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Cosmic ray physics in space: the role of Sergey Vernov's scientific school

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Abstract. Cosmic rays were discovered almost 100 years ago. Since then the scientific world has learned a lot from their nature: the particles nascent in the Universe, both in our Galaxy and outside, the basic mechanisms of their acceleration, transfer in the interstellar environment and the interaction of the primary cosmic rays with the atmosphere surrounding the Earth. Before 1957, i.e., the beginning of the Space Era, researchers' capabilities were limited to experiments performed on the ground, underground and in near-ground atmosphere to flight altitudes of aerostats, airplanes and rockets, i.e., where only secondary radiation is in existence, this is the result of the interaction of cosmic rays with the Earth's atmosphere. The launching of spacecraft allowed the scientists to commence exploring the Universe's primordial matter itself outside the atmosphere, i.e., the primary cosmic rays. Sergey Vernov, the Russian scientist, was among them.


D.V. Skobeltsyn   G.T. Zatsepin

Fig. 1. D. V. Skobeltsyn and G. T. Zatsepin have developed a theory of extensive air showers.

1 Introduction

V. Hess (Hess, 1911), who ascended by a balloon in 1912, discovered the considerable increase of the air ionization rate at altitudes of more than 1 km. He was the first who supposed that the air ionization at such altitudes could relate to the radiation of a cosmic nature. He was honoured with the Nobel Prize many years later (in 1936) for this very supposition. P. Auger (Auger and Ehrenfest, 1935) proved, by experiments, that the air ionization is created by a cascade of secondary particles born as the result of the interaction of primary ones, which penetrate the atmosphere from outer space, with air atoms. D. V. Skobeltsyn (Skobeltsyn, 1936) and G. T. Zatsepin (Zatsepin, 1949) (Fig. 1), in 30 s – 40 s, developed the mechanism of interaction of the primary radiation with the atmosphere, i.e., the cascade theory, which became the basis of the physics of cosmic rays in the atmosphere and in other mediums thereafter.

Experimental discovery of the cascade process is also connected with D.V. Skobeltsyn. He 'saw' cosmic-ray showers for the first time in experiments with the Wilson chamber and discovered tracks of two-three particles born simultaneously therein. They were possibly the first observations of multiple processes in high-energy nuclear physics (Skobeltsyn, 1927). Due to the cascade theory, it became feasible to measure the primary particle energy experimentally per the number of cascade secondary particles, i.e., the so-called 'extensive air shower' (EAS). However, up to the 1940s, the primary cosmic radiation nature and its composition were not known. Understanding that the primary cosmic rays consist mainly of positive-charged particles, i.e., the protons, it became feasible to research works that were implemented by a series

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Fig. 2. S. N. Vernov and his colleagues from the Moscow University – N. L. Grigorov, A. E. Chudakov and Yu. I. Logachev – succeeded in performing the first physical experiment in space onboard the Second Soviet artificial Earth satellite – cosmic rays measurements using Geiger-Muller counter.

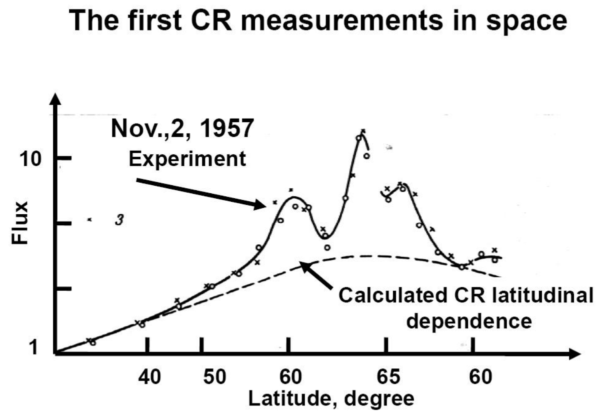

Fig. 3. Research of S. N. Vernov's group performed onboard the Second Soviet satellite resulted in a discovery of bursts of the particle currents, with their amplitudes exceeding the particles' current expected on the base of calculated cosmic rays latitudinal dependence.

of task-oriented experiments on the study of the "East-West effect", relating to the particles penetration into the Earth's magnetic field (Johnson, 1933) and also experiments using balloons (Shein et al,, 1941). After the Second World War, the cosmic rays researchers began using rockets at altitudes of more than 100 km. Such experiments were implemented both in the USSR (S. N. Vernov together with A. E. Chudakov and others) and in the USA (J. Van Allen, F. Singer and others) (Van Allen and Singer, 1950). The altitude dependence of the cosmic rays intensity follow the maximum at altitudes of $15-20$ km, where there is the greatest number of EAS secondary particles, and then the intensity decrease occurs when coming out to the plateau. The rocket-based experiments allowed scientists to approach the atmosphere boundary, but not to extend into the outer space where the cosmic rays were to be observed, which have not yet interacted with the terrestrial atmosphere. The cosmic rays study outside the atmosphere became feasible due to the Space Era, i.e., the launching of the Earth's First Artificial Satellite in 1957.

2 First satellite experiments

S. N. Vernov and his colleagues from the Moscow University (Van Allen and Singer, 1950) were the first who succeeded in arranging equipment for the cosmic rays study onboard the Second Soviet Satellite launched on 2 November 1957 Fig. 2).

Using the KS-5 instrument based on the simple Geiger-Muller counter, the first ever physical experiment in the outer space was performed. The scientists expected to research the spatial distribution of the cosmic rays (CR) outside the atmosphere experimentally by means of it. The CR latitudinal dependence (the dashed line in Fig. 3), expected from the calculations and caused by the nature of their penetration into the Earth's magnetic field, did not prove true in the first satellite orbit. There were the counting rate bursts at latitudes of $\sim 60° - 65°$. The first hypothesis to explain the observed deviation became possible owing to solar energetic particles (SEP) from the solar flare, which had occurred just several hours before observing the bursts. It was incorrect and it had a dramatic effect on the first experiment studying CR in the outer space. The scientists were faced with an absolutely new natural phenomenon, i.e., energetic charged particles trapped into the Earth's magnetic field, i.e., radiation belts (RB). The space exploration pioneers observed so-called 'precipitation' of particles from the RB, however, they could not explain the phenomenon due to lack of information (see the review Logachev, 2007).

Two months later, American scientists, headed by J. Van Allen, launched the Explorer 1 satellite. The scientists wondered how much readings to take of a saturated Geiger-Muller counter (the same as S. N. Vernov had used). That was the response to the unexpected high counting rate of the instrument in individual intervals of the satellite orbit (Van Allen, 1960). However, the interpretation following this observation was incorrect, i.e., J. Van Allen referred the observed phenomenon to auroral particles causing auroras, i.e., low-energetic radiation penetrating from high latitudes to the equator. Perhaps, this idea was dominate for J. Van Allen due to the fact that during his previous career, he had studied the auroral radiation exactly by means of the rocket experiments. It was even more striking that another American scientist F. Singer, a year before the Explorer 1 satellite launching, had published an article (Singer, 1957), in which he had been directly proving possible existence of the

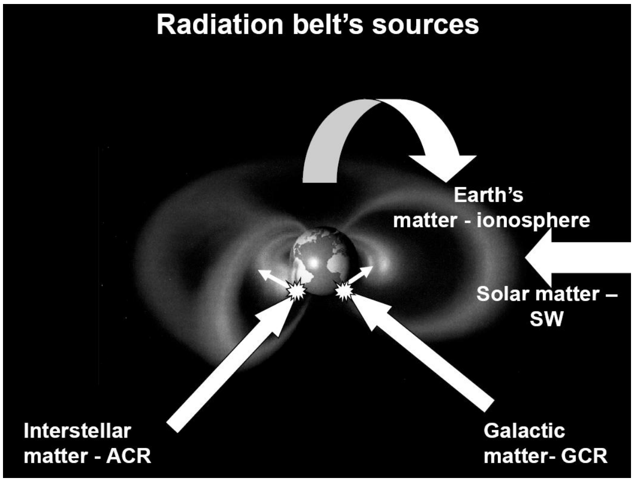

Fig. 4. Main sources of the Earth's radiation belts' particles: ionospheric plasma, solar plasma and cosmic rays (galactic and anomalous component).

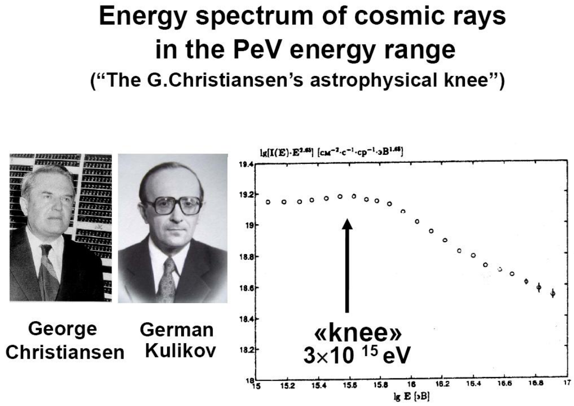

Fig. 5. G. B. Khristiansen and G. V. Kulikov from Moscow University discovered a sharp curve in the cosmic rays energy range at the energies of $3 \cdot 10^{15}$ eV – so-called 'knee', that played a major role in the development of cosmic rays astrophysics. Represented in the picture is the spectra from their first paper, devoted to the discovery of the 'knee'.

charged particles 'ring currents' in the Earth's magnetic field, i.e., the RB. F. Singer had no luck. He lost a contest to J. Van Allen to place his instrument onboard the Explorer 1 satellite. If he had launched his instrument onboard Explorer-1, he could have declared the trapped energetic radiation around the Earth. However, J. Van Allen could not have know about those F. Singer's works! It is currently known that the RB is a natural phenomenon inherent in all planets with magnetic fields and having just mediated the relation to the cosmic rays themselves. There are several RB sources (Fig. 4).

This is, for instance, the solar wind plasma penetrating into the magnetosphere and is accelerated in it. Along with the solar plasma, the terrestrial ionospheric plasma is also a powerful source of energetic particles, i.e., the RB. The SEP can penetrate the magnetosphere and become partially trapped in the magnetic field. But it occurs seldom, i.e., during magnetic storms when there is a depression of the Earth's magnetic field allowing relatively low-energetic solar particles to penetrate inside the radiation belt.

As for high-energetic CR, i.e., anomalous (ACR) and galactic (GCR) ones, they are also the RB sources, but indirect ones, since their Larmor radius (ρ_L) in the Earth's magnetic field is too long to provide stable trapping formulated by H. Alfvén (Alfvén, 1950) $\rho_L/\rho_m \ll 1$ (ρ_m – magnetic force line curvature radius). Such as the ACR ions (oxygen, neon and others) having a minimum charge state of 1^+, freely penetrate to low altitudes and can be re-discharged in the atmosphere's upper layers. Newly-generated multiple-charged ACR ions, flying out of the atmosphere, replenish the RB. A similar mechanism for the GCR is observed. The GCR nuclei, having enough impulse to overcome the geomagnetic barrier, can cause nuclear reactions with the atmosphere atoms with the generation of secondary particles replenishing the radiation belts. As for the GCR protons, they, interacting with the atmosphere, generate a flux of albedo neutrons, which, flying out of the atmosphere, generate energetic protons and electrons, which can be then trapped by the magnetic field.

The initial stage of the outer space explorations, i.e., discovery of the RB, refers to this mechanism of particles generation by means of the CR generating the albedo neutrons. S. N. Vernov and A. I. Lebedinsky were the first to formulate it (Vernov et al., 1958). In the USA, F. Singer published a work describing a similar mechanism (Singer, 1958). It happened in July-August 1958, soon after the first experiments in outer space. The Cosmic Ray Albedo Neutron Decay (CRAND) model became the final milestone of the first stage of the near-Earth space researches concerned with the RB discovery. The initial stage of the space researches can be differently evaluated. Expecting problems, however, it is currently obvious that the two groups of scientists in the USSR and in the USA working independently from each other during a very short period of time, discovered new natural phenomenon, i.e., the RB, and developed the first physical model of their forming.

3 First measurements of high energy cosmic rays in outer space

The year 1957 became the striking and significant milestone in the CR physics. One outstanding discovery was already mentioned above. That is the Earth's radiation belts. However, in the same year, there was one more discovery in CR physics, i.e., a 'knee' in the CR energy spectrum at an energy of $3 \cdot 10^{15}$ eV. It is imperceptible in the common log-log scale, but it becomes apparent in the vertically 'extended' scale (Fig. 5).

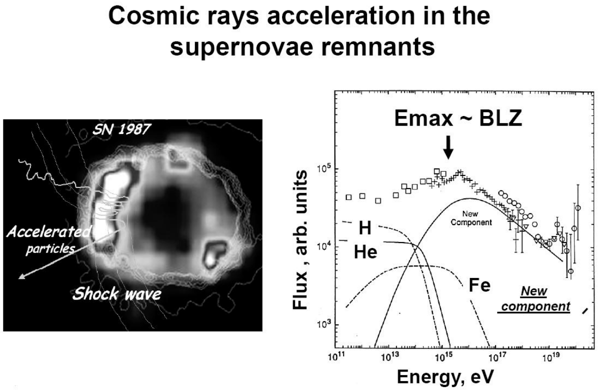

Fig. 6. The main point of the 'standard' model of CR acceleration – acceleration of particles at the shock fronts, generated in the supernovas' explosions. The 'knee' in the energy spectra of single CR components may be due to the energies' upper limit for cosmic accelerators of this kind.

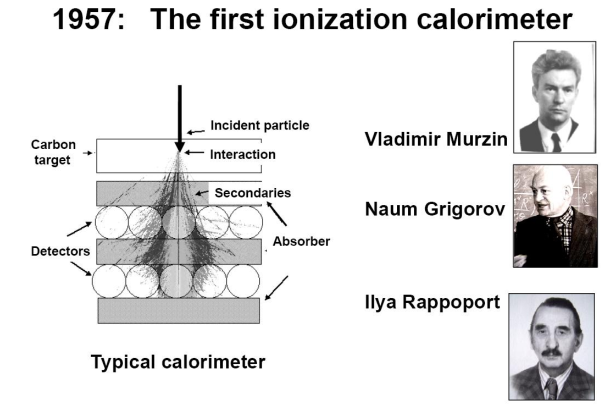

Fig. 7. In 1957, N. L. Grigorov, V. S. Murzin and I. D. Rapoport from the Moscow University proposed an idea of and created the first ionization calorimeter – an instrument for measuring cosmic rays (high energy particles) energy.

S. N. Vernov's colleagues – G. B. Khristiansen and G. V. Kulikov – from the Moscow State University were the first who observed that 'knee'. Currently, it is often referred to as 'Khristiansen astrophysical knee'. Attempts to interpret the 'knee' at $\sim 3\cdot 10^{15}$ eV played an exclusively important role in developing the cosmic ray physics. First of all, it concerned the CR acceleration mechanisms in the Galaxy. It turned out that the 'knee' position is close to the upper energy limits of the particle accelerated in remnants of supernovas. Indeed, it can be shown that, when there is the Fermi-type acceleration on the shock front of the supernovas (Fig. 6), the accelerated particle maximum energy is $E_{\max} \sim B\cdot\rho_L\cdot Z$ (here B – the interstellar magnetic field, ρ_L – particle Larmor radius, Z – charge).

It follows that when the interstellar magnetic field is $B \sim 3\mu Gs$, $E_{\max} \sim 10^{14}$ eV. Up-to-date models based on G. F. Krymsky's ideas (Krymski, 1977; Berezhko et al., 1996) give $E_{\max} \sim 10^{16} - 10^{17}$ eV but not more. Therefore, the 'knee' area is the key energy area for the cosmic ray astrophysics. To get experimental demonstrations of the standard model (Krymski, 1977; Berezhko et al., 1996) in this energy area it means to prove predominance of the CR acceleration process in supernovas' explosions compared to other models. Energetic 'grounds' are more than profound for it. In supernovas explosions up to 10^{52} erg, i.e., 10 ‰ , can be released; this energy is enough to accelerate all particles existing in the Galaxy. The problem with this experiment in that energy area is that the 'knee' area is, in a sense, the 'watershed' between earth-based experiments on the one hand, and balloon or space experiments on the other hand. The EAS methods do not allow for the studying of the CR at energies of $< 10^{14}$ eV, since such energy particles cannot penetrate into the atmosphere. Therefore, it is necessary to apply 'direct' methods of CR measurement by installing the equipment onboard balloons and satellites. However, the difficulty is the method of such particles' energy measurement. Scientists N. L. Grigorov, V. S. Murzin and I. D. Rapoport of the Moscow University proposed a fundamentally new method of energy measurement of high-energy particles, i.e., the ionization calorimeter method (Fig. 7) in the same year, 1957.

Currently, this method is widely applied in the physics of high energies both in Earth-based acceleration experiments as per the particle physics and the physics of cosmic rays. Ionization calorimeters for CR measurement were produced for the first time for mountain researches and then were launched into space. The history of the first space experiments with calorimeters is significant. The balloon experiments with their short-time flights have upper limits of measured energy because of insufficient statistics. In this regard, satellites with a longer existence have advantages over the balloons. However, large dimensions and, as a consequence, heavy weight of the instruments required to provide good statistics of recorded events, are a fundamental importance for these experiments. Soviet scientists S. N. Vernov and N. L. Grigorov had the opportunity to implement large-scale experiments with calorimeters in 1960s. They succeeded in arranging scientific equipment, i.e., ionization calorimeters, in place of dimension-weight models of nuclear warheads when test launching of military ballistic missiles (Fig. 8).

There were four launches of rockets with Proton 1–4 satellites having ionization calorimeters onboard from 1965 to 1968. The weight of the heaviest SEZ-14 calorimeter (Proton-4) was 12,5 tons! It has been unsuccessful to launch such heavy instruments for the CR study so far. It must be mentioned that a 'blank spot', i.e., the area of energies before the 'knee' not filled with experimental data, remained in the CR energy spectrum right up to 1960s. The Protons' experiments, for the first time, overlapped the spectrum in

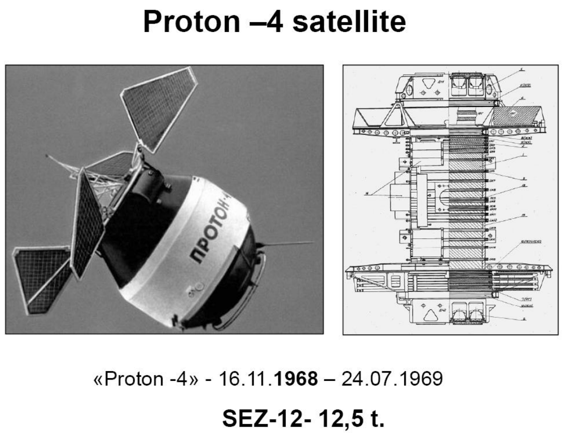

Fig. 8. Proton-4 – the heaviest ionization calorimeter, launched to space in 1968 by the initiative of S. N. Vernov and N. L. Grigorov. This experiment, per se, was the beginning of the "space stage" of ultra-high cosmic rays researches.

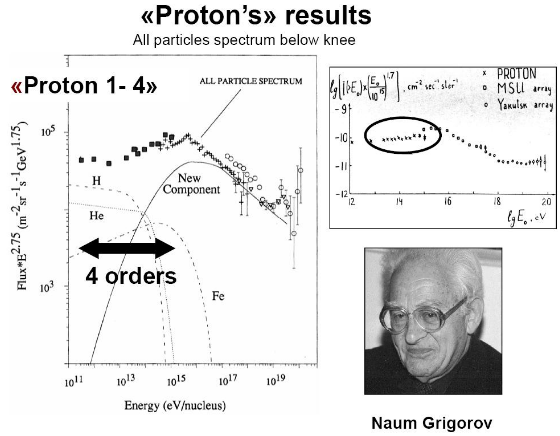

Fig. 9. The main result of the Proton's "space odyssey" that haven't been repeated up to now – measurements of spectra of all CR particles in the wide energy range from 10^{11} to 10^{15} eV.

the widest range of 10^{11} to 10^{15} eV (Fig. 9). The 'direct' experiment onboard the satellites closed with results of the earth-based EAS units (Grigorov et al., 1972). It was a great success of the national science. The Protons measured the spectrum of all particles. However, information about the CR chemical composition in the range of energies before the 'knee' remained limited.

The determination of nucleus chemical compositions in the 'knee' area must play a key role in the identification of the specific acceleration mechanism of the particles and their transport in the interstellar medium. The CR composition changes in this area of energies are expected both from models of shock acceleration and from models of propagation, for which $E_{\max} \propto Z$. In other words, in this interesting area of energies, the CR composition 'weighting' is possible, i.e., the increase of relative content of heavy nuclei over protons. On the other part, when energies after the 'knee', particles are expected, which are probably accelerated in other astrophysical objects (a 'new component'), which are more powerful than the supernovas.

During years following the Protons epoch, three experimental studies of the CR chemical composition with energies before the 'knee' were executed. They were the American CRN onboard the Spacelab orbital station in the 80s (Swordy et al., 1982) and soviet Sokol-1 and Sokol-2 onboard satellites in the beginning of the 90s (Ivanenko et al., 1993; Grigorov, 1990). Along with the balloon CR measurements (there have been 9 of them to date), these experiments have considerably advanced our knowledge about energetic and mass characteristics of the CR. In spite of the divergence of some experiments and limited statistics (especially in the area of energies $> 10^{13}$ eV), these data are evidence of a tendency of weighting of the CR chemical composition before the 'knee'. However, the 'knee' area has not been reached yet and information about the chemical composition in this area is severely limited. This conclusion is also correct for results of the EAS CR measurements, the data are also discrepant here. Therefore, the future of the CR researches in the 'knee' area is, of course, large-scale space experiments with large geometrical factors to provide statistics and with good resolution per weights to identify wide spectrum of nuclei to iron and further.

One of the first observations of the SEP in the outer space was executed aboard the Soviet Third Artificial Satellite in May 1958 using scintillation and Cherenkov detectors designed at the Moscow State University (the Skobeltsyn Institute of Nuclear Physics of the Moscow State University, lead by S. N. Vernov) (Logachev, 2007) and the Lebedev Institute of Physics of the Academy of Sciences (Kurnosova et al., 1958). It happened 16 years after the first experimental proofs of acceleration of particles on the Sun up to a several GeV had been obtained by S. Forbush in 1942. Since then, the problem of the solar particles acceleration, i.e., the mechanism of the acceleration and its localization, remains central for the physics of the SEP. It is obvious today that the particles of solar origin can accelerate up to gigantic energies compared to the GCR energies (up to 10 GeV) as the result of various in its nature acceleration mechanisms both in the Sun's chromosphere and during their spreading in the interplanetary medium.

4 Conclusions

At the beginning of the Space Era, i.e., the launch of the Earth's First Artificial Satellite in 1957, is the beginning of a new stage of cosmic ray physics as well and research of them by means of spacecraft. S. N. Vernov was among the pioneers of this new and very important further development of cosmic ray physics. This stage of cosmic ray physics has brought much new and unexpected development in our understanding of the origin of high energy particles in the Universe, the processes of their transport, acceleration and destruction, and their sources. In saying, without the space experiments, we could not conceive the energy spectrum of high energy particles or the most important physical characteristics of them. This means that if we remained on the Earth, we could not approach the understanding of the cosmic rays nature.

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