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# 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.

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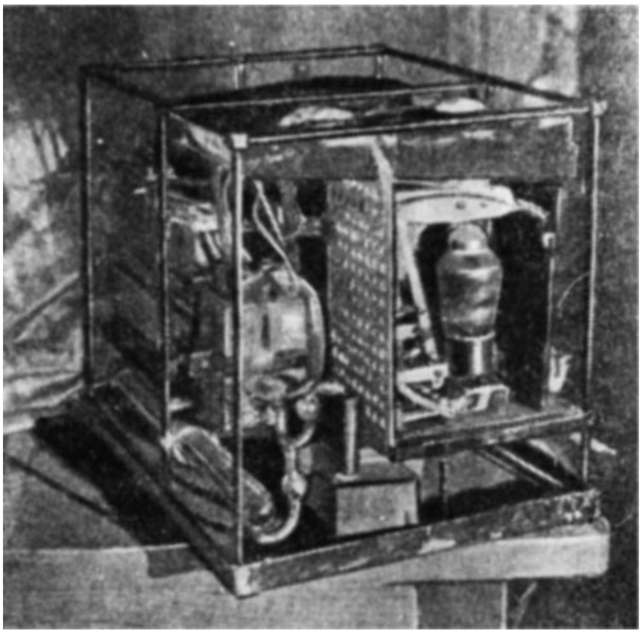

**Figure 1.** The first radio probe developed by S N Vernov for measurements of CR fluxes at different altitudes in Earth's atmosphere. For the first time the data were transmitted to the ground by radio. The weight of the radio probe was 28.6 kg.

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 ($\sim$ 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.

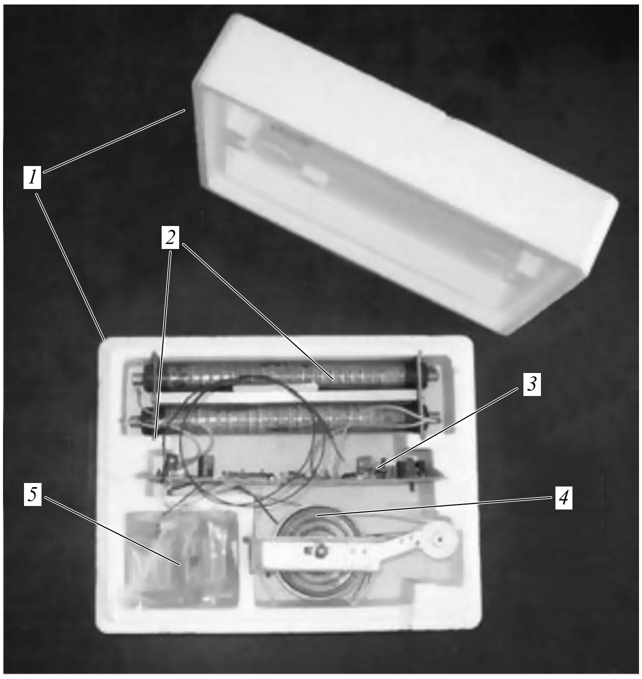


**Figure 2.** A standard radiosonde for measurements of charged particle fluxes in Earth's atmosphere. *1* — foam plastic box; *2* — charge particle detectors consisting of two STS-6 gas-discharge counters made in the Russia, with a 7-mm-thick aluminum filter between them; the filter allows separating 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

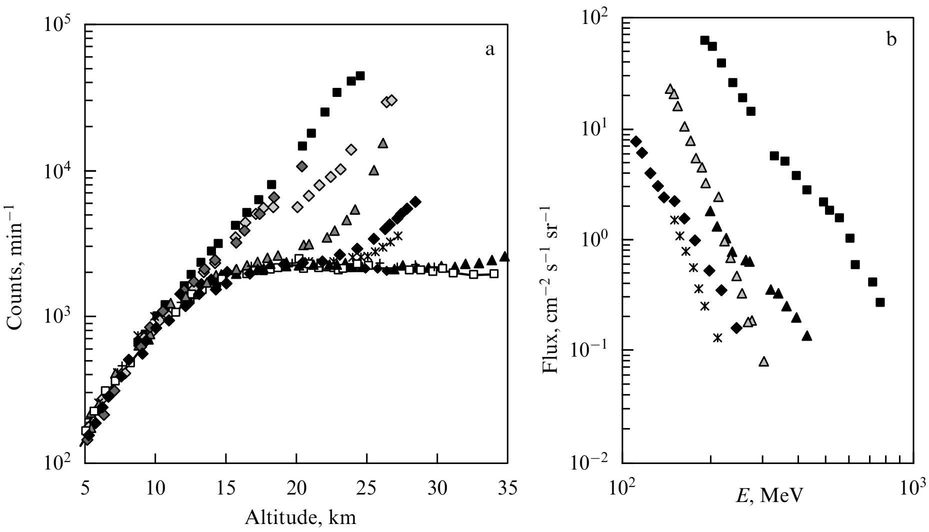


**Figure 3.** (a) The altitude profile for CRs observed in several radiosonde flights before and after a series of large solar flares occurred on 9, 14, and 16 June 1959. The measurements were performed at northern polar latitudes from 9 to 17 July 1959. Data for different flights are marked by different 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).

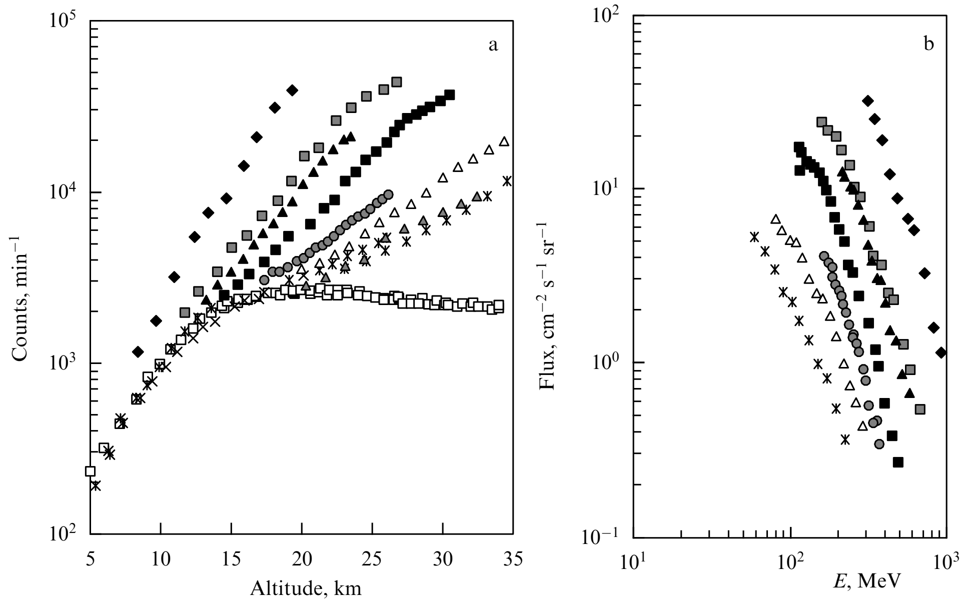


**Figure 4.** (a) The altitude profile for CRs observed in one of the last large solar CR flares on 20 January 2005. The measurements were performed at northern polar latitudes from 20 to 21 January 2005. The galactic ray background is marked by white squares. (b) The solar proton integral spectra that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

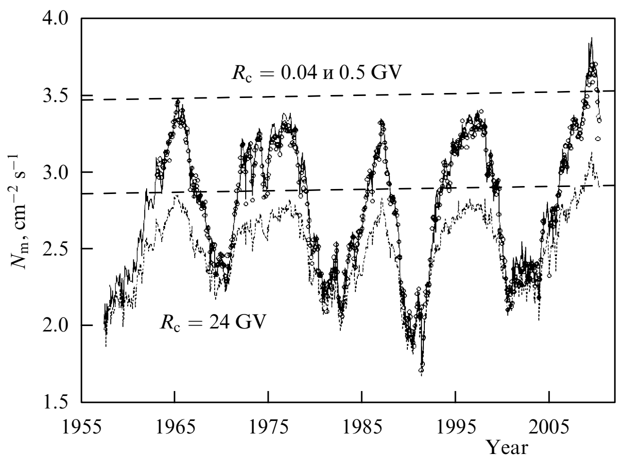


**Figure 5.** Monthly means of galactic CR fluxes in the atmosphere at the peak $N_m$ in the transition curve. The data were obtained at northern polar latitudes with geomagnetic rigidity cutoff of $R_c = 0.5$ GV (upper solid line), in Antarctica with $R_c = 0.04$ GV (white circles), and at the middle 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.

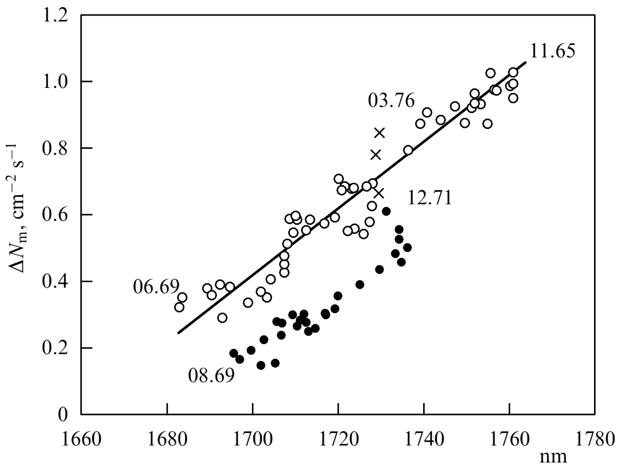


**Figure 6.** The regression $\Delta N_{\rm m}$ between the galactic CR fluxes for low energies [$E \approx (0.5-1.5)$ GeV] and high energies ($E > 12$ GeV). The fluxes of low-energy particles were obtained from measurements in the polar and mid-latitude atmosphere at the altitude ranging 18–23 km. Data 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.

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# 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).

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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