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A E Chudakov as scientific pioneer

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Contents

Abstract. **Alexander Chudakov was the first to do many things in science. Presented below is a short review of his work including pioneering experiments that the fates surely favored, in the sense that Chudakov's ideas and the methods he suggested were realized in many subsequent experiments and even in whole branches of science. Some large modern projects are mentioned, those either in operation or only in the design phase, the path to which started from the pioneering initiatives of Chudakov and their first practical implementation.**

Keywords: cosmic rays, neutrinos, muons, radiation belts, gamma ray astronomy, underground physics

The author of the presented opus is undoubtedly a genius. Nevertheless, Cambridge University can award him an academic degree.
Bertrand Russell on L Wittgenstein and his *Tractatus Logico-Philosophicus*

1. Introduction

Alexander Evgenievich Chudakov was the sort of scientist one meets more and more rarely these days. According to modern criteria of successful scientists, he can hardly be called a scientist at all. His citation index is indecently low:[1] all his publications were in conference papers or in journals that are currently called low ranking. And the total number of publications is pretty small by contemporary standards. Not a single dissertation was publicly defended by him (his candidate dissertation was devoted to secret topics and his doctoral degree was awarded to him *honoris causa*). Nevertheless, Chudakov passed through all the stages of the usual scientific career, up to member of the Presidium of the Russian Academy of Sciences, and everyone who needed knew about him and valued him extremely highly. Professor John Linsley from the University of New Mexico (USA) in a letter to the author used the words 'his undoubted genius' applied to Chudakov. Professor Sir Arnold Wolfendale, former Royal Astronomer for England (Durham University, UK), wrote the following about him: "Chudakov was a 'gentle giant,' a man of towering physical presence and towering intellect. His contributions to Cosmic Ray Physics were many; indeed, very, very few have done such important work." Professor Gianni Navarra from Torino University (Italy) called him 'outstanding maestro' in English and 'mostro sacro' in Italian. The latter is an Italian idiom applied to an especially great man. The Italian–Russian vocabulary suggests pillar, VIP, and unreachable peak as variants of the translation.

What is the secret of such a sharp contrast between formal scientometric indicators and the real authority of the scientist? The fact is that nearly all of Chudakov's work had the character of pioneering investigations.

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[1] G T Zatsepin, a friend and rival of Chudakov during their entire long joint scientific carrier, once said that Chudakov's work was more important than those of himself. Nevertheless, the citation index of Zatsepin is larger than that of Chudakov by a factor of almost 30.

Chudakov was a pioneer in such different fields of science as cosmic-ray physics, gamma-ray astronomy, neutrino astronomy, geophysics, and underground physics.

But, at the same time, he was very careless about publications and advertising his results.

2. Experiments with rockets and the Chudakov effect

Chudakov's first studies were connected with secret topics and there are no open publications about them. Special reports were kept in the secret department of the Lebedev Physical Institute. After Chudakov's death, my attempt to find them failed, since they were already sent to some other office and no traces were found. However, it is known to what matter these studies were devoted. In paper [1], we read: "In 1946 while still being a student of Moscow University A E Chudakov started his job in the Physical Institute of the USSR Academy of Sciences (FIAN) in a group whose task was to investigate cosmic rays with the use of rockets." The head of this group, S N Vernov, "organized a team making experiments during flights of high-altitude rockets at the Kapustin Yar township. This stage in studying cosmic rays is very poorly described in literature. All investigations made during the flights of these rockets were top secret. It is about experiments in 1947–1951 with German rockets FAU and with domestic more advanced rockets reaching altitudes of 70–100 km. It is natural that these first steps in developing the rocket technology and even the very facts of rocket launches were classified, and any publications were out of the question" [2]. And further on: "Rocket experiments in Kapustin Yar were headed... by A E Chudakov. They were not only the prototype of experiments onboard future space vehicles, but provided a number of valuable scientific results" [2]. These results were casually mentioned in a report by Vernov and Chudakov at the UN International Conference on the Peaceful Uses of Atomic Energy (Geneva, 1958) [3]:

"1. Investigations of cosmic rays with the use of rockets were performed in the USSR in the period 1947–1951.

These works pursued the following two aims: (1) to get some data about the primary cosmic rays, and (2) to study some problems associated with interactions of primary cosmic rays with nuclei of atoms of matter (in particular, production of the electron-photon component was under study).

In 1947–1949 and in 1951 the flux of charged particles was measured by Geiger counters at altitudes of 50–100 km. It was found to be constant within 5% accuracy and equal to 0.150 particles cm^{-2} s^{-1} sr^{-1}.

In 1949 the data on the intensity of photons at high altitudes were obtained. The energy fluxes of photons with energies of order of 10^7 eV and less than 10^6 eV appeared to be approximately equal, constituting together less than one thousandth of the energy flux of cosmic rays. It is quite possible to explain so low intensity by secondary photons produced by cosmic radiation in the atmosphere or, in view of the recent data, by electron fluxes at high altitudes."

There are also mentions about some other results of this period, but we can restrict ourselves to the above information communicated by the authors [3].

In 1949, Chudakov considered the phenomenon that later became known as the Chudakov effect [4]. Figure 1 presents the curves of total ionization of a high-energy electron–positron pair calculated by Chudakov [5]. One can see that,

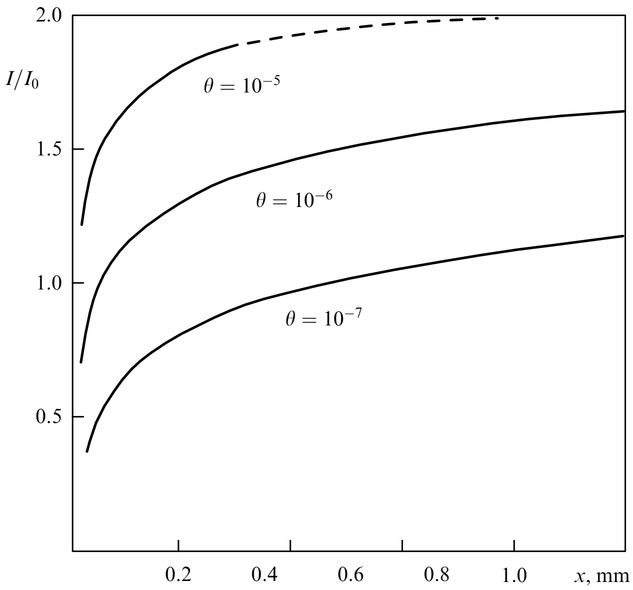

Figure 1. Total ionization of an electron–positron pair as a function of the path from the origin point for three values of divergence angle θ.

at a considerable distance (depending on energy) from the point of pair origination, the total ionization is substantially lower than the doubled ionization of a single particle. This is a result of interference of wave functions of the particles at a small divergence of their trajectories, and this is what is called the Chudakov effect. As became clear much later, this effect is in fact universal. Now, it is taken into account in quantum chromodynamics, where it reveals itself as the screening of the color fields of narrow pairs of quarks and gluons. The effect quickly found a practical application in measuring the energy of an electron–positron pair when studying nuclear interactions by the method of nuclear emulsions. For this purpose, Chudakov later designed and manufactured a special instrument to measure the darkening of charged particle tracks in photo emulsions [6]. By the way, it was one of many instruments designed by Chudakov or under his supervision. We can mention, for example, an X-ray source for calibration of a large number of scintillation detectors [7], a high-precision digital barometer [8], an instrument for measuring the electric field of the atmosphere, etc. As for the Chudakov effect, it is a good example of long delays in publishing important results, very typical of Chudakov. As is said above, he considered this effect in 1949, but the paper was published only in 1955. And there was a talk that Nobel Prize winner I M Frank insisted on this publication.

However, an even more amazing situation took place with the first observation of transition radiation (TR) in the optical waveband. In all *personalia* on Chudakov, it is written that he observed TR in 1953 when preparing his experiments with Cherenkov radiation. One can read the same in many memoirs and in some dissertations. But presumably Chudakov did not take care to publish his observations. Therefore, Wikipedia communicates in the paper "Transition radiation": "Experimentally, the effect was discovered in 1958 at the Yerevan Physical Institute." Strictly speaking, TR was observed in Yerevan in the X-ray energy range. Optical TR was observed by P Goldsmith and J V Jelley in 1959. But, in any case, Chudakov was the first, though there remained no traces of this activity, most probably because it was a by-product result obtained during preparations of a large-scale

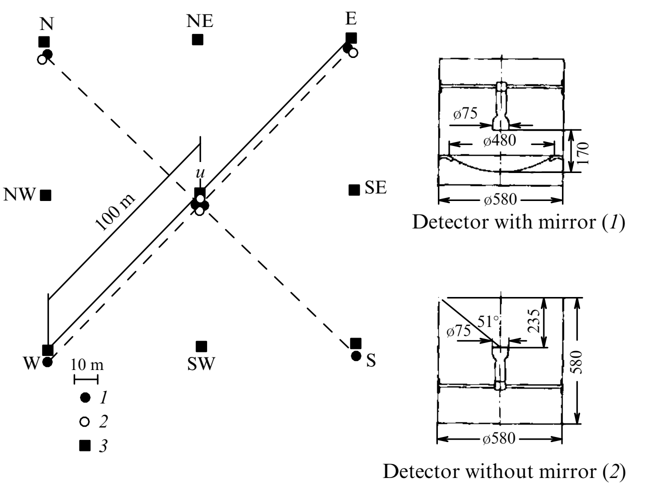

Figure 2. Arrangement of Cherenkov radiation detectors (*1* and *2*) in the Pamirs experiment made by Chudakov. Hodoscopic system (*3*) includes 96 Geiger counters (with an area of 330 cm^2) in every hodoscope unit, shown by black squares.

experiment aimed at observing the Cherenkov radiation of extensive air showers (EASs) in the Pamirs.

3. Pamirs experiment

Not long before the beginning of this experiment, EAS Cherenkov radiation was first observed by W Galbraith and J V Jelley [9] with a very primitive experimental setup. They used a photomultiplier tube 5 cm in diameter in the focus of a small (25 cm) mirror placed in a blackened dustbin. Chudakov's experiment [10] was performed on a much greater scale (Fig. 2): detectors of two types (with mirrors and without them) were located at distances of 100 m from the central ones. Many things were done in this experiment for the first time. The lateral distribution function of the Cherenkov light in EAS was investigated, and the energy spectrum of primary cosmic radiation was measured with the use of the technique of fast data taking in eight oscilloscopic channels simultaneously. Present-day facilities of this type, for example, Tunka [11], now incorporated into the TAIGA (Tunka Advanced Instrument for cosmic rays and Gamma-Astronomy) astrophysical complex in the Tunka valley near Lake Baikal, are designed in principally the same way. But even against this background (Tunka-133 consists of 175 optical detectors arranged in an area of 3 km^2), the Pamirs Chudakov installation looks quite impressive.[2] Moreover, the work on the method of this experiment resulted in a couple of important by-products. One of them is the above-mentioned observation of transition radiation. Another one is the estimation of ionization glow of the showers in the atmosphere, which allowed Chudakov to suggest a new method of detection of giant EASs. This point will be discussed below in Section 6. One can find more details about the role of Chudakov in developing methods that use Cherenkov radiation for studies in cosmic rays in paper [12].

[2] The first version of the array, Tunka-25, which very successfully operated in 2000–2005, was quite comparable to the Chudakov array in dimensions and capability, but they were separated by almost half a century!

4. First measurements with satellites and the dramatic story of discovering Earth's radiation belts

With the onset of the space era, Chudakov was immediately involved in investigations of cosmic rays aboard satellites. Two identical Geiger counters (for mutual verification of operation) installed by him aboard Sputnik-2 were the first detectors of elementary particles ever launched into space. Sputnik-3 was already equipped with a scintillation counter (sodium iodide crystal) much more sensitive to gamma rays. Sputnik-2 was launched in November 1957, and its orbit crossed Earth's inner radiation belt. Sputnik-3, in May 1958, traversed the outer radiation belt. In the interval between these two launches, two American satellites were launched in January (Explorer-1) and March (Explorer-3) of 1958. What follows below is the sad story of how Soviet scientists were the first to observe the intensity increase due to particles trapped by the geomagnetic field, but failed to publish their results.

In [13], Prof. Joseph Lemaire briefly, but exhaustively described the situation with the first observation of the radiation belt, concluding this description by a moral maxim of a philosophical nature.

"The Geiger counters of Sputnik-2 (this was the satellite carrying the dog Laika) had detected the trapped radiation near apogee over Australia with KS-5, the first orbiting instrument for cosmic ray studies. But since S N Vernov and A E Chudakov did not receive the data from the Australian receiving station they did not see the rapid rise in intensity with altitude until much later. At Sydney, Australia, the scientists with Professor H Messel, a noted cosmic ray researcher and head of the School of Physics at the University of Sidney, recorded the telemetry signals from Sputnik-2. But they did not have the telemetry code. Asked about this during the Cosmic Ray Congress in 1959, Messel said to Singer "They would not send us the code and we were not about to send them the data" (Hess, 1968). This is why in the November 23, 1984, issue of *Science*, Alex Dessler published an editorial titled "*The Vernov Radiation Belt* (*Almost*)." This piece of History re-opens the issue of who, in scientific races, are remembered as the key actor and discoverer: the pioneer who had the idea first, who designed an experiment to check this idea and prove it to be correct, or, the author(s) whose paper passed the refereeing process and who, luckily, first published the results in open literature. In Geophysics it is the latter who wins this Guinness Book of Records competition."

We can only add to this that such a situation takes place not only in geophysics. What causes certain amazement is the position of Prof. Messel, who wanted to study data that did not belong to him before sending it to the owners. As for me, to demand decoding other people's data is as indecent as opening other people's letters. Probably, Prof. Messel was not taught as a child that it is wrong to do so. In any case, it is because of his position that American scientists got a chance to publish earlier the data obtained later. And now in the western literature, Earth's radiation belts are called Van Allen belts. Though, strictly speaking, even based on the dates of publication, the Americans can only claim the discovery of the inner radiation belt, while the Sputnik-3 discovery of the outer radiation belt earned Vernov, Chudakov, and their team a well-deserved Lenin Prize.

5. First large water Cherenkov detector and first gamma-ray telescope

In 1959, Chudakov constructed a tremendous (at that time) detector to observe Cherenkov radiation of charged particles in water. The detector was a container in the form of a truncated cone filled with water (85 t), whose volume was surveyed by 16 PM tubes with a large diameter photocathode (Fig. 3). This initiative was powerfully continued decades later in the form of such giant water-Cherenkov detectors as IMB (Irwine–Michigan–Brookhaven) and Super-Kamiokande. Both these detectors were among those that detected the neutrino signal from supernova SN1987A in the Large Magellanic Cloud on February 23, 1987. The latter is especially famous, since the chief investigators of two experiments performed there were awarded at different times with two Nobel Prizes. However, this line of research, started by Chudakov, who initiated construction of giant water-Cherenkov detectors, now continues to further develop in the Hyper-Kamiokande project [14] that is under design at the moment at a distance of 8 km from Super-Kamiokande. The future installation amazes by its size. It comprises a giant cylinder with a height of 60 m and diameter of 74 m. It will contain 260,000 t of super-pure water surveyed by 40,000 high-sensitivity photo detectors. Scientific tasks of the project include investigation of *CP*-violation in the lepton sector and of parameters of neutrino mixing, the search for nucleon decay, and detection of atmospheric neutrinos and neutrinos of astrophysical origin. This water-Cherenkov detector of the next generation will also be used as a remote detector in a long-distance accelerator experiment for studying neutrino oscillations. The J-PARC accelerator (Japan Proton Accelerator Research Complex) will serve as a neutrino beam source. Moreover, a few years after starting the installation, it is planned to construct a second one on a single line with the first in Korea in order to detect a neutrino beam at two distances, 295 and 1100 km.

It is rather strange that Chudakov signed no article as author about the first detector of this type. Its construction was described in paper [15] by his assistant V L Dadykin, while Yu N Vavilov and collaborators published in [16] the results of an experiment made with this detector, aimed at searching for narrow muon bundles near the EAS axes. Chudakov himself was at that time totally involved in the construction of a new instrument which made him a pioneer of gamma-ray astronomy.

Paper [17] describes in some detail a story about a suggestion published by Zatsepin and Chudakov [18] of a new method that was immediately realized by Chudakov in the Crimea [19]. At the moment a journal with paper [18] came out in 1961, observations with the first version of the gamma-ray telescope with four mirrors had already been completed in the season of 1960. The next year, the telescope was fully equipped with 12 mirrors 1.5 m in diameter. The telescope operated in this configuration during the period 1961–1963.

The first Cherenkov gamma-ray telescope made by Chudakov was the first ever instrument designed for observations of cosmic gamma rays.

In [17], the inscription made by the authors of the monograph *Gamma Ray Astronomy*, A W Wolfendale and P V Ramana-Murty, on the gift copy is reproduced: "To Prof. A E Chudakov — a founding father of the subject — from PVRM & AWW." A short history of the development of Cherenkov gamma-ray astronomy after Chudakov is also given in [17], and the main achievements in this field are listed in brief. At the present time, the following systems of third generation gamma-ray telescopes (2003–present time) are in operation: HESS (High Energy Stereoscopic System) in Namibia, MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov telescope) in the Canary Islands, and VERITAS (Very Energetic Radiation Imaging Telescope Array System) in Arizona, USA. In the near future, the next generation telescopes are expected to be put into operation. The project CTA (Cherenkov Telescope Array) [20] will be the main one. Two systems of Cherenkov telescopes of this project will be constructed simultaneously in the northern (Canary Islands) and southern (Atacama Desert in Chile) hemispheres.

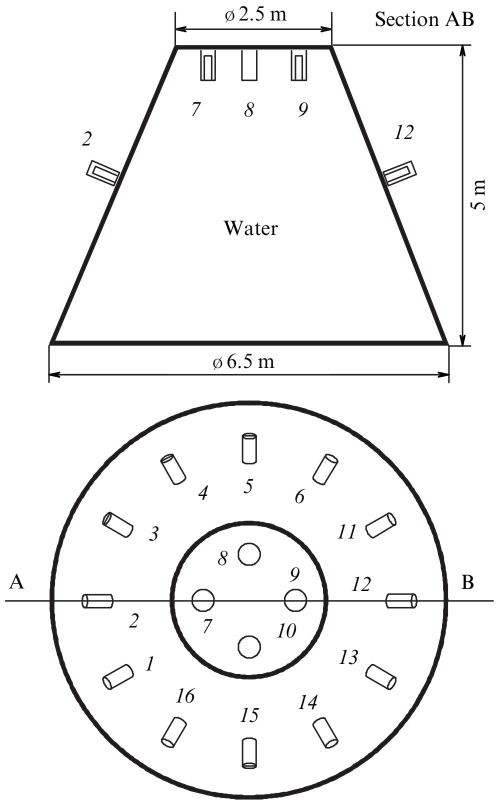

Figure 3. World's first large-volume water Cherenkov detector constructed by Chudakov (1959). *1–16* are PM tubes.

6. Suggested methods of detecting extensive air showers by fluorescence of air and snow-reflected Cherenkov light

John Linsley wrote about Chudakov's priority in suggesting the fluorescent method to detect cosmic-ray EASs: "I tried... to get clarification from Chudakov himself in his later years about an *idea that apparently came to him before it came to others*: to observe EAS by means of atmospheric scintillation. In a well-known remark of his at the 1962 Interamerican Symposium in La Paz, Bolivia, published in the Proceedings, he described his idea in some detail, dating it to 1955–1957, the time he made pioneering measurements on atmospheric Cerenkov radiation from EAS." The well-known remark had been made in a report by Japanese scientist K Suga [21], while the idea was finally published a few years later in paper [22], written together with his student. Thus, the idea originated in the middle of the 1950s, was publicly announced in 1962, and only in 1966 was published in a journal! Chudakov paid attention to the fact that Cherenkov radiation of charged particles directed forward in an EAS becomes at a large distance from the shower axis weaker than the isotropic glow produced by ionization of the same particles. The development plan of a new type of detector is described in paper [22] like this: "Ionization glow becomes prevailing somewhere at a distance of 3 km, and it dominates strongly at distances of 5 km and more.... In principle, using pulse-shape analysis at several points one would be able to determine not only the axis position in space, but the form of the cascade curve as well, and, accordingly, the energy released in the atmosphere. It is possible to detect strongly inclined and nearly horizontal showers."

The Fly's Eye detector, built in 1981, followed these recommendations absolutely, and it was quite successful. Currently, all large-scale ground-based arrays for EAS detection are equipped with fluorescence detectors. For example, the Pierre Auger Observatory array in Argentina that occupies an area of 3000 km^2 has four such detectors on its periphery, and they view the space above the array from different directions. Some projects planning the use of this method with Earth satellites are at the moment under construction.

Another possibility of using Cherenkov radiation of ultra-high energy EASs that attracted Chudakov's attention [23] consisted in the detection of light reflected from a ground surface covered by snow. His idea was to place an optical detector aboard a plane in order to measure the reflected Cherenkov signal during the flight. From the point of view of the reflecting surface quality and the time of possible exposure, the snow-covered tundra during the polar night represents ideal conditions for such an experiment. Unfortunately, this idea still remains unrealized in its original form. Some attempts were made to carry out an experiment of this type in the mountains using reflections from glaciers and to use tethered aerostats (the Sfera project). A possible variant with a high-altitude balloon in Antarctica was also discussed.

Speaking of Chudakov's proposals, it is worthy of note that the first deep underwater neutrino telescope was built by a team headed by G V Domogatsky in Lake Baikal also based on Chudakov's suggestion.

7. Facilities of the Baksan Neutrino Observatory and their first results

The decision to build a neutrino station (now called the Baksan Neutrino Observatory, BNO) was made in1963, and Chudakov started to work on designing and creating at BNO large-scale instruments to detect cosmic muons and neutrinos and to carry out investigations of cosmic-ray physics. Several facilities were built and put into operation when Chudakov was still alive: the Carpet air shower array (1974), the Baksan Underground Scintillation Telescope (BUST) (1977), and the Andyrchi air shower array (1995). Currently, all of them are still in operation, though they have been modernized more than once.

The Carpet air shower array [24, 25] was the first big setup created at Baksan. The main part indeed represents a carpet of 400 scintillators with a total area of 200 m^2, and it served as a model of one plane of a future underground telescope. In spite of such a specific purpose in creating it, the Carpet array has turned out to be an instrument of enormous value in itself for the field of cosmic-ray physics. Originally, the central scintillation carpet was surrounded by six huts, each of which had 18 standard scintillation counters and a set of Geiger counters for calibration purposes (the laboratory of G B Khristiansen from the Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University participated in installing and equipping these huts). Later on, a neutron monitor and a muon detector were added to this original set of detectors. The experimental complex was modernized several times and is still in operation. Moreover, at the moment, the Carpet-3 project is being realized based on it: it is being shown that after a radical increase in the muon detector area, the array can reach a good sensitivity to primary cosmic diffuse gamma rays in the energy range of 10–100 TeV due to selection of muon-poor showers [26].

The very first experiments with Carpet were associated with investigations of the lateral distribution function (LDF) of particles in EASs. Owing to the very large area and fine structure of the array, the shower axis was determined with very high accuracy, while the remote huts with large-area scintillators also measured particle density with good accuracy. These two factors allowed really high-precision measurements of the LDF to be performed, though in a limited range of distances from the shower axes [27, 28]. Such uniquely high accuracy permitted discovering anomalous showers with strong fluctuations in the LDF [29]. Furthermore, the large area of Carpet allowed the spatial structure of EASs near the axis to be studied in detail [30], so multi-core air showers could be investigated [31, 32]. Sub-cores in multi-core showers were interpreted to be a result of the generation by leading particles of large transverse momentum jets at an effective energy estimated to be equal to 500 GeV in the center of mass. At that time, some calculations of this process had already been made in the framework of quantum chromodynamics (QCD) for 540 GeV — the energy of the SPS (Super Proton Synchrotron) collider that was under construction at that moment. In [33], it was demonstrated that the cross section of production of high transverse momentum jets derived by analyzing multi-core showers detected by Carpet was in good agreement with QCD predictions. When the SPS collider at CERN started its operation, a similar result was obtained by the UA1 and UA2 collaborations, but a year and a half later. Figure 4, taken from [34], presents these two groups of data in comparison. Other results of the Carpet array are discussed in Section 9.

8. Neutrino astronomy and physics of muons

When designing the Baksan underground scintillation telescope [35, 36], the detection of atmospheric neutrinos was considered from the very beginning as its main task. Let us take note, however, that the word 'neutrino' never even appeared in its name. In this way, the multi-purpose property of the telescope was (maybe unconsciously) characterized. Before the BUST creation, two experiments involving the detection of atmospheric neutrinos were done in India and South Africa. Both were performed at very large depths underground (to reduce the background of cosmic ray muons) in mines of, so to say, natural (industrial) origin. And both detected the horizontal flux of atmospheric neutrinos. The Baksan facilities were the first for which

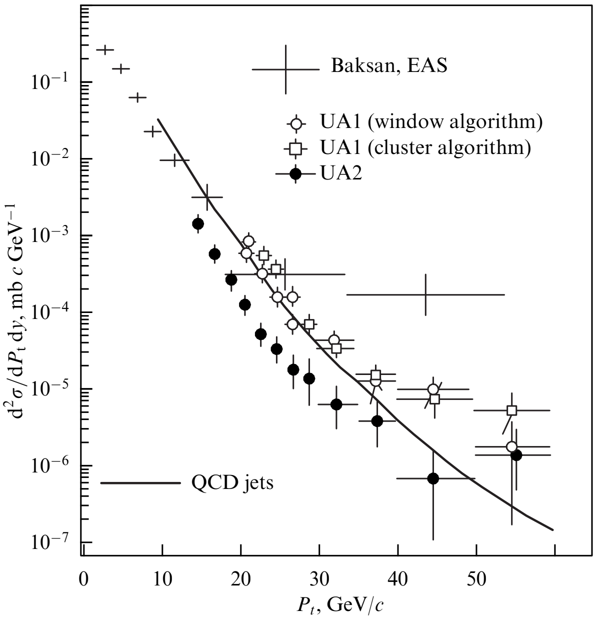

Figure 4. Cross section of production of high transverse momentum jets as deduced by analyzing multi-core EASs with the BNO Carpet array (estimated effective energy in the center of mass is 500 GeV), calculated in the framework of QCD (Horgan and Jacob, 1981) and measured by two collaborations at the CERN SPS collider (540 GeV in the center-of-mass system).

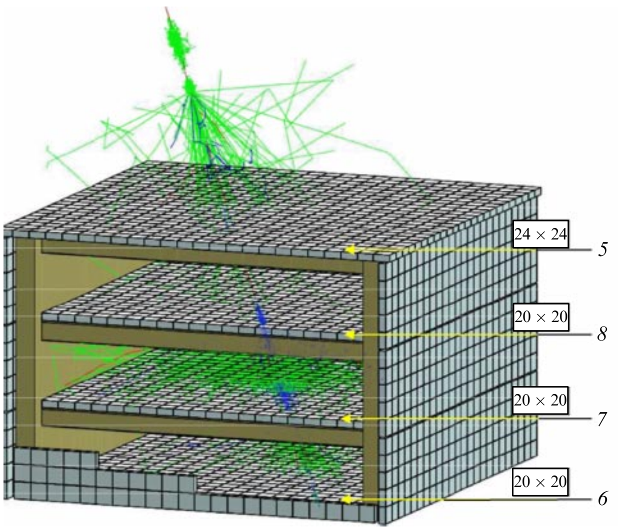

Figure 5. (Color online.) High-energy muon passage through BUST (simulation with the help of GEANT-4 code from paper [37]). Digits show the numbers of detectors in telescope planes and numeration of the planes.

special underground chambers were excavated. BUST was designed to detect vertical neutrinos passing through the globe, and it was located at such a depth where the muon background from above exceeded the sought neutrino signal by many orders of magnitude.

Figure 5, borrowed from paper [37], presents a sectional drawing of BUST with an example of detection of a high-energy muon hitting it from above. Such events made the task of recognizing neutrino events extremely difficult, but allowed simultaneously solving many problems associated with muons (measurement of the muon flux and its variations, investigation of muon interactions, muon bundles, and so on). Thus, one can consider BUST to be the first instrument of so-called underground physics.

The problem of selecting neutrino events from the muon background, many orders of magnitude more intensive, was successfully solved using the time-of-flight technique, and the first vertical neutrino from 'antipodes' was detected on December 14, 1978 at 08:31:10 local time. In spite of a very low counting rate of neutrino events, their statistics, allowing estimates of the parameters of neutrino oscillations to be made, were accumulated rather quickly [38, 39]. The ratio of measured and expected flux values $R = 0.95 \pm 0.22$ resulted in the estimated difference of squared masses $\Delta m^2 \sim 6 \times 10^{-3}$ eV^2 at a 90% confidence level (for two types of neutrinos and the maximum mixing angle). This limit improved the value existing at that time by a factor of 100 at once. The program of muon detection from the lower hemisphere continues to accumulate data. The total live time of data recorded according to the neutrino program equals 300,759.3 h (34.33 years, 81.7% of calendar time) over the entire period since 1978 until December 31, 2020 (Fig. 6). The total number of recorded neutrino events is 1810.

In 1982–1989, BUST was used for an experiment studying electromagnetic and nuclear (hadronic) cascades produced by muons underground [40]. The number of $\pi-\mu-e$ decays detected in a single event was used to separate nuclear and electromagnetic cascades. The efficiency of separating the cascades turned out to be $\geqslant 99\%$. The energy spectrum of muons was determined in this experiment [41, 42] (based on the energy spectrum of electromagnetic showers) in the range of 1–30 TeV, and the cross section of photon-nucleon interaction was measured in [43] (by measuring the ratio $R(E)$ of the number of nuclear showers to that of electromagnetic ones) in the range of photon energies of 0.8–10 TeV in the laboratory system (this corresponds to the energy range in the center of inertia of the photon–nucleon system $\sqrt{s} = 40-130$ GeV).

The beginning of research into muon bundles was laid by Chudakov in paper [44]. As a result of studies on this subject, data were obtained about the character of changes in the energy spectrum and the composition of primary cosmic radiation in the energy range of $10^{15}-10^{17}$ eV [45]. A method of detecting muon bundles with a multiplicity > 1800 was suggested for BUST and realized in the experiment. This method uses calorimetric properties of BUST and allows avoiding limitations due to the spatial resolution of the telescope. In addition, the method makes it possible to study the muon component in the shower core, which is impossible to do when other methods of muon detection are used.

The method of conversion of the BUST muon multiplicity spectrum into the spectrum of the total number of muons in EAS was developed and realized [46–48]. Unlike the muon multiplicity spectrum, the latter is an objective (independent of the experiment and event selection criteria) characteristic of the flux of primary cosmic rays (PCRs). This method allows one to make a direct comparison of the data obtained in different experiments with muon bundles. The EAS spectrum of the total number of high-energy muons ($E > 220$ GeV) was obtained for the first time in the range $75 \leqslant n_{\mu} \leqslant 4000$, which corresponds to a PCR energy range of $10^{15}-10^{17}$ eV. These data give indications that the energy of the break in the PCR spectrum increases with growing nuclear charge. This means that the mass composition of PCR gradually becomes heavier in this energy range.

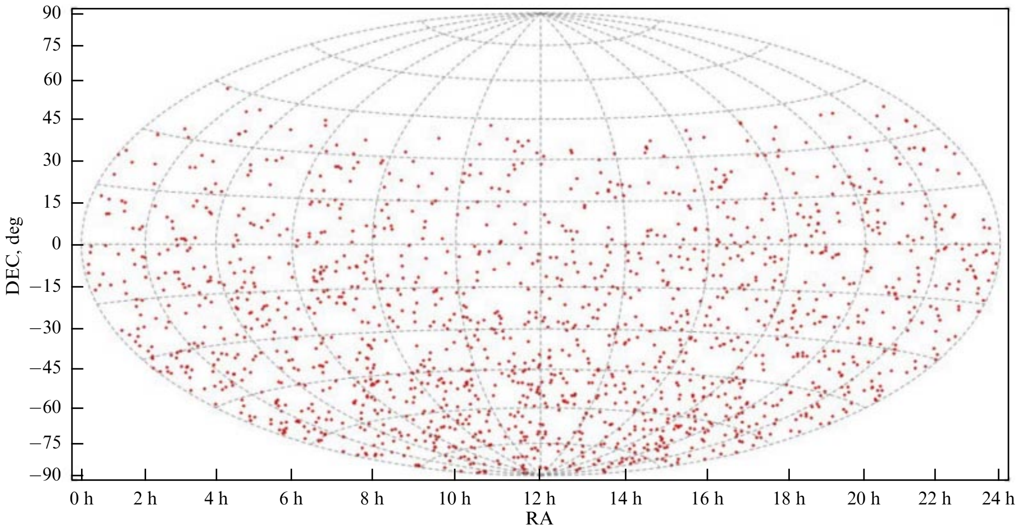

Figure 6. (Color online.) Arrival directions of neutrino events in equatorial coordinates. BUST data for 31 years of observation.

It should be noted that the principles of multitasking and the universality of BUST construction allowed successfully solving problems that did not exist when the telescope was designed and built. The problem of nucleon stability arising in the context of Grand Unification models is among them. For this experiment, some small constructive changes were made in the telescope in order to improve the anticoincidence shield of the inner planes. The lower limit of the proton lifetime obtained in paper [49] was equal to 1.25×10^{30} years (at a 90% confidence level) for all neutrinoless modes of decay. This result was a world best for some time. Another limit, for the flux of magnetic monopoles, maintained primacy for a much longer time. Theoretical work on the super heavy magnetic monopole first appeared at the beginning of the 1980s, and BUST turned out to be the most suitable instrument in the world to search for it. The first result on this topic was published in 1983 [50]. It remained the best in 1988 when the American–Italian collaboration MACRO (Monopole Astrophysics and Cosmic Ray Observatory) started at the Gran Sasso National Laboratory, a giant experiment whose main task was formulated in [51] in the following way: "Its principal goal was to observe magnetic monopoles or set significantly lower experimental flux limits than had been previously available in the velocity range from about $\beta = 10^{-4}$ to unity." This collaboration failed to "set significantly lower experimental flux limits." When in 2000 MACRO stopped functioning, it succeeded only in reaching the BUST limit (marginally exceeding it at certain monopole velocities) [52]. So, the result of BUST remained the best in the world for almost 20 years.

At the same time, BUST is still a neutrino detector, and not only for atmospheric neutrinos. The search for neutrinos from collapses in supernova explosions is one of the problems of neutrino astronomy, and this program was crowned with considerable success, when BUST appeared to be among the four detectors which recorded the signal from supernova SN1987A in the Large Magellanic Cloud [53]. The three others were LSD (Large Scintillation Detector) under Mont Blanc, IMB in the US, and Kamiokande (KII) in Japan. Observations on this program continue in the present time. Live time exposure is 34.9 years since 1980, and the upper limit on the frequency of collapses in the Galaxy according to BUST data is equal to 0.066 per year at a 90% confidence level [76]. This is the world-best constraint on the rate of collapses in our Galaxy.

9. Variations in cosmic rays during thunderstorms and anisotropy of cosmic rays

In the late 1970s, the Carpet array permanently observed so-called meteo effects: considerable variations in the counting rates during thunderstorms and rain. Such phenomena had been observed earlier, but they were interpreted as disturbances caused by sharp changes in pressure, wind velocity, and temperature. Chudakov initiated measurements of the near-ground electric field, and, in a series of pioneering experiments with his collaborator V G Sborshikov, the influence of the atmospheric electric field on cosmic ray intensity was proved [54–56]. After Sborshikov's early death, these experiments were interrupted, but they were restarted in 2000 at a new level [57–59]. The observations continue to date, and review paper [60] summarizes some results of the experiment that indicate several new physical effects associated with the dynamics of cosmic rays in the thunderstorm atmosphere. As an example, Fig. 7 shows a thunderstorm event on September 24, 2000 that demonstrates some specific features of the behavior of the electric field and secondary cosmic rays during the thunderstorm: a burst in intensity of the soft component (Fig. 7b), positive and negative disturbances of muon intensity with a duration of several minutes, and a long (about 1 h) suppression of the muon intensity (Fig. 7c)

Unfortunately, the most interesting results of this experiment were obtained only after Chudakov's passing, but, having remarkable intuition, he had in fact envisaged them. One can say that it was his favorite experiment, and Chudakov used to say as a joke that this experiment was the only real discovery made at Baksan. In general, he was always pleased with unusual results. For example, the fact that one can measure temperature in the stratosphere with an accuracy of tenths of a degree using muon flux deep underground always fascinated him. As for variations in cosmic rays during thunderstorms, his pioneering experiments gave birth to a whole direction of scientific research, to which the annual

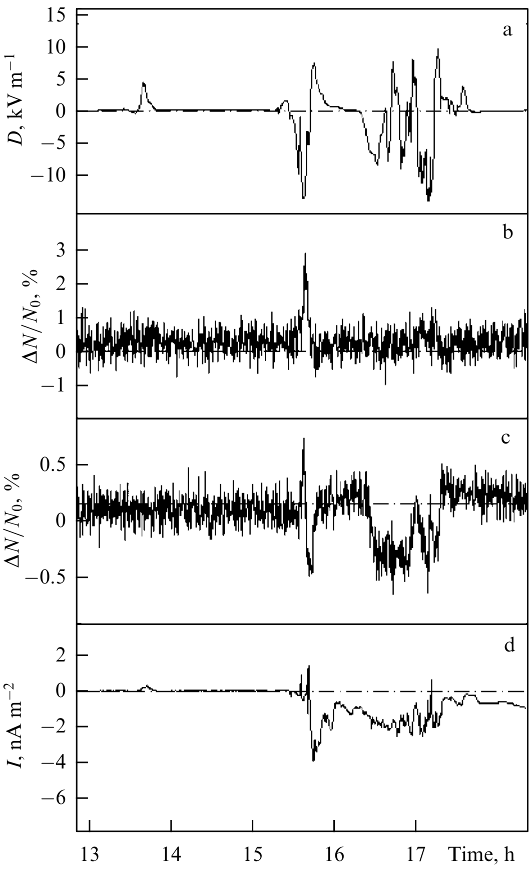

Figure 7. Thunderstorm on September 24, 2000 in the Baksan Valley: (a) near-ground electric field, (b) counting rate of soft CR component (electrons, positrons, and gamma rays, 10–30 MeV), (c) intensity of muons with a threshold of 100 MeV, (d) precipitation electric current.

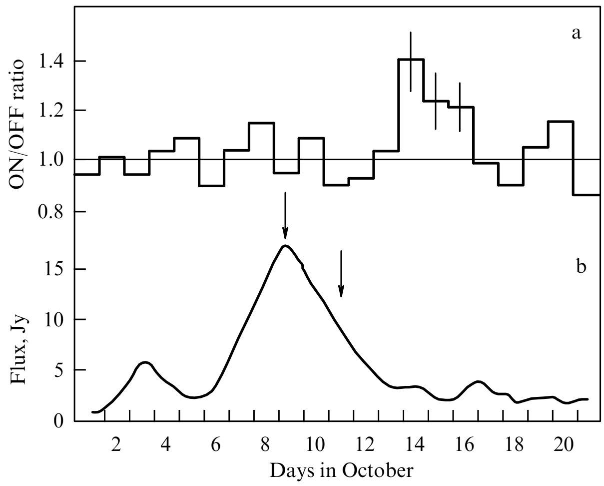

Figure 8. Burst of Cygnus X-3 source in October 1985 as observed by the Carpet array (a) and a strong radio flare preceding it (b). Arrows mark the maximum of radio emission and time of the gamma ray burst at 1 TeV detected by the Cherenkov gamma ray telescope Gulmarg in India.

workshops Thunderstorm Elementary Particle Acceleration (TEPA) were devoted before the beginning of pandemic constraints.

The anisotropy of cosmic rays was estimated by measuring the diurnal wave of intensity in sidereal time at three BNO facilities at energies of 2.5 TeV (BUST), 10 TeV (Carpet), and 100 TeV (Andyrchi) [61, 62]. In [63], based on the data of two of these arrays, the true direction of a CR anisotropy vector was reconstructed.

10. Gamma-ray astronomy of ultra-high energies

In the 1980s, Chudakov had to return to research on gamma-ray astronomy, but no longer the Cherenkov astronomy that he founded, and that came to be called very high energy (VHE) gamma ray astronomy. Unlike VHE, ultra-high energy (UHE) gamma ray astronomy is based on the detection of EASs by ground-based arrays of scintillation detectors. The obviously wrong (as it became clear much later) work by the Kiel University group that had announced the observation of a signal from the X-ray source Cygnus X-3 at an EAS energy higher than 10^{15} eV initiated a great number of papers, both experimental and theoretical, on ultra-high energy gamma ray astronomy. The Carpet array also took part in this campaign [64]. However, in general, this tumultuous activity ended in virtually nothing, with, perhaps, only one exception: possible bursts of ultra-high gamma rays detected from two sources. The results of experiments that recorded the permanent flux of emission from the Cygnus X-3 source (in addition to the above-mentioned Kiel group, the positive signals were registered by the Plateau Rosa and Haverah Park arrays) were disproved, as were others, by the Baksan experiment by the upper limits obtained for the flux value. But it is difficult to refute sporadic signals, especially when they have independent confirmations.

In October 1985, a signal from the angular cell of Cygnus X-3 exceeded the background value significantly for three successive days, and this was interpreted as a gamma ray burst [65]. It turned out that, several days before, a powerful burst of radio emission had been recorded from the source (the strongest in all the history of preceding observations). In addition, the Gulmarg Cherenkov telescope in India [66] observed a noticeable signal from Cygnus X-3 on October 10 and 12 (Fig. 8). Based on these data, V S Berezinsky built a theoretical model [67] that explained the different delays of gamma rays with energies 1 TeV (Gulmarg) and 100 TeV (Baksan) relative to the radio burst.

In paper [68], the Baksan group announced a possible burst in the Crab Nebula on February 23, 1989 at energies of about 100 TeV. The KGF (Kolar Gold Fields) in India confirmed this result [69], and, in summary paper [70], the data of two other groups were also presented (Tien-Shan and EAS-TOP in Italy) which confirmed the existence of the effect too, though with modest significance. After reducing the times of event detection to the Solar System barycenter, a phase analysis of data was performed at the frequency of pulsar PSR531 located in the center of the Crab Nebula. It was found that almost all excess could be constructed by a single bin (equal to 0.1 of the pulsar period) of the phase curve. These events are highlighted in black in Fig. 9, and they form three groups whose duration is approximately equal to their period of repetition (about 1 h).

The results of paper [70] were perceived with understandable distrust, since at that time a burst of gamma rays of such high energy (some hundred TeV) seemed to be too exotic, especially from a source which, though it had already been detected by Cherenkov telescopes in the TeV energy range, was believed to be a stability pattern (to such an extent that for many years it was considered to be a 'standard candle'

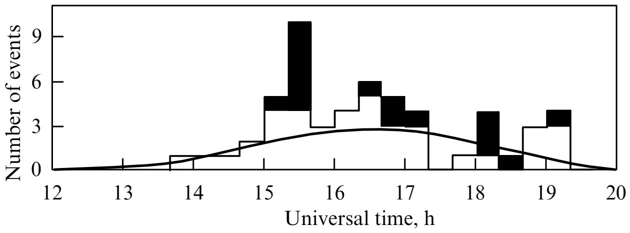

Figure 9. Number of events from an angular cell with a radius of 2.5° around the Crab Nebula on February 23, 1989. Curve represents expected background intensity. Events from one bin (0.1 periods of the PSR531 pulsar at the nebula center) on the phase diagram are colored in black.

both in X-ray and gamma-ray astronomy). However, many years later, gamma ray bursts in the Crab Nebula were detected by the satellite gamma ray telescopes AGILE (Astro-rivelatore Gamma a Immagini LEggero) and Fermi LAT (Large Area Telescope) in the energy range of several hundred MeV. One of these bursts, detected by AGILE [72], as was shown in paper [71], had absolutely the same time structure as the February 23, 1989 burst (taking the scale factor into account: days instead of hours). This compels us to take this burst very seriously: after all, this is the signal from a celestial source at an energy which is a record high for gamma-ray astronomy.

11. Conclusion

Ideas and suggestions generated by Chudakov continue to be implemented in many modern experiments. Some facilities planned and constructed under his leadership are still in operation. The project Carpet-3, now being developed on the basis of the Carpet array, was mentioned above. BUST continues monitoring possible neutrino bursts from stellar collapses in the Galaxy [76]. Alerts about candidates for neutrino burst events are not only sent to all employees via mobile phones and e-mail, but should be communicated to the global collapse net SNEWS. At the moment, in connection with the transition to a new format (SNEWS 2.0), communication with SNEWS 2.0 is under testing.

Among the results obtained at BNO after Chudakov passed away, in addition to the cosmic-ray variations during thunderstorms mentioned above, let us point out measurements of the spectrum of high-energy (100 TeV) muons by the method of multiple interactions [37]. And, as before, the BNO facilities are ready to solve unexpectedly arising new problems. Starting from the end of the 1990s until now, the problem of dark matter has stirred great interest in the world. Here, again, BUST appears to be a quite competitive detector [73], though nothing of this kind was in foreseen when it was designed. In [74], the upper limits on the rate of annihilation of the neutralino (hypothetical particle of cold dark matter) in the bowels of the Sun and Earth were obtained. Currently, estimates of the cross section of WIMP (Weakly Interacting Massive Particle) scattering by protons, made on the basis of BUST data, are at the level of the better limits provided by other experiments [75]. The combination of two BNO data channels, a neutrino telescope (BUST) and detector of ultra-high energy gamma rays (Carpet), is naturally included in the tendency of modern astronomy to multi-messenger observations. The events recorded by them are checked for coincidences with alerts from other satellite and ground-based observatories, such as Swift BAT (Burst Alert Telescope), Fermi-GBM (Gamma-ray Burst Monitor), Fermi-LAT, INTEGRAL (INTErnational Gamma-Ray Astrophysics Laboratory), IceCube, and HAWC (High Altitude Water Cherenkov observatory). An excess of Carpet photon-like events discovered recently to coincide with one of the neutrino events of the IceCube telescope is a very promising result [77].

I would like to conclude this paper devoted to the memory and centenary of the birth of a remarkable scientist who was our contemporary with a characteristic of true scientists (Alexander Chudakov, in my opinion, was one of them) given by a recognized genius.

"Many kinds of men devote themselves to Science, and not all for the sake of Science herself. There are some who come into her temple because it offers them the opportunity to display their particular talents. To this class of men science is a kind of sport in the practice of which they exult, just as an athlete exults in the exercise of his muscular prowess. There is another class of men who come into the temple to make an offering of their brain pulp in the hope of securing a profitable return. These men are scientists only by the chance of some circumstance which offered itself when making a choice of career. If the attending circumstance had been different they might have become politicians or captains of business. Should an angel of God descend and drive from the Temple of Science all those who belong to the categories I have mentioned, I fear the temple would be nearly emptied. But a few worshipers would still remain — some from former times and some from ours....

I am quite aware that this clearance would mean the driving away of many worthy people who have built a great portion, and even perhaps the greatest portion, of the Temple of Science. But at the same time it is clear that if the men who have devoted themselves to science consisted only of the two categories I have mentioned, the edifice could never have grown to its present proud dimensions, no more than a forest could grow if it consisted only of creepers." (Albert Einstein, Prologue to Max Planck's book *Where is Science Going*?) [78].

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