolaevich on Grazhdanskii prospect when he had a cold. He said that he cured himself by a simple down-to-earth method and asked me about my attitude to a small glass of Zubrovka vodka, whose healing properties were not appreciated by his relatives. Here, I was on the side of Sergei Nikolaevich.

Usually, when I was going to leave, Sergei Nikolaevich said: "Let's walk and I will escort you to your home." I understood that Sergei Nikolaevich needed a walk and we went first to my home and then back. I felt that Sergei

The 70th birthday of S N Vernov (from right to left): S N Vernov, V A Dergachev (PTI), G B Khristiansen (MSU RINP), G V Kulikov (MSU RINP), G E Kocharov (PTI), and G Ya Goryacheva (FIAN) (Moscow, 1980).

Nikolaevich wanted to share his thoughts about his successors who would continue his work. Thus, we discussed candidates for the position of the deputy director of the MSU RINP and the head of the Baikal neutrino experiment to which Sergei Nikolaevich paid great attention. I remember how acutely he understood this situation. He said that it was very difficult to find a head who would have high moral values and at the same time could deal with Party bodies which could provide the help, otherwise everything could be spoiled. It was necessary not only to have talent, staying power, and the capacity for work, but to be able to orientate in the political life of the country under those conditions in order to obtain the many excellent results which were achieved due to the efforts of S N Vernov himself. When we separated after each walk, Sergei Nikolaevich used to say: "Well, we have discussed not only scientific but also political problems."

During one of my visits to the MSU RINP for discussing the program of the next Leningrad seminar, I entered the office of Sergei Nikolaevich and he said that he had to go home then because his wife, Mariya Sergeevna, was ill and needed continuous care, and nobody was near her at this moment. He apologized for involving me, a stranger, in his family affairs and invited me to discuss our problems at his home during dinner. The dinner resembled a simple student dormitory meal: there was cheese, sausage, and a bottle of dry wine on a table covered with a cloth. When Sergei Nikolaevich told me about the grave illness of Mariya Sergeevna, I understood how much strength this constant pain took from him. He lovingly cared for his wife.

Fate gives everybody his own life span to accomplish all that he can do. And Sergei Nikolaevich showed what one can do if he is devoted to his work. He was a unique person and all his life was given up to science. Let us admit that now there is no other scientist in the field of cosmic ray physics who is capable of combining equally the cosmophysical and nuclear–physical aspects of cosmic rays. Really, of no little significance was to gather around himself at the MSU RINP creative people capable of developing space science and due to their activity promoting the formation of a first-class research institute widely known not only in this country.

I felt his special attitude towards experimental studies. He believed that cosmic ray physics could not be completely understood without experiments. "Never abandon experiments," Sergei Nikolaevich used to say to me. And I follow his 'experimental' testament, heading a cosmic ray laboratory at which we are now performing two cosmic experiments: the study of the charge and energy spectra of cosmic rays with solid-state track detectors mounted aboard the International Space Station, and the polarization study of solar radiation with a satellite-borne Compton polarimeter.

100 years is a serious jubilee, and different thoughts about the future, present, and past come to mind. And they are interrelated because nothing vanishes into thin air. Sergei Nikolaevich long ago left us, but now we are peering into the short life of this unique man with undying interest and it seems that he is near and you will meet him now. And you are waiting to see what new things Sergei Nikolaevich will propose for us to do. We still remember him and will remember in the future.

The creative life of Sergei Nikolaevich took place in the Soviet Union in tortuous times. However, it should be emphasized that Soviet rule created more favorable conditions for the work of scientists than the present conditions in our science. But we must maintain the high level of cosmophysics created by Sergei Nikolaevich and attract young talent into this field of science. How can we help many curious youngsters to choose the right way in their life? To do this, we should write a book about S N Vernov in a series 'The Life of Remarkable People'. The biography of S N Vernov described in this book can encompass the entire history of cosmic physics and tell about our contemporaries who have made noticeable contributions to cosmic science. A young reader, especially a gifted one, cannot help but pay attention to the scientific aspect of the S N Vernov biography, which can initiate their contemplations about their own life ideals.

6. In lieu of a conclusion

The time when Sergei Nikolaevich Vernov lived was truly grandiose and was related to the realization of the dream of a human to escape from Earth's limits. And this was accomplished. And Sergei Nikolaevich was among those who realized this dream. I would rather conclude my recollections by the most objective estimate of that time and the contributions of those who realized this dream of humankind. I will cite part of the concluding remarks from the paper "Decades of great accomplishments" by S M Krimiges, a participant in the First Leningrad Cosmophysics Seminar (1969) in book [2]: "*By contemplating the beginning of the cosmic era, I am amazed by the fact that a key role was played by the 'cold war'. It is difficult to imagine that high-carrying capacity missiles, which were used to launch satellites and space probes, would be developed in the absence of the arms race caused by the competition of superpowers. It is possible that such missiles would also have been built without the 'cold war', but this would have taken much more time, so that the beginning of the space age would be delayed. So, the cosmic science benefited by the 'cold war' in this strange way. It is undoubtedly, however, that the space age was an inevitable next step in the development of our civilization and it was of much benefit to all of humankind. Thus, we should thank the prophets and pioneers of this era: Korolev, von Brown, Van Allen, Vernov, and all their colleagues following their dream and acting it out by their imagination and skills.*"

References

1. Dergachev V A, in *Akademik Sergei Nikolaevich Vernov: k 100-Letiyu so Dnya Rozhdeniya* (Academician Sergei Nikolaevich Vernov: to the 100th Anniversary of the Birthday) (Moscow: Moscow State University Publ., 2010) pp. 286–297
2. Krimiges S M, in *4 Oktyabrya 1957 Goda. Nachalo Kosmicheskoi Ery. Pervaya Kosmicheskaya* (4 October 1957. The Cosmic Era Beginning. The First Cosmic Era) (Comp. O V Zakutnyaya) (Moscow: Space Research Institute, RAS, 2007) p. 202
3. *Trudy II Mezhdunar. Seminara po Probleme "Generatsiya Kosmicheskikh Luchei na Solntse", Leningrad, 8–12 Dekabrya 1970 g.* (Proc. of the II Intern. Seminar on the problem 'Generation of Cosmic Rays in the Sun', Leningrad, 8–12 December 1970) (Moscow: MSU, 1971)
4. *Trudy III Mezhdunar. Seminara po Probleme "Uskorenie Chastits v Kosmicheskom Prostranstve (Okolozemnom i Mezhplanetnom Kosmicheskom Prostranstve), Galaktike i Metagalaktike", Leningrad, 13–15 iyulya 1971 g.* (Proc. of the III Intern. Seminar on the problem 'Acceleration of Particles in Space (Circumterrestrial and Interplanetary Space), the Galaxy and the Metagalaxy', Leningrad, 13–15 July 1971) (Moscow, 1972)
5. Kocharov G E, Dergachev V A (Eds) *Trudy IV Leningradskogo Mezhdunar. Seminara "Edinoobrazie Uskoreniya Chastits v Razlichnykh Masshtabakh Kosmosa", Leningrad, 16–18 Avgusta 1972 g.*

(Proc. of the IV Leningrad Intern. Seminar on 'The Uniformity of the Particle Acceleration on Different Space Scales', Leningrad, 16–18 August 1972) (Leningrad, 1972)
6. Kocharov G E, Dergachev V A (Eds) *Trudy V Leningradskogo Mezhdunar. Seminara " Solnechnye Kosmicheskie Luchi i ikh Proniknovenie v Magnitosferu Zemli, Leningrad, 26–29 Iyunya 1973 g.* (Proc. of the V Intern. Seminar on 'Solar Cosmic Rays and Their Penetration into Earth's Magnetosphere', Leningrad, 26–29 June 1973) (Leningrad, 1973) 408 pp.
7. Kocharov G E, Dergachev V A (Eds) *Trudy VI Leningradskogo Mezhdunar. Seminara "Uskorenie Chastits i Yadernye Reaktsii v Kosmose", Leningrad, 19–21 Avgusta 1974 g.* (Proc. of the VI Leningrad Intern. Seminar on 'Particle Acceleration and Nuclear Reactions in Space', Leningrad, 19–21 August 1974) (Leningrad, 1974) 403 pp.
8. Dergachev V A, Kocharov G E (Eds) *Trudy VII Leningradskogo Mezhdunar. Seminara "Korpuskulyarnye Potoki Solntsa i Radiatsionnye Poyasa Zemli i Yupitera", Leningrad, 25–28 Maya 1975 g.* (Proc. of the VII Leningrad Intern. Seminar on 'Corpuscular Solar Fluxes and Earth and Jupiter Radiation Belts', Leningrad, 25–28 May 1975) (Leningrad, 1975)
9. Dergachev V A, Kocharov G E (Eds) *Trudy VIII Leningradskogo Mezhdunar. Seminara "Aktivnye Protsessy na Solntse i Problema Solnechnykh Neitrino", Leningrad, 25–27 Sentyabrya 1976 g.* (Proc. of the VIII Leningrad Intern. Seminar on 'Active Processes in the Sun and the Problem of Solar Neutrinos', Leningrad, 25–27 September 1976) (Leningrad, 1976)
10. Dergachev V A, Kocharov G E (Eds) *IX Leningradskii Seminar po Kosmofizike*: *Trudy Mezhdunar. Seminara po Kosmofizike "Solnechnye Kosmicheskie Luchi*: *Generatsiya i Vzaimodeistvie s Veshchestvom ot Istochnika do Zemli", Leningrad, 23–25 Dekabrya 1977 g.* (The IX Leningrad Cosmophysics Seminar: Proc. of the Intern. Cosmophysics Seminar on 'Solar Cosmic Rays: Their Generation and Interaction with Matter from the Source to Earth', Leningrad, 23–25 December 1977) (Leningrad: Leningrad Institute of Nuclear Physics) 404 pp.
11. Dergachev V A, Kocharov G E (Eds) *X Leningradskii Seminar po Kosmofizike*: *"Yadernaya Kosmicheskaya Fizika", Leningrad, 6–8 Oktyabrya 1978 g.* (The X Leningrad Cosmophysics Seminar on 'Nuclear Cosmic Physics', Leningrad, 6–8 October 1978) (Leningrad: Leningrad Institute of Nuclear Physics, 1978)
12. Kocharov G E (Ed.) *XI Leningradskii Seminar po Kosmofizike*: *"Vzaimodeistvie Kosmicheskikh Luchei so Sredoi", Leningrad, 30 Noyabrya–2 Dekabrya 1979 g.* (The XI Leningrad Cosmophysics Seminar on 'The Interaction of Cosmic Rays with a Medium', Leningrad, 30 November–2 December 1979) (Leningrad: Leningrad Institute of Nuclear Physics, 1979)
13. Dergachev V A, Kocharov G E (Eds) *Kosmicheskie Luchi*: *7-i Evropeiskii Simpozium po Kosmicheskim Lucham, Leningrad, 15–19 Sentyabrya 1980 g.* (Cosmic Rays: The 7th European Cosmic Ray Symposium, Leningrad, 15–19 September 1980) (Leningrad, Leningrad Institute of Nuclear Physics, 1980); *Izv. Akad. Nauk SSSR, Ser. Fiz.* (7) (1981)
14. Dergachev V A, Kocharov G E (Eds) *XII Leningradskii Seminar po Kosmofizike*: *"Kompleksnoe Izuchenie Solntsa", Leningrad, 6–8 Fevralya 1982 g.* (The XII Leningrad Cosmophysics Seminar on 'Complex Studies of the Sun', Leningrad, 6–8 February 1982) (Leningrad, Leningrad Institute of Nuclear Physics, 1982) 208 pp.
15. Kocharov G E (Ed.) *XIII Leningradskii Seminar po Kosmofizike*: *"Intensivnost' Kosmicheskikh Luchei i Kosmogennye Izotopy", Leningrad, 19–21 Noyabrya 1982 g.* (The XIII Leningrad Cosmophysics Seminar on 'The Intensity of Cosmic Rays and Cosmogenic Isotopes', Leningrad, 19–21 November 1982) (Leningrad: Physical-Technical Institute, 1982)

PACS numbers: 94.20.wq, 96.50.Vg, 96.50.Wx
DOI: 10.3367/UFNe.0181.201102l.0218

S N Vernov and cosmic ray research in the Earth atmosphere

Yu I Stozhkov, G A Bazilevskaya

1. Introduction

Sergei Nikolaevich Vernov (1910–1982) devoted all his scientific life to the investigation of cosmic rays (CRs). The energy spectrum of CRs occupies a huge energy range from $\sim 10^8$ to $\sim 10^{20}$ eV, and S N made important contributions to studying the properties of cosmic particles in practically all this range. In the present report, we discuss the range of energies from $\sim 10^8$ to $\sim 2 \times 10^{10}$ eV. The energies of more than 95% of the cosmic particles crossing the atmospheric boundary fall into this range. Almost all the particles and their energy are absorbed by Earth's atmosphere.

Cosmic rays — the radiation that enhances with altitude in the atmosphere — were discovered by V F Hess in 1912, and it was clear by the early 1930s that this radiation comes from outer space. S N Vernov understood that, because of the absorption of particles in Earth's atmosphere, observations in upper atmospheric layers have significant advantages over ground-based measurements.

Active studies of the properties of CRs were initiated by S N in the 1930s, when he was a postgraduate student at the Radium Institute in Leningrad and developed the first radio probe aimed at studying CRs at different altitudes in the Earth atmosphere (Fig. 1) [1, 2]. As a prototype of this probe, he had chosen a meteorological probe developed by Professor P A Molchanov, who advised the young scientist. Data on CR fluxes were transmitted to the ground by radio. This device was launched for the first time on-board meteorological balloons in 1935. From this point on, studies of CR properties in the Earth atmosphere have been performed.

2. Early studies of cosmic rays in Earth's atmosphere (from 1935 to 1957, the launch of the International Geophysical Year project)

In the middle of the 1930s, the origin and main properties of CRs were unknown. At that time, the key question was whether these enigmatic space particles have a charge. If they have a charge, Earth's magnetic field will act on these particles in such a way that their fluxes in the equatorial and mid-latitude atmosphere will be different: the CR fluxes near the equator should be smaller than those at middle latitudes. To solve this fundamental problem, S N Vernov organized in 1935–1938 the performance of experiments at the middle and equatorial latitudes. Radio probes were launched into the atmosphere both from the ground and from a ship; the ship was going from the Black Sea to the far east [3–6]. Latitudinal variations of CR fluxes were observed, confirming the existence of the electric charge for cosmic particles.

Yu I Stozhkov, G A Bazilevskaya P N Lebedev Physical Institute, Russian Academy of Sciences, Russian Federation
E-mail: stozhkov@fian.fiands.mipt.ru

Uspekhi Fizicheskikh Nauk **181** (2) 218 –223 (2011)
DOI: 10.3367/UFNe.0181.201102l.0218
Translated by V V Lobzin; edited by A Radzig

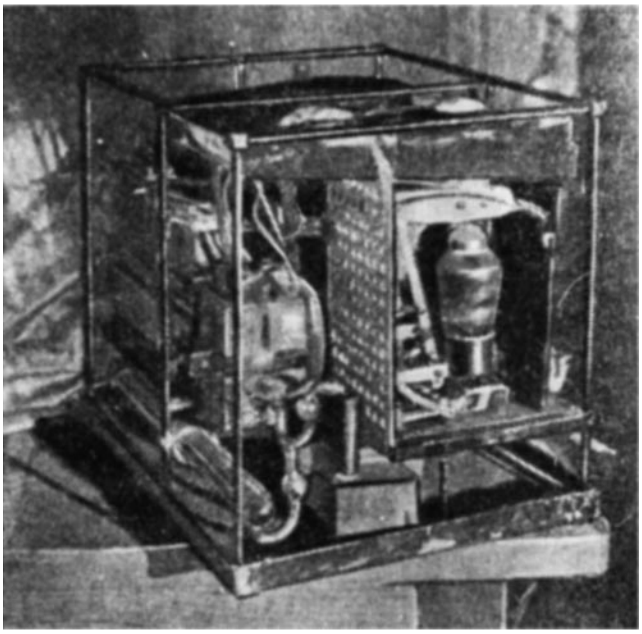


Figure 1. The first radio probe developed by S N Vernov for measurements of CR fluxes at different altitudes in Earth's atmosphere. For the first time the data were transmitted to the ground by radio. The weight of the radio probe was 28.6 kg.

The Great Patriotic war (the World War II) interrupted the investigations on CR physics. The studies were recommenced when the war was over. At that time, the main challenge was related to the nature of cosmic rays and the sign of charge. The charge can be determined from the difference in particle fluxes coming from the east and west directions. Estimates showed that the difference attains its maximum value at high altitudes in the Earth atmosphere near the geomagnetic equator. Because of this, S N Vernov with his colleagues from the Lebedev Physical Institute (LPI) and the 2nd Scientific Research Institute of Physics (SRIP-2) of Moscow State University (MSU) organized in 1949 a new sea survey expedition to equatorial regions of the Indian Ocean. One of the main results of this expedition was the detection of the east–west effect in CR fluxes. The flux of particles coming from the west was bigger than that from the east [7]. This undoubtedly proved that cosmic particles were positively charged, i.e., they were protons.

After the war, the country had to develop a nuclear (and then thermonuclear) weapon as soon as possible. The information on the interaction of particles with different atomic nuclei was required. At that time, accelerator engineering had made only the first steps and CRs (particles accelerated to high energies at a natural accelerator) were used to study nuclear interactions. This area of CR studies was called nuclear physics (as opposed to the space physics area which will be considered in what follows).

In 1946, new scientific institutions were established in this country destroyed by the war for studies of nuclear interactions of CRs with matter. These were the 2nd Scientific Research Institute of Physics of Moscow State University (now the Skobeltsyn Institute of Nuclear Physics of Moscow State University (MSU SINP)), the LPI Pamir high-altitude station located at the altitude of 3860 m, and the LPI Dolgoprudny Scientific Station (LPI DSS), which in 1996 was named after S N Vernov.

A wide range of problems was solved at that time by experiments arranged and conducted in the terrestrial atmosphere by S N and his colleagues, in particular, revealing the basic processes of CR interaction with the atmosphere and determining the main characteristics of the nuclear and electromagnetic components. Using the experimental data, they developed a theory of air showers, which included the electromagnetic and nuclear components [8]. It was shown that the cross section for the interaction of CRs with matter is constant in the energy range $E \approx (3-40)$ GeV, and the energy spent for nuclear fission weakly depends on the energy (~ 400 MeV) of the primary particles.

In the late 1940s and early 1950s, S N organized measurements of CR fluxes in the upper atmosphere layers at altitudes of 70–100 km. Rockets were launched from the site of Kapustin Yar. An important result was obtained: the flux of these particles is constant at altitudes of $\approx (35-100)$ km. The experiments were directed by A E Chudakov.

In 1951, 'a flying laboratory' was established on-board a military airplane for studies of the high-energy part of the CR spectrum. Particles with energies $E \sim (10^{11}-10^{13})$ eV were studied at altitudes of 9–12 km. The experiments were directed by Yu A Smorodin, who worked at the LPI DSS. In these experiments, modern (for those times) equipment was utilized (a Wilson chamber in the magnetic field, spark chambers, air shower setups, and X-ray emulsion chambers). A scale invariance was found, i.e., the similarity of spectra of particles emerging in nuclear interactions of particles with different energies. This work initiated the Pamir large-scale international X-ray emulsion experiment aimed at studying nuclear interactions of high-energy cosmic particles ($E > 10^{14}$ eV). The experiment was conducted over several decades in the Pamir mountains at an altitude of 3860 m. Further details about this period of S N's activity are given in the paper [9].

In 1949, the Stalin Prize of the First Class was awarded to S N Vernov for a series of studies of CR interactions with matter in Earth's atmosphere.

3. A method of frequent regular measurement of cosmic ray fluxes in the atmosphere

In connection with the International Geophysical Year project commenced in 1957, S N Vernov and N V Pushkov established a network of ground-based and stratospheric stations for studies of temporal and spatial variations of CR fluxes. These Russian ground-based stations, which have been working successfully up to the present time, are a necessary constituent of the worldwide network. Stratospheric stations represent the only setups in the world for studies of the CR modulation in the stratosphere, i.e., in the particle energy range that is not accessible to ground-based instruments.

Continuous measurements of CRs by an ionization chamber on the Earth surface were commenced by S Forbush in 1935. In the USSR, the first ionization chamber was constructed by N L Grigorov, Yu G Shafer, and S P Muratov in the late 1940s. Beginning in 1949, a continuous recording of CR fluxes commenced in the cite of Yakutsk and in the Moscow region at the Institute of Terrestrial Magnetism, the Ionosphere, and Radio Wave Propagation (IZMIRAN in *Russ. abbr.*) [10].

It was known at that time that the observed temporal variations of the CR fluxes depend on the particle energies.

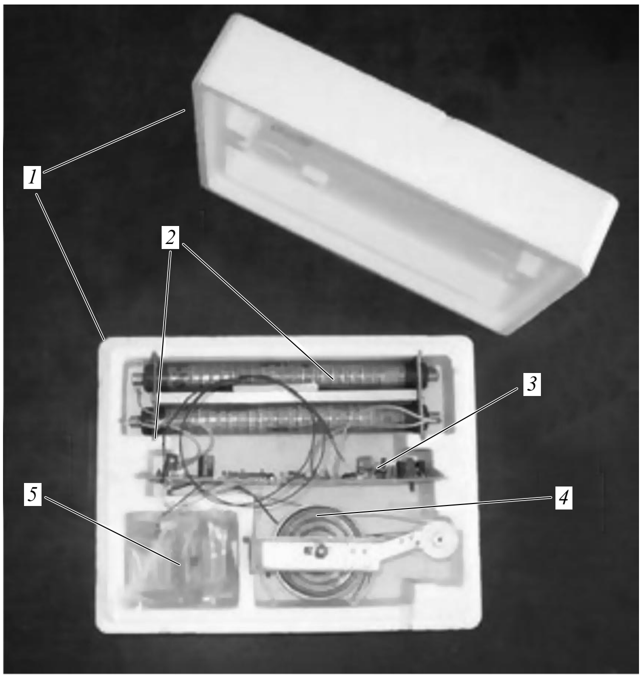


Figure 2. A standard radiosonde for measurements of charged particle fluxes in Earth's atmosphere. *1* — foam plastic box; *2* — charge particle detectors consisting of two STS-6 gas-discharge counters made in the Russia, with a 7-mm-thick aluminum filter between them; the filter allows separating radioactive particles from CR particles; *3* — electronic circuit with a high-voltage convertor and radio transmitter; *4* — atmospheric pressure sensor, and *5* — chemical batteries. The radio probe weight is about 0.6 kg.

The variations increase with a decrease in the energy. This forms the basis for regular measurements of CR fluxes in the atmosphere, from Earth's surface to altitudes of approximately 30–35 km.

In the middle of 1957, S N Vernov and A N Charakhch'yan commenced regular measurements of the charged particle fluxes in Earth's atmosphere. A special radiosonde and a ground-based receiver were developed for these measurements [11]. The same detectors (STS-6 gas-discharge counters made in the USSR) are also employed in the modern radiosonde (Fig. 2).

Earth's atmosphere and magnetic field are used for studies of the CR flux variations for different particle energies in the range from 0.1 to 20 GeV.

Initially, daily measurements were performed in the mid-latitude atmosphere (Dolgoprudny in the Moscow region) and the northern polar latitudes (Murmansk region). Since 1963, they have also been performed at the Mirny observatory (Antarctica). For several decades, the measurements were performed by the same instruments in the Crimea, the Alma-Ata region, Erevan, Noril'sk, and Tiksi [12]. Several sea survey expeditions were organized, where the planetary distribution of CR fluxes was measured for periods of maximum and minimum solar activity [13]. Since the early 1990s, due to shrinking resources the number of radiosonde launches has decreased. Instead of daily launches, now 3 launches per weak are performed at the middle latitudes (Dolgoprudny), at the northern polar latitudes (Apatity), and at the Mirny observatory in Antarctica. Up to now, more than 83,000 radiosondes have been launched.

4. Main results of long-term regular observations of the cosmic rays in Earth's atmosphere

Almost immediately after commencement of regular observations of charged particles in the terrestrial atmosphere, increases in their fluxes were detected. These were particles accelerated in explosion-like processes on the Sun (solar cosmic rays) and arrived at Earth. The first flares of solar cosmic rays were detected in 1958. Earlier, similar particles had been detected by ground-based instruments. Such events were rare (6 events were occurred from 1942 to 1956). In the stratosphere, their occurrence frequency increased several times and the solar CR fluxes were bigger than the galactic background fluxes by a factor of 10 to 100.

Figures 3a and 4a display the altitude profile for CRs before and at the time of arrival of particles accelerated in solar flares. The first event was registered in July 1959, and the

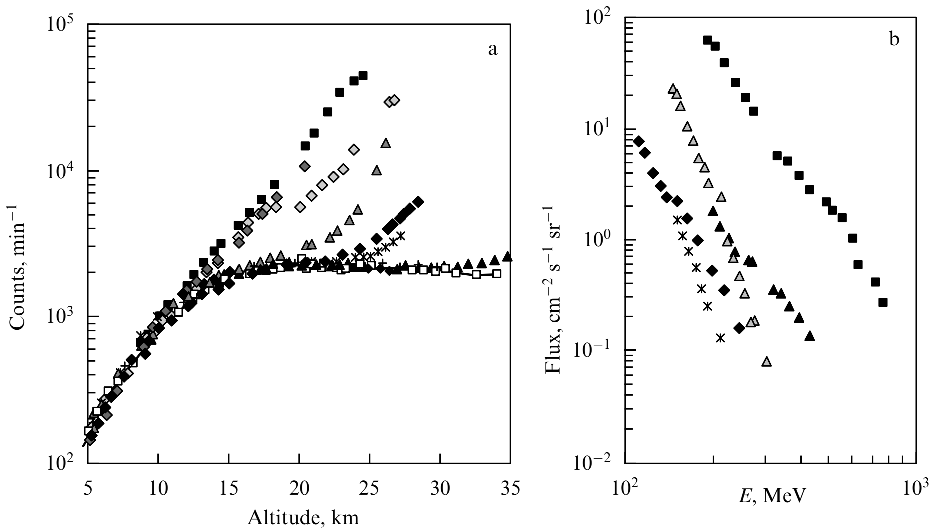


Figure 3. (a) The altitude profile for CRs observed in several radiosonde flights before and after a series of large solar flares occurred on 9, 14, and 16 June 1959. The measurements were performed at northern polar latitudes from 9 to 17 July 1959. Data for different flights are marked by different symbols. The galactic ray background is shown by white squares. (b) The solar proton integral spectra that were obtained from the radio probe data shown in panel (a).

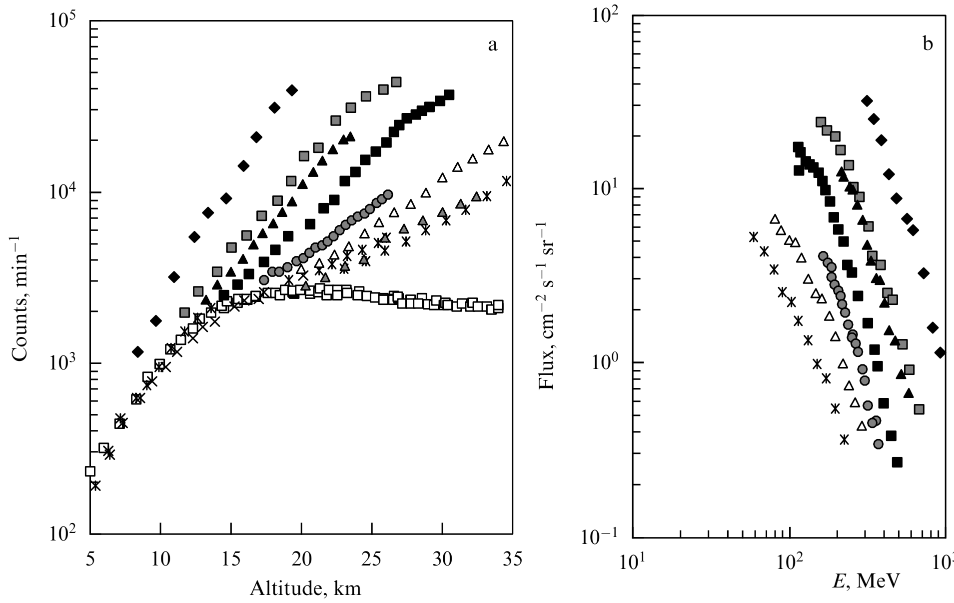


Figure 4. (a) The altitude profile for CRs observed in one of the last large solar CR flares on 20 January 2005. The measurements were performed at northern polar latitudes from 20 to 21 January 2005. The galactic ray background is marked by white squares. (b) The solar proton integral spectra that were obtained from the radiosonde data shown in panel (a).

second (one of the last flares) in January 2005. It is seen that at altitudes higher than 20 km the particle fluxes are bigger than the galactic ray background by a factor of several dozen. Figures 3b and 4b show the energy spectra of the solar protons. The spectra were obtained from the radiosonde data shown in panels (a).

To date, 112 events of particles accelerated in solar flares have been detected in the stratosphere. In 1959, a new phenomenon was discovered for the first time — solar energetic particles arrived at Earth being additionally accelerated at a shock wave front.

Regular measurements of charged particle fluxes allowed obtaining new data on modulation effects for galactic CRs. Figure 5 illustrates temporal variations of monthly means of galactic CR fluxes observed in the polar and mid-latitude atmosphere from 1957 until now. Shown are data in maximums of the transition curve (values of N_m), which are observed at altitudes ranging 18–23 km in the atmosphere [13].

Several characteristic properties in the temporal variations of N_m exist. Large-amplitude variations of CR fluxes with a period of about 11 years are observed (up to 60%, while ground-based instruments record changes up to $\approx 20\%$). An alternation of sharp peaks of N_m (1957–1969, 1981–1989, 2001-now) with flattened maxima (1970–1979, 1990–2000) was discovered. The complete cycle of variations comprises about 22 years and coincides with the 22-year period of the solar magnetic field variations.

Temporal variations of CR fluxes are caused by the corresponding variations in solar activity. The correlation coefficient between yearly means of CR fluxes in the northern and southern polar latitudes and the sunspot number R_z equals approximately 0.9 for the 1 year time lag Δt between the CR fluxes and the level of solar activity.

About 15 years after the commencement of regular measurements of CR fluxes in the terrestrial atmosphere, a new phenomenon in the modulation of CR fluxes in the heliomagnetosphere was discovered. Later on, it was found that this effect results from the existence of a regular component of the interplanetary magnetic field in the heliosphere; this field component causes the drift motion of charged particles. The direction of the CR drift depends on the particle charge sign and the direction of the magnetic field lines.

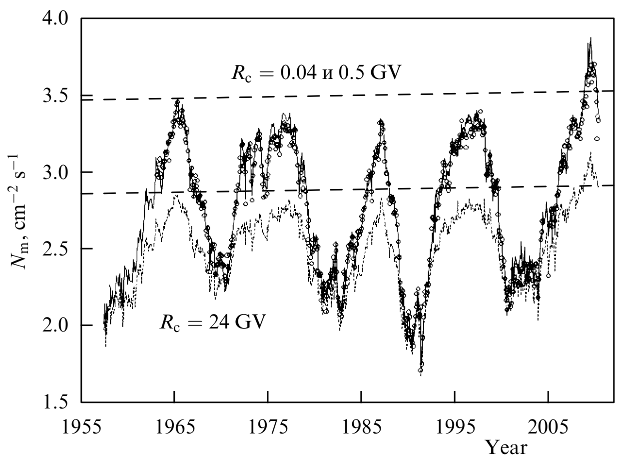


Figure 5. Monthly means of galactic CR fluxes in the atmosphere at the peak N_m in the transition curve. The data were obtained at northern polar latitudes with geomagnetic rigidity cutoff of $R_c = 0.5$ GV (upper solid line), in Antarctica with $R_c = 0.04$ GV (white circles), and at the middle latitudes with $R_c = 2.4$ GV (lower dashed line). Horizontal dashed lines show the maximum galactic CR fluxes observed in 1957–2008, up to the abnormal increase in fluxes in 2009.

The interplanetary space contains the solar wind plasma with the magnetic field frozen in it. If periods of high solar activity are excluded, the interplanetary magnetic field can be roughly presented as a dipole field with the field lines stretched along a solar radius and twisted into Archimedean spirals by the rotation of the Sun. Approximately every 11 years, the inversion of the field occurs at the solar activity maximum (or in its vicinity). At that time, the direction of the magnetic field in the polar region of the Sun and in the interplanetaryspace changes. The directions of the CR drift in the heliomagnetosphere are also reversed.

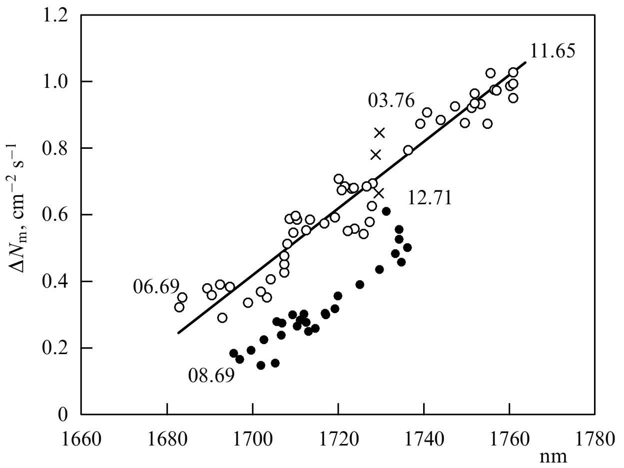


Figure 6. The regression $\Delta N_{\rm m}$ between the galactic CR fluxes for low energies [$E \approx (0.5-1.5)$ GeV] and high energies ($E > 12$ GeV). The fluxes of low-energy particles were obtained from measurements in the polar and mid-latitude atmosphere at the altitude ranging 18–23 km. Data of the equatorial neutron monitor Huancayo provide fluxes of particles with high energies. Different symbols correspond to different time periods: white circles for 02.1965 to 07.1969; black circles for 08.1969 to 12.1971, and crosses for 01.1972 to 03.1972. Here digits show the periods of measurements (month, year). As a rule, there is a linear relationship between the low-energy galactic CR fluxes and the high-energy ones, which is shown by the solid line. However, during the magnetic field inversion period (07.1969–12.1971) this relationship is violated: the data shown by dark circles are outside of the general relationship.

The effect of sign changing in the solar magnetic field (its inversion or polarity reversing) is clearly seen in the emergence of CR hysteresis, when the relationship between the fluxes of particles with different rigidities (energies) is violated because of the dependence of their diffusion coefficient on the energy changes. The hysteresis of galactic CRs is observed for each inversion period of magnetic fields, but it was most conspicuous in 1969–1972 (Fig. 6).

An unexpected effect in the galactic CR modulation was revealed at the end of 2008 and the beginning of 2009. The fluxes detected during this period were the highest for more than 50 years of observations (see Fig. 5). At the beginning of 2009, the value of $N_{\rm m}$ at the polar latitudes exceeded its level for 1965 by approximately 15% (the increase detected by neutron monitors at sea level was less than 2%).

Large galactic CR fluxes in Earth's orbit are caused by the very long period of low solar activity. The interplanetary magnetic field was $B \approx 3.5$ nT. Usually, $B \approx 5$ nT for low solar activity periods. In the middle of 2010, the CR fluxes reached the values observed in the solar activity minimum in 1965.

It is worth noting that the minimum of the current 24-yr solar cycle is unprecedentedly long and it still continues. It is highly probable that we have entered a long-lasting period of low solar activity like the Maunder Minimum (1645–1715) or the Dalton Minimum (1790–1820).

In 1976, the Lenin Prize was awarded to a group of the staff members of the LPI Dolgoprudny Scientific Station and their scientific leader A N Charakhch'yan for the discovery of frequent solar CR flares observed in the stratosphere, for the discovery of the influence of a general magnetic field of the Sun on CRs, and for unique experimental data on CR modulation and its relationship with the solar activity.

About 15–20 years ago it became clear that CRs are an essential constituent of all electric phenomena observed in Earth's atmosphere [14]. CRs lose most of their energy in the atmosphere, which is transferred to the ionization and excitation of atmospheric atoms. CRs create ions at almost all altitudes from Earth's surface to about 35 km. These ions allow the global electric circuit to operate and take part in the formation of thunderclouds. Highly energetic cosmic ray particles with energies exceeding 10^{14} eV produce extensive air showers consisting of a number of secondary charged particles. During thunderstorms, lightning propagates along the ionized tracks of these particles.

By means of the creation of charged centers of condensation (ions created by CRs attach to the neutral centers of condensation), CRs have an effect on the formation of clouds and thunderclouds, thereby affecting atmospheric precipitation. The atmospheric precipitation decreases when the CR fluxes decrease abruptly (Forbush decreases); the precipitation increases upon arrival of additional particles accelerated by large solar flares [14].

Since 2009, an international experiment CLOUD has been performed at the CERN accelerator in collaboration with the LPI Dolgoprudny Scientific Station. This experiment is aimed at finding physical mechanisms for the influence of charged particles on the terrestrial atmosphere.

5. Future of regular observations of cosmic rays in Earth's atmosphere

Despite the difficulties with financial and human resources that our science has faced with during approximately the last 20 years, regular observations of the charged particle fluxes in the terrestrial atmosphere continue due to the financial support of RFBR and programs of the Presidium of the Russian Academy of Sciences.

There is no doubt that it is necessary to conduct these measurements and studies of the CR modulation effects during the current and following solar cycles. It is very likely that the solar activity during cycles in the near future will be anomalously low. This will allow constructing a practical model combining the processes in the Sun with those in cosmic rays. These studies will be useful for space weather forecasting in the Solar System. Such forecasts are necessary to enhance the radiation security of long-term space missions.

A new area of research where CRs have a dominant role is the study of their relationships with electrical phenomena in Earth's atmosphere. CRs are responsible for all electric phenomena observed in the atmosphere. During the last few years, many studies have been devoted to the influence of CR fluxes on atmospheric processes and Earth's climate.

Scientists monitoring cosmic rays in Earth's atmosphere will do their best to obtain new experimental data and new scientific results in the coming decades.

6. Conclusion

Sergei Nikolaevich Vernov had unique powers of intuition when choosing promising avenues for future research on CR physics. One of the most propitious and fruitful ideas suggested by S N Vernov in the distant 1930s was to study CRs in Earth's atmosphere. Vernov's method of frequent and regular stratospheric measurements allowed obtaining fundamental results on CR modulation effects, their relationships with solar activity, and the role of CRs in atmospheric processes. These studies are still going on, giving new results and having a bright future.

References

1. Vernov S N, in *Trudy Vsesoyuz. Konf. po Izucheniyu Stratosfery, 31 Marta–6 Aprelya 1934 g.* (Proc. All-Union Conf. on Stratospheric Studies, 31 March–6 April 1934) (Leningrad–Moscow: Izd. AN SSSR, 1935), p. 423
2. Vernoff S *Nature* **135** 1072 (1935)
3. Vernov S N *Dokl. Akad. Nauk SSSR* **14** 263 (1937)
4. Vernov S N *Izv. AN SSSR* (5/6) 738 (1938)
5. Vernov S N *Dokl. Akad. Nauk SSSR* **23** 141 (1939)
6. Vernov S N, Mironov A V *Dokl. Akad. Nauk SSSR* **23** 138 (1939)
7. Vernov S N et al. *Dokl. Akad. Nauk SSSR* **68** 253 (1949)
8. Zatsepin G T *Dokl. Akad. Nauk SSSR* **57** 993 (1949)
9. Bazilevskaya G A, Stozhkov Yu I, in *Akademik Sergei Nikolaevich Vernov: k 100-Letiyu so Dnya Rozhdeniya* (Academician Sergei Nikolaevich Vernov: to the 100th Anniversary of the Birthday) (Moscow: Izd. MGU, 2010) p. 315
10. Shafer G V, Shafer Yu G *Pretsizionnye Nablyudeniya Kosmicheskikh Luchei v Yakutske* (High-Precision Observations of Cosmic Rays in Yakutsk) (Novosibirsk: Nauka, 1984) 733 pp.
11. Charakhch'yan A N *Usp. Fiz. Nauk* **83** 35 (1964) [*Sov. Phys. Usp.* **7** 358 (1964)]
12. Stozhkov Yu I et al. "Potoki kosmicheskikh luchei v maksimume krivoi pogloshcheniya v atmosfere i na granitse atmosfery" ("Cosmic ray fluxes at the maximum in the absorption curve in the atmosphere and at its boundary"), Preprint No. 14 (Moscow, P N Lebedev Physical Institute, 2007)
13. Stozhkov Y I et al. *Adv. Space Res.* **44** 1124 (2009)
14. Stozhkov Y I *J. Phys. G: Nucl. Part. Phys.* **29** 913 (2003)

PACS numbers: **01.65.+g**, 94.20.wq, 96.50.S–
DOI: 10.3367/UFNe.0181.201102m.0223

S N Vernov and cosmic ray research in Yakutia

E G Berezhko, G F Krymsky

The 100th anniversary of the discovery of cosmic rays will be celebrated soon. Many lines of inquiry related to cosmic ray physics were elaborated by S N Vernov and his colleagues, disciples, and successors. When S N Vernov commenced his investigations, it had been only 20 years since cosmic rays had been discovered, and not so much was known about them. It was unknown whether they are composed of charged particles, how big their masses and charges are, or when and where cosmic rays originate. In his groundbreaking studies, S N Vernov answered some of these questions, while the answers to other question were searched for, were found, and are still being found by numerous colleagues and successors who belong to his scientific school.

Establishing this school and supporting appropriate studies in different regions of the USSR and abroad consumed much of Sergei Nikolaevich's time and seething energy. We consider it our duty to describe a part of this huge work, namely, establishing cosmic ray studies in one of the most remote regions of the country — Yakutia (the Sakha Republic).

These studies were initiated in the pre-war period, owing to the enthusiasm of young Yu G Shafer, who had graduated from Tomsk University. In 1938, Yu G Shafer commenced studies of cosmic rays at the Physics Department of the Yakutsk Pedagogical Institute. Together with the director of this institute, he sent a letter to the P N Lebedev Physical Institute (LPI) in Moscow. The letter was addressed to D V Skobeltsyn and reported that the institute has approved a plan of scientific research work on cosmic ray physics for 1939. The plan included the registering of cosmic rays and correlating these data with the barometric, temperature and geomagnetic measurement results and the intensity of solar radiation, as well as with the phenomena of auroral emissions at the latitudes of Yakutia. In the letter it was also mentioned that a provisional consent was given that D V Skobeltsyn and S N Vernov "will provide advice for this work in writing and also provide strong encouragement." The authors asked D V Skobeltsyn "to support this topic, which is included in the institute's plan of scientific research work, in the RSFSR People's Commissariat of Education if it is necessary." From that time, S N Vernov was for many decades a scientific leader of these studies in Yakutsk.

In 1947, the Yakutsk Research Base of the USSR Academy of Sciences (USSR AS) was established. The Chairman of the USSR AS Council of Branches and Bases, Academician V G Volgin, wrote to the President of the USSR AS S I Vavilov: "When determining the structure of the Yakutsk Base of the Academy of Sciences of the USSR, it was taken into account that the Lebedev Physical Institute of the USSR AS, the Institute of Terrestrial Magnetism of the Main Directorate of Hydro-Meteorological Services of the USSR Council of Ministers, the 2nd Scientific Research Institute of Physics of Moscow State University, and research fellows of Yakutsk research institutions recommended including cosmic ray studies on the scientific program of the Base and to establish a cosmic ray Station at the Yakutsk Research Base of the USSR AS." Yu G Shafer, who was back from the front, was recommended to pursue these studies. On 25 December 1947, the Presidium of the USSR AS issued an order whereby the Scientific Council of the Yakutsk Base was approved, consisting of 30 members. Doctor of Physicomathematical Sciences S N Vernov was a member of the Council.

Also in 1947, Academician V G Volgin and the Director of the Scientific Research Institute for Terrestrial Magnetism [now N V Pushkov Institute of Terrestrial Magnetism, the Ionosphere, and Radio Wave Propagation (IZMIRAN in *Russ. abbr.*) of the Russian Academy of Sciences] N V Pushkov addressed Academician S I Vavilov and substantiated the necessity of deploying a network of stations on the territory of the USSR for continuous registering of cosmic rays by sensitive instruments to be purchased in the USA. Since attempts to purchase this equipment (ionization chambers) failed, it was decided to develop them independently in the USSR. Yu G Shafer was charged with doing that in the Laboratory of Cosmic Rays at the Research Institute for Nuclear Physics (RINP) of Moscow State University (MSU). From the very beginning, this activity was supported by S N Vernov. Designing and technological resources available at RINP were involved in this work. The engineering part of the work was directed by the Head of the Workshop, A S Muratov. N L Grigorov, who had experience in the development and manufacturing of high-precision torsion

E G Berezhko, G F Krymsky Yu G Shafer Institute of Cosmophysical Research and Aeronomy, Siberian Branch of the Russian Academy of Sciences, Yakutsk, Russian Federation
E-mail: berezhko@ikfia.ysn.ru, krymsky@ikfiaa.ysn.ru

Uspekhi Fizicheskikh Nauk **181** (2) 223–239 (2011)
DOI: 10.3367/UFNr.0181.201102m.0223
Translated by V V Lobzin; edited by A Radzig

electrometers of a unique design, was also involved. In his memoirs he wrote: "A developmental prototype S-2 was designed and manufactured in 1947–1948. It was a 20-litre spherical chamber made of steel and filled with chemically pure argon. A compensation chamber was placed inside the main chamber, and the ionization current was carried in the former by beta particles from a radioactive substance. The compensation current had the same value as the current produced by the cosmic rays in the main chamber, but its flow direction was opposite. Hence, the device measured deviations of the cosmic ray-produced ionization current from an average value, which was compensated for by the current in the compensation chamber. This so-called null method provided high sensitivity of the device."

In 1948, the developmental prototype of the ionization chamber was successfully tested in Yakutsk. In 1950, the Stalin Prize was awarded to Yu G Shafer, N L Grigorov, and A S Muratov for the design and manufacture of this device.

Based on the prototype, two ionization chambers, ASK-1 and ASK-2, were developed, with volumes of 900 and 50 litres, respectively. In 1950–1952, the Fizpribor plant made the first run of the production items, which were installed at nine Soviet stations for cosmic ray observations.

These sensitive chambers operated for more than 30 years at several stations, and the ASK-1 device installed in Yakutsk in 1953 is still operational! The network of stations, in addition to its scientific significance, played the role of a catalyst promoting scientific research work on the vast territory of the USSR.

Already during the first working period of the new equipment in Yakutsk, it was possible to test in detail E L Feinberg's and L I Dorman's theory of meteorological variations of cosmic ray intensity. The sharply continental climate of Yakutia favored studies of the seasonal variations predicted by the theory. The reason for these variations is as follows. The thickness of the atmosphere increases with its temperature, and muons created in its upper layers due to collisions of cosmic rays with atmospheric atoms have a higher probability of decaying when moving to the chamber; hence, their flux decreases.

Variations in the cosmic ray fluxes measured by the ionization chamber were observed during transits of cyclones and geomagnetic storms. Periodic variations with the period of 1 solar day were also detected. It was hypothesized that these variations are caused by atmospheric temperature variations as well. However, A I Kuz'min showed using the data on temperature monitoring in Yakutsk and a theory of meteorological effects that the influence of the temperature results in increased amplitudes of the diurnal variations rather than in decreased ones. It was, therefore, proved that the device observed the anisotropy of cosmic rays [1].

For many years, A I Kuz'min and his disciples conducted experimental and theoretical studies of the cosmic ray anisotropy and its physical origin and consequences. For this purpose, they developed muon telescopes which consisted of Geiger–Müller gas-discharge counters. The counters were placed in trays (several counters in each tray) and the trays were arranged in a stack with three horizontal arrays, one over another. A coincidence scheme selected simultaneous detections by all three arrays. The trays were combined in such a way that the coincidence scheme selected muons coming from north or south (east or west). Each such combination of trays was called a muon telescope. Telescopes that detected muons arriving from north and south formed a system of 'crossed' telescopes. The crossed telescopes were installed on the ground and in a mine tunnel at a water-equivalent depth of 7, 20, and 60 m (the actual depth was less, approximately by a factor of 1.8). The Yakutsk underground array of crossed telescopes allowed performing precise measurements of the cosmic ray anisotropy and its energy spectrum, as well as of spectra of other variations in the cosmic rays.

The complex of crossed telescopes allowed observing cosmic ray intensity diurnal variations caused by the anisotropy of cosmic ray angular distribution in the near-Earth space. These variations, unlike other variations, including meteorological ones, had different amplitudes and phases when measured by different telescopes. If the telescope geometry is known, it is possible to determine the exact parameters of the anisotropy. Studies of the anisotropy and its temporal variations allowed revealing its physical origin. On the average, the observed anisotropy is caused by the excess of particles arriving at the evening side of Earth. It can be interpreted in terms of the cosmic ray transport by the solar wind with the frozen-in interplanetary magnetic field [2]. Due to such transport, an ordered motion of cosmic ray particles develops in the radial direction from the Sun. The resulting deficit of cosmic rays in the inner Solar System is compensated for by their diffusion in the opposite direction. If the interplanetary magnetic field had been totally random (turbulent), the diffusion would also have created a radial ordered motion of the cosmic rays to the Sun. As a result, the anisotropy would not exist in a stationary state. However, the interplanetary magnetic field has a regular component, which is extended in the radial direction and twisted to an Archimedean spiral by the solar rotation. That is why cosmic ray diffusion occurs predominantly at an angle to the radial direction. The radial diffusion is compensated for by the convective outflow of cosmic rays with the solar wind, while the tangential component of the diffusion flow, which is perpendicular to the line between Earth and the Sun, is uncompensated. Theoretical estimates of this effect gave a magnitude which was less than the experimental finding by 15–20%.

The paradox is resolved by taking into account the adiabatic change in the energy of fast charged particles as they propagate in a scattering medium: the particle energy decreases in an expanding medium, and increases in a compressing one.

The solar wind plasma expands everywhere. Therefore, the cosmic ray particles lose their energy within Earth's orbit, and this additionally contributes to their deficit. Compensation for the deficit due to enhanced diffusion solves the problem. This solution led to a correct transport equation for the cosmic ray distribution function $f(\mathbf{r}, \mathbf{p}, t)$ [2]:

$$\frac{\partial f}{\partial t} = \nabla(\varkappa \nabla f) - \mathbf{w}\nabla f + \nabla \mathbf{w}\, \frac{\mathbf{p}}{3}\, \frac{\partial f}{\partial p} \,.$$

Here, t is the time, $\mathbf{r}$ is the radius vector, and $\mathbf{p}$ is the momentum of the cosmic ray particles. The first term on the right-hand side describes the spatial diffusion of cosmic rays with the diffusion tensor $\varkappa$. The second term is responsible for the convective transport due to the motion of the scattering medium with a velocity $\mathbf{w}$. The third term describes the adiabatic change in the cosmic ray energy in the compressible medium. Somewhat later, this equation was derived by E Parker [3], and then by A Z Dolginov and I N Toptygin [4], who applied a fully kinetic approach.

It turned out that the transport equation can describe the particle acceleration in media that contract rather than expand. Such a situation occurs at the fronts of shock waves, where the conditions favor the regular acceleration of cosmic rays, which is the most efficient acceleration. When the problem of charged particle acceleration by a strong shock wave was solved [5], S N Vernov appreciated this result at its true value and presented this paper to the journal *Doklady Akad. Nauk SSSR* (*Sov. Phys. Dokl.*). It is worth noting that S N Vernov had experts substantiate this decision. Most commonly, the experts worked at the MSU RINP. In this case, it was Boris Arkad'evich Tverskoy who directed Vernov's attention to this solution. The discovered mechanism of regular particle acceleration can be widely applied to cosmic ray astrophysics (see, e.g., review [6]). The development of the theory of regular acceleration of the cosmic rays in supernova remnants, especially of the nonlinear theory [7] that consistently takes into account the backaction of the accelerated particles on the structure and dynamics of the shock front, strongly supports the hypothesis that the observed spectrum of cosmic rays with energies of up to 10^{17} eV is formed in the galactic supernova remnants (see reviews [8, 9]). It is important to note that the nonlinear theory is able to predict in detail the properties of supernova-remnants nonthermal emission due to the cosmic ray particles accelerated in remnants. Comparing theoretical predictions for a particular remnant with observations, which are performed in a wide range of wavelengths (from radio up to gamma-ray range), it is possible to obtain crucial evidence related to both the nature of the nonthermal emission of the remnants and the origin of the observed cosmic ray spectra. For instance, Figures 1 and 2 plot the results of calculations of the photon energy dependence of the nonthermal emission energy flux for the RXJ1317.7-3946 and SN 1006 supernova remnants together with the observations. It is seen that the theoretical results are in good agreement with the experimental data. This led to the conclusion that the remnants of interest effectively produce cosmic rays, thereby confirming the idea that galactic supernova remnants are the sources of cosmic rays with energies of up to 10^{17} eV.

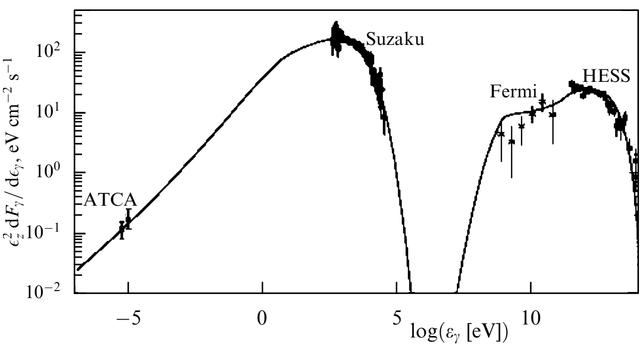


Figure 1. The energy flux for the nonthermal emission of the RXJ1317.7-3946 supernova remnant versus the photon energy. The calculations were performed in the framework of the nonlinear kinetic theory for cosmic ray acceleration [10]. The results of measurements of the radio emission [Australia Telescope Compact Array (ATCA)], X-rays (Suzaku space observatory), and TeV emission [HESS system of gamma-ray telescopes (High Energy Stereoscopic System)] are also shown. The GeV-emission data obtained by the Fermi Gamma-Ray Space Telescope in 2009 are also presented.

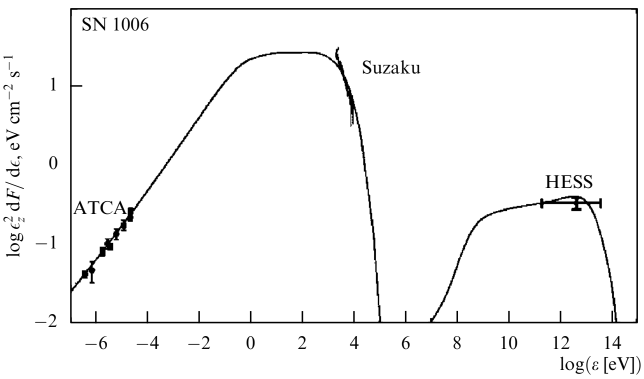


Figure 2. The energy flux for the nonthermal emission from the SN 1006 supernova remnant versus the photon energy. The calculations were performed in the framework of the nonlinear kinetic theory for cosmic ray acceleration [11]. The results of measurements of the radio emission (ATCA radio telescope), X-rays (Suzaku space observatory), and TeV emission (HESS system) are also shown.

The registering of cosmic rays by the ASK-1 chamber in Yakutsk led to the initiation of studies in another important area. The ionization current in the chamber, which is registered by the chamber electrometer, sometimes undergoes abrupt increases. In the records, they look like discontinuities or spikes. When studying cosmic ray variations, such spikes are considered to be noise and are removed on treating measurement data. D D Krasil'nikov, who was a research fellow of the Institute of Cosmophysical Research and Aeronomy (ICRA) at the Yakutsk Branch of the USSR Academy of Sciences, noticed these spikes and commenced studying them. The amplitude spectrum of the spikes turned out to be power-law, with the exponent close to that for the cosmic ray energy spectrum. The spikes are caused by secondary particles that are created in interactions of nuclear-active particles (predominantly pions) with the chamber walls, as well as by electromagnetic cascades caused by bremsstrahlung photons produced by high-energy muons. Employing special tricks, D D Krasil'nikov filtered out the spikes of nuclear-active origin and studied muon spikes. The interest in cascade processes inspired him to create a small experimental array for studying extensive air showers (EASs). The array consisted of only three trays with Geiger–Müller counters. Later on, the array was extended to 5 pavilions on a site of about 1 hectare. Careful data processing allowed determining the upper limit of the anisotropy of 10^{15}-eV particles with an accuracy of better than 0.1%; it was the best result for that time (1967).

In the 1950s, typical EAS arrays became more informative and covered a larger area. The biggest arrays in the USSR were the MSU RINP array and LPI array installed in Tien Shan; the studies were directed by G B Khristiansen and S I Nikol'sky, respectively. At that time, there were EAS arrays abroad covering areas of more than 10 km^2. As early as 1963, Sergei Nikolaevich Vernov initiated the development of an array that was competitive with the best foreign counterparts. He performed the overall direction of the design. S I Nikol'sky and G B Khristiansen also took an active part in this work. The work became much more active when relict radiation was discovered and it was predicted that a black-body cut-off exists in the cosmic ray spectra at an energy of

6×10^{19} eV. This cut-off inevitably arises due to cosmic ray energy losses as a consequence of the ray interaction with the relict photons provided that the cosmic rays of extreme energies originate outside of the Galaxy. Yakutsk was selected as the place for the array development. The weighty argument in favor of this decision was related to the experience accumulated at ICRA and the available qualified human resources. As often happens, making a decision about the financial support of the studies was not easy and required significant efforts, mainly of S N Vernov. It is sufficient to mention that the first response by M A Lavrent'ev, who was the Chairman of the Siberian Branch of the USSR AS, was not favorable enough. The positive decision about the construction of the Yakutsk EAS array was obtained to a large part due to the active position of S N Vernov. He met the leaders of the USSR AS SB many times, and organized an extensive discussion of the problem by the scientific community. In connection with this, it is worth citing the letter from V L Ginzburg to the Vice President of the USSR AS B P Konstantinov: "Dear Boris Pavlovich! As I have been informed, you would like to know my opinion on whether it is expedient to construct a big array for studies of extensive air showers in Yakutsk. My attitude to this project is very positive... Finally, to the point, the Yakutsk array will be able to measure spectra in the range of $3 \times 10^{17} - 10^{20}$ eV, where data are almost absent and where we may expect a substantial contribution of the metagalactic component... Thus, the construction of this array is a 'good business': it is important not to be late and to launch it as soon as possible and, in addition, to have a plan for its extension to 10^{21} eV. Sincerely yours, V L Ginzburg. 29 January 1968."

Vernov's efforts were successful: on 11 April 1968 the State Committee for Science and Technology of the USSR Council of Ministers issued resolution approving the construction of the Yakutsk EAS array. The tasks for the Institute were formulated, and human and other resources for the construction were specified. More than 200 institutions were involved in the array development in one form or the other. Sometimes, S N Vernov took part in meetings with the leaders of these institutions.

The Yakutsk EAS array was opened for operation on 14 April 1973. The array can be considered as a set of observational stations which are distributed over an area of 20 km^2 (by now the area has been diminished to 12 km^2) and working in coordination. The EAS registering is aimed at determining the following main characteristics of cosmic rays with energies above 10^{15} eV: the energy spectrum, anisotropy, and the mass composition. A peculiarity of the Yakutsk air shower array is that it has detectors for all the main components of the EASs, i.e., for the electron–photon and muon components, and for Cherenkov radiation.

Since Cherenkov radiation is integrated over the entire altitude of the atmosphere, its registration allows one to estimate rather precisely the total energy of electrons in a shower and, hence, to obtain a reliable estimate of the energy of a primary particle. These measurements also make it possible to calibrate the electron–photon registration channel.

Given the energy of a primary particle, the number ratio of muons and electrons in the extensive air shower it produces is sensitive to the particle mass, thereby allowing an estimation of the mass composition of cosmic rays.

During the almost 40 years of its operation, the array has been upgraded. The next scheduled upgrade is being performed now. The directors of the work at the Yakutsk EAS array, N N Efimov and D D Krasil'nikov, were awarded the Lenin Prize in 1982.

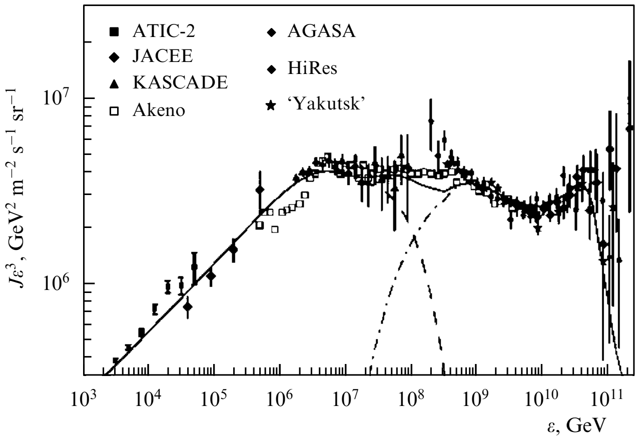


Figure 3. The cosmic ray flux versus particle energy [13]. The dashed line shows the spectrum of cosmic rays produced by galactic supernova remnants; the dot-and-dash line corresponds to the spectrum of rays from extragalactic sources, and the solid line demonstrates the sum of the two. The measurements of balloon [ATIC-2 (Advanced Thin Ionization Calorimeter) and JACEE (Japanese-American Collaborative Emulsion Experiment)] and ground-based KASCADE (KArlsruhe Shower Core and Array DEtector), Akeno, AGASA, HiRes, and 'Yakutsk' ESA experiments are also presented.

One of the main characteristics of cosmic rays observed by air shower arrays is their energy spectrum at particle energies above 10^{15} eV. By the end of the 20th century, a large body of experimental data on cosmic ray spectra for extreme energies had been obtained. The data allowed arguing with confidence that several peculiarities exist in the spectra in the energy range from 10^{15} to 10^{19} eV. In addition to the break (steepening of the cosmic ray spectra at the energy of 3×10^{15} eV; now the break is called a knee or the first knee) that was found in 1958 by research fellows working at MSU RINP and led by S N Vernov, new peculiarities were observed: a second knee at energies of 5×10^{17} eV, and a depression at 6×10^{18} eV (Fig. 3). In these events, data obtained with different air shower arrays [Fly's Eye and HiRes in the USA, AGASA (Akeno Giant Air Shower Array) in Japan, and the Yakutsk array] were in good agreement regarding the shape of the measured spectra; however, they differ in amplitudes and positions of the peculiarities on the energy axis. As has been suggested many times (see, e.g., Ref. [12]), these differences almost vanish if the individual particle energy ε measured in each experiment is replaced by $\lambda\varepsilon$, where λ falls in the range $0.8 < \lambda < 1.2$ (see Fig. 3, which depicts the experimental data obtained with all three air shower arrays mentioned above). Such a procedure is quite appropriate because the accuracy of cosmic ray energies measured in such experiments is about 20%.

Before 2007, the measurements did not allow one to argue unambiguously that a blackbody cut-off in the cosmic ray spectra exists. In Fig. 3 it is seen that the data obtained with the Yakutsk air shower array were not at variance with the existence of the cut-off. However, since the number of measurements is limited for the energies $\varepsilon > 4 \times 10^{19}$ eV, it is difficult to make a definitive conclusion. At the same time, the measurements performed with the AGASA array, whose relative aperture is more than an order of magnitude bigger

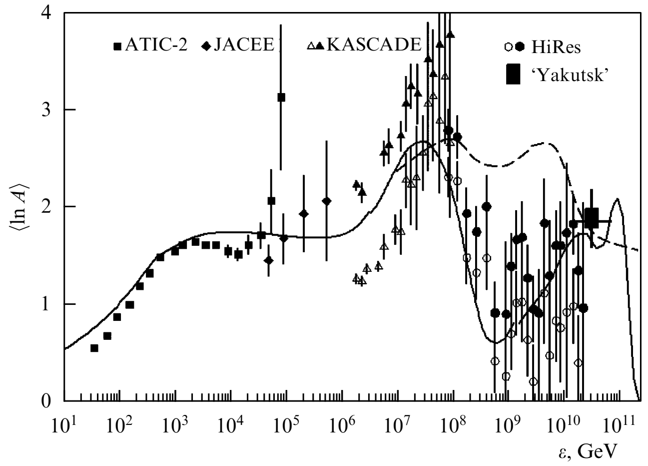


Figure 4. The mean logarithm for the cosmic ray atomic number versus the energy [16]. The solid and dashed lines correspond to different scenarios for the formation of the cosmic ray spectrum for energies $\varepsilon > 10^{17}$ eV. The measurements performed with the balloons (ATIC-2 and JACEE) and with the ground-based arrays KASCADE, HiRes, and 'Yakutsk' (Yakutsk) are also shown [17].

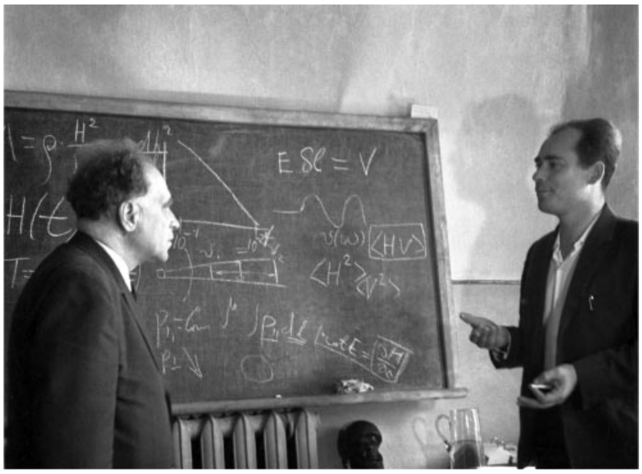
than that of the Yakutsk EAS array, quite definitely favored the absence of any steepening of cosmic ray spectra for the energies $\varepsilon < 10^{20}$ eV. Only in 2007 did the experiments HiRes and Auger proved the existence of the blackbody cut-off quite soundly. This fact quite definitely evidences that the cosmic rays of extreme energies originate from extragalactic sources. Now the search for these sources, measurements of the spectra of the extragalactic component of cosmic rays, and experimental determination of the transition region between these two components in the observed cosmic ray spectrum are on the agenda.

In accordance with energy-based considerations, the most probable sources of extragalactic cosmic rays with extreme energies are active galactic nuclei (see, e.g., Ref. [12]). This hypothesis is favored by the correlations between the directions of arrival of cosmic rays with energies $\varepsilon > 3 \times 10^{19}$ eV and the angular positions of active galactic nuclei, as was established by the Auger experiment [14] and the Yakutsk EAS experiment as well [15].

Two different scenarios for the formation of the overall cosmic ray spectrum exist. In the first one, the extragalactic component dominates for energies $\varepsilon > 2 \times 10^{17}$ eV (see Fig. 3), while in the second scenario it takes place only for $\varepsilon > 10^{19}$ eV. In the latter case, the galactic component dominates in the observed cosmic ray spectrum at energies up to $\varepsilon \approx 3 \times 10^{18}$ eV. It is not clear whether the galactic supernova remnants are able to accelerate the particles to such high energies or an additional source (or reacceleration mechanism) shows its worth in the Galaxy.

It is important that the two scenarios mentioned above predict considerably different mass composition of cosmic rays for particle energies $\varepsilon > 10^{17}$ eV (see Fig. 4, which depicts numerical results for the mean logarithm of the atomic number for cosmic rays versus their energy for the two scenarios). The data are in better agreement with the first scenario. However, rather large uncertainties do not allow one to reach a definitive conclusion. To determine the cosmic ray mass spectrum more reliably, the Yakutsk air shower array is equipped with complementary differential Cherenkov detectors, which can separately detect the Cherenkov radiation arriving from different depths in the atmosphere.

S N Vernov (center) with Yakutsk cosmophysicists: A I Kuz'min to the left of S N Vernov, and G V Shafer and Yu G Shafer to the right (Yakutsk, 1967).



S N Vernov (left) with G F Krymskii at a seminar at the Institute of Cosmophysical Research and Aeronomy (Yakutsk, 1967).

After the establishment of the Institute of Cosmophysical Research and Aeronomy, SB RAS in 1962, its activities were at the center of Sergei Nikolaevich Vernov's attention. The Scientific Council of the USSR Academy of Sciences on Cosmic Rays, where he was the Chair, periodically organized All-Union Conferences on Cosmic Ray Physics in different cities in the country.

In 1967, ICRA organized the next conference due in Akademgorodok near Novosibirsk. S N Vernov conducted a workshop, which was held at the Institute of Nuclear Physics at the time of the conference. Before the commencement of the conference, he visited ICRA and discussed there the problems related to the development of the Yakutsk EAS array.

The All-Union Conferences on Cosmic Rays were held in Yakutsk in 1962, 1977, and 1984. In 1972, a symposium was organized on the site of the already constructed air shower array, with the participation of scientists from different scientific centers of the USSR and East Europe. A wide range of problems on cosmic ray physics were addressed, with the main emphasis on cosmic rays with extreme energies. Sergei Nikolaevich had considered it necessary to make a scientific presentation for the Yakutsk regional committee of the Communist Party of the Soviet Union, where all the

S N Vernov (foreground) with Yakutsk cosmophysicists. From left to right: A I Kuz'min, I E Sleptsov, A S Rymar', V A Orlov, D D Krasil'nikov on the site of the air shower setup (Yakutsk, 1972).

republic authorities were present. He also visited the almost finished by that time Yakutsk air shower array.

In 1976, the Presidium of the USSR AS SB discussed once again the activities of ICRA. S N Vernov, who took part in this meeting, made a presentation and highly appreciated the scientific achievements of the Institute. Under the aegis of the International Union of Pure and Applied Physics (IUPAP), conferences on cosmic rays are organized every two years in different countries. Sergei Nikolaevich personally composed the Soviet delegations for each of the conferences. Beginning in 1959, representatives from ICRA (Yakutsk) have attended all these conferences.

Sergei Nikolaevich in every way promoted cooperation with our colleagues abroad. In 1981, one of the authors (GFK) received an invitation to work at the Institute of Nuclear Physics in Heidelberg as a visiting scientist. Sergei Nikolaevich supported this proposal and the visit was made. In the following years, the cooperation between the institutes became more active and still continues.

In conclusion, it is worth saying that the establishment and development of the fundamental studies on cosmic ray physics in Yakutia were successful thanks largely to the active support and participation of S N Vernov, as well as his colleagues and disciples.

References

1. Kuz'min A I *Zh. Eksp. Teor. Fiz.* **28** 614 (1955) [*Sov. Phys. JETP* **1** 560 (1955)]
2. Krymskii G F *Geomagn. Aeron.* **4** 977 (1964)
3. Parker E N *Planet. Space Sci.* **13** 9 (1965)
4. Dolginov A Z, Toptygin I N *Zh. Eksp. Teor. Fiz.* **51** 1771 (1966) [*Sov. Phys. JETP* **24** 1195 (1967)]
5. Krymskii G F *Dokl. Akad. Nauk SSSR* **234** 1306 (1977) [*Sov. Phys. Dokl.* **22** 327 (1977)]
6. Berezhko E G, Krymskii G F *Usp. Fiz. Nauk* **154** 49 (1988) [*Sov. Phys. Usp.* **31** 27 (1988)]
7. Berezhko E G, Elshin V K, Ksenofontov L T *Zh. Eksp. Teor. Fiz.* **109** 3 (1996) [*JETP* **82** 1 (1996)]
8. Berezhko E G *Adv. Space Sci.* **35** 1031 (2005)
9. Berezhko E G *Adv. Space Sci.* **41** 429 (2008)
10. Berezhko E G, Völk H J *Astron. Astrophys.* **451** 981 (2006)
11. Berezhko E G, Ksenofontov L T, Völk H J *Astron. Astrophys.* **505** 169 (2009)
12. Berezinsky V , Gazizov A, Grigorieva S *Phys. Rev. D* **74** 043005 (2006)
13. Berezhko E G, Völk H J *Astrophys. J.* **661** L175 (2007)
14. Abraham J et al. (The Pierre Auger Collab.) *Science* **318** 938 (2007)
15. Ivanov A A *Pis'ma Zh. Eksp. Teor. Fiz.* **87** 215 (2008) [*JETP Lett.* **87** 185 (2008)]
16. Berezhko E G *Astrophys. J.* **698** L138 (2009)
17. Glushkov A V et al. *Pis'ma Zh. Eksp. Teor. Fiz.* **87** 220 (2008) [*JETP Lett.* **87** 190 (2008)]