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G T Zatsepin and the birth of gamma-ray astronomy

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Contents

Abstract. The centenary of G T Zatsepin, a well-recognized authority on cosmic ray physics and nuclear and neutrino astrophysics, offers an opportunity both to look back on the work he is well known for and to take a look at some of his lesser-known ideas, even to specialists. One example is his pioneering proposal to employ the Cherenkov emission from electromagnetic cascades in the upper atmosphere as a tool to search for local gamma-ray sources on the celestial sphere. First published by G T Zatsepin and A E Chudakov in 1961, the idea was immediately put into practice by the latter in constructing the world's first gamma-ray telescope in the Crimea. Zatsepin and Chudakov's method is still today the basis for very high-energy gamma-ray astronomy, with the number of discovered sources approaching two hundred. New grandiose projects that are currently underway in this rapidly developing field of astronomy hold promise for an order of magnitude increase in the sensitivity of the method.

Keywords: very high-energy gamma-ray astronomy, extensive air showers, Cherenkov radiation

1. Historical myths in gamma-ray astronomy

Wikipedia, a popular information source, tells readers in the 'Gamma-ray astronomy' article in the 'Early history' section, [1] (after mentioning some theoretical studies, of which the main one is P Morrison's program paper [2]) that "The first gamma-ray telescope carried into orbit, on the Explorer 11 satellite in 1961, picked up fewer than 100 cosmic gamma-ray photons. They appeared to come from all directions in the Universe, implying some sort of uniform 'gamma-ray background'."

At the same time, one can learn from the 'Detector technology' section of the same article that "high-energy photons produce extensive showers of secondary particles in the atmosphere that can be observed on the ground, both directly by radiation counters and optically via the Cherenkov light which the ultrarelativistic shower particles emit." And further: "Gamma radiation in the TeV range emanating from the Crab Nebula was first detected in 1989 by the Fred Lawrence Whipple Observatory at Mt. Hopkins, in Arizona in the USA."

In principle, all the quoted facts are true; however, the picture they present is at least incomplete and, as a matter of fact, grossly distorts reality.

The early stage of gamma-ray astronomy is distorted even more strongly than in the 'pop history' in a compilation of NASA's High Energy Astrophysics Science Archive Research Center (HEASARC), a report on high-energy astrophysics titled "A history of gamma-ray astronomy including related discoveries" [3]. This paper by Leonard and Gehrels, which looks like a serious study, represents the sequence of events at the initial stage of gamma-ray astronomy as follows:

"1959 — Cocconi proposes to search for cosmic sources of very high-energy gamma rays via the ground-based air-shower technique;

1960 — Chudakov et al. of the Lebedev Institute follow up on Cocconi's suggestion and start a search for air showers from very high-energy gamma rays at a site in the Crimea. The experiment runs for several years, but no clear detections are made.

1968 — The first purpose-built atmospheric Cherenkov gamma-ray telescope is constructed in Arizona at the Mount Hopkins Observatory (later renamed the Whipple Observatory). This 10-m telescope is still in operation."

In this version of history, everything is wrong except two facts: Guiseppe Cocconi actually delivered a report [4] at a cosmic ray conference in Moscow in 1959, and the atmospheric Cherenkov gamma-ray telescope in Arizona was built. However, first, it was actually completed in 1977, while in 1968 activities at the Whipple Observatory had only started. The first observations were made there using two movable small-size mirrors. Even after a 10-meter mirror had been produced, studies that involved focal-plane imaging commenced in full as late as 1984, and reliable registration

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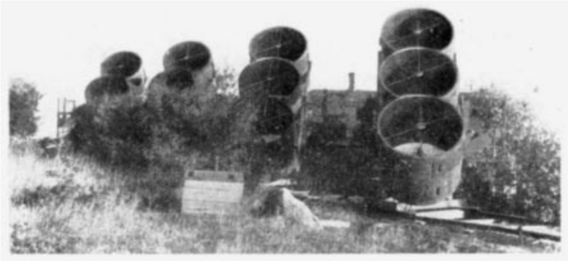


Figure 1. First Cherenkov gamma-ray telescope (and gamma-ray telescope in general), built by A E Chudakov and collaborators in the Crimea.

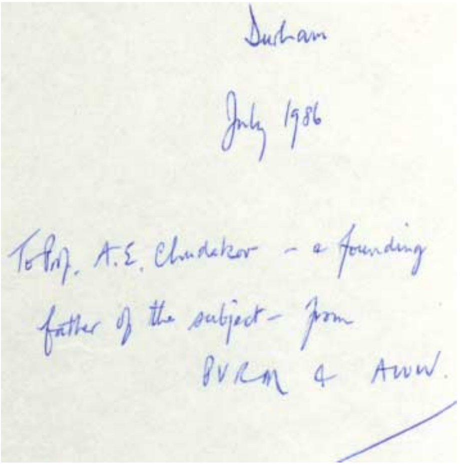
of the signal from the Crab Nebula occurred no earlier than 1989, as Wikipedia correctly notes.

Second, Cocconi proposed registering events not on the ground but using a high-altitude mountain-based array of scintillation counters. This means a transition from the energy region characteristic of extensive air showers to significantly lower energies and, respectively, to much higher event counting rates. Cocconi also estimated the strength of the signals expected from some sources, including the Crab Nebula (it was found later that he was mistaken by three orders of magnitude).

Third, Chudakov's facility in the Crimea [5] was by no means a development of Cocconi's idea, but rather its opposite. It is this facility that actually was "the first purpose-built atmospheric Cherenkov gamma-ray telescope" (Fig. 1) rather than the Arizona telescope. Moreover, the latter was not even the second telescope of this kind. Number two was a small two-mirror telescope built in Dublin in 1964, when Chudakov's experiment had been completed long before (1963). Later on, there were more attempts to conduct observations using small-size telescopes (see Section 3). However, even after the first next-generation large-mirror telescope had been completed (i.e., the 10-meter telescope in Arizona, and it would be reasonable to refer to it in this way), several years of observations were needed to obtain the first statistically reliable results. Wikipedia's statement "Gamma radiation in the TeV range emanating from the Crab Nebula was first detected in 1989" means that by that time the accumulated excess of data over background was nine standard deviations [6]. By that time, the Mount Hopkins laboratory experiment had been carried out for 21 years. Given this context, the statement referring to Chudakov's telescope ("the experiment runs for several years, but no clear detections are made") then sounds quite different.

2. Chudakov's Crimea telescope and the results obtained

Chudakov's experiment was, simply speaking, much ahead of its time. It would be sufficient to say that many types of objects that were discovered later as very high-energy gamma-radiation sources had not been known at that time. For example, pulsars were only discovered five years after Chudakov's experiment ended. Chudakov and his collaborators primarily considered radio galaxies as promising objects for observations. Unfortunately, due to a confluence of unfortunate circumstances, at the first observation sessions one such galaxy (Cygnus A) yielded some excess over background. Due to this, an unreasonably long time was spent to observe specifically this object. Eventually, no significant signals were detected. However, even the upper limits for TeV gamma-radiation fluxes set as a result of those observations were of importance. In particular, Chudakov's experiment evidenced for the Crab Nebula that electrons are directly accelerated in the source. However, the fact of utmost importance is that, contrary to the statement made in Ref. [3], Chudakov's Crimea facility was actually the first Cherenkov telescope. Moreover, it was just the first device designed especially for gamma-ray astronomy. It is for this reason that Sir Arnold Wolfendale, the former British Astronomer Royal, wrote on a gift copy of *Gamma-Ray Astronomy*, a book he published in collaboration with Ramana Murthy, an Indian physicist, the following words: "To Professor A E Chudakov, a founding father of the subject' (Fig. 2).



Durham
July 1986
To Prof. A.E. Chudakov – a founding
father of the subject – from
PVRM & AWW.

Figure 2. Inscription in *Gamma-Ray Astronomy*, a book by P V Ramana Murthy and A W Wolfendale: "To Professor A E Chudakov, a founding father of the subject — from PVRM and AWW."

3. True history of gamma-ray astronomy and G T Zatsepin's role

Leonard and Gehrels were correct when calling Cocconi's report at the *International Cosmic Rays Conference, Moscow, 1959* a historical landmark. It was the report that prompted G T Zatsepin to advance further. As was stated in Section 1, Cocconi's idea was to reduce the energy threshold for primary-particle showers owing to a significant increase in the shower registration altitude. Zatsepin's idea was to increase much more radically the detection level moving it to the upper atmospheric strata where relativistic charged particles from low-energy showers generate Cherenkov radiation that may be registered on moonless and cloudless nights on the ground. The reduction in the observation time (in those locations on the globe that are the most favorable for such observations, it is not over 10% of calendar time) is more than compensated by an increase in the count rate owing to the reduced energy threshold. It was specifically this idea that Zatsepin presented to Chudakov. The addressee was chosen correctly. By that time, Chudakov was a renowned specialist in studies of the Cherenkov radiation from extensive air showers (EASs) of cosmic rays. The experiments conducted in the Pamir Mountains were really pioneering steps of that method.

After Galbraith and Jelley [8] registered for the first time EAS Cherenkov radiation in 1952, Chudakov almost immediately started exploring this phenomenon in the Pamir

Mountains. While the discoverers used a very primitive facility (a mirror 25 cm in diameter and a 5-centimeter photomultiplier placed in a blackened dust bin), Chudakov's experiment [9] was large-scale and thorough. Eight Cherenkov detectors were located at a distance of up to 100 m from the center of the facility (versions with and without mirrors were implemented). Energy spectra of cosmic rays were obtained for the first time using the Cherenkov method, and the spatial distribution of Cherenkov light in showers was studied. Notice that, in preparing the Pamir experiment, Chudakov observed for the first time the transition radiation predicted by V L Ginzburg and I M Frank in 1945. He was also the first to come to the idea that the atmospheric ionization luminescence generated by EASs may be used as a new method for observing the showers. (The first detector of that type, the Fly's Eye, was created in 1981; currently, fluorescent detectors are used in all major ground facilities for detecting EASs. Projects that use this method on board spacecraft are now under implementation.)

Chudakov immediately supported Zatsepin's idea, and they published a paper [10] in which they proposed a new method for registering ultrahigh-energy cosmic gamma-quanta. Concurrently, Chudakov commenced activities in the Crimea to implement without delay Zatsepin's idea. The speed with which it was done is really striking. By the time paper [10] was published in 1961, observations had been conducted (in 1960) using the first phase of a Cherenkov telescope consisting of four mirrors. The following year, the telescope was fully equipped with 12 mirrors 1.5 m in diameter; with this setup, observations were made from 1961 through 1963. Thus, Chudakov is actually the founding father of gamma-ray astronomy, but since paper [10] was published by two authors, there were two founding fathers. A E Chudakov, being a person very delicate on issues of scientific priority, always stressed in private conversations that the original idea belonged to G T Zatsepin. It is noteworthy that for the latter this was nothing but a brief episode in his multifaceted scientific activity. Everything was done as if in passing... .

4. Progress in and current state of the Cherenkov method and very high-energy gamma-ray astronomy

By 1989 [6], the Cherenkov method could be 'proud' of one reliably established gamma-ray source (the Crab Nebula). In 1992, the first extragalactic source was unambiguously observed (Mrk 421). By 2003, ten galactic and eight extragalactic sources were already known [11]. Currently, the total number of gamma-ray sources detected using the Cherenkov method is close to 200, and this number keeps growing.

Trevor Weekes, who was the first to successfully use the 10-meter mirror in Arizona, categorized Chudakov's telescope as the first-generation telescope (1965–1980), with or without weak background discrimination. Weekes also included in that category the Dublin telescope mentioned in Section 1 and small telescopes operated by the Whipple Observatory and Narrabri Observatory (Australia). Weekes included in the second generation (1985–2003) the large telescope of the Whipple Observatory, the Crimea-based A A Stepanyan GT48 telescope, the CAT (Cherenkov Array at Themis) telescope in the French Pyrenees, the HEGRA (High Energy Gamma Ray Astronomy) experiment based in the Canary Islands, the Mark telescope operated by Durham University (England), and the first version of the Australia-based CANGAROO (Collaboration of Australia and Nippon for a Gamma Ray Observatory in the Outback) telescope. The third generation of telescopes (2003–present) comprises the Namibia-based HESS (High Energy Stereoscopic System), MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov telescope) based in the Canary Islands, VERITAS (Very Energetic Radiation Imaging Telescope Array System) in Arizona, and CANGAROO III in Australia. It is owing to these telescopes, all of which (except the last one) are currently operating, that the number of discovered sources has sharply increased. MAGIC has a mirror with the largest diameter (17 m); however, HESS is the leader in the number of discovered sources and, therefore, may be considered the most successful project. One should take into account, however, that HESS is located in the Southern Hemisphere, where the central part of the galactic disc with the highest density of galactic sources is observed. This was the reason for the new project CTA (Cherenkov Telescope Array), which is discussed below, to be designed in a nonsymmetric setup: its southern part will be much larger than the northern one.

The generation-based classification of telescopes quoted above is not quite complete (a more comprehensive list may be found, for example, in paper [12]). The essential feature of this classification is that it reflects changes in methodology. The second-generation telescopes have a large-diameter mirror with a mosaic consisting of a large number of photoelectron multipliers (PMs) located in the focus. The Cherenkov radiation of showers from primary gamma-quanta and protons yields different images of the showers on that mosaic, this circumstance being used in selecting events to suppress background. Those are the telescopes based on imaging technique. Actually, Chudakov was a pioneer in this technique as well: he used in his experiments several PM tubes located in the focus of a mirror. However, this was nothing more than an approach to the technique. T Weekes started with 37 PM tubes. Currently, photodetectors used for imaging contain hundreds or even thousands of pixels. The third-generation telescopes are designed as systems consisting of several large-diameter mirrors (a VERITAS-system telescope is shown as an example in Fig. 3) separated by large distances to enable stereoscopic observations. Notice that the mirrors featuring very large diameters are usually assembled

Figure 3. A VERITAS array reflector: a typical third-generation Cherenkov telescope.

from individual standard elements, flat polygons or small spherical mirrors, as is the case shown in Fig. 3 (a Davies–Cotton reflector). During the time period under consideration, progress in the technique consisted of continuous growth in the diameters of mirrors (to a lower energy threshold and enhanced sensitivity) and an increase in their number, growth in the field of view, and enhancement of the angular resolution of the telescopes.

An interesting avenue in the Cherenkov gamma-ray astronomy technique concerns with the employment of solar power plants as gamma-ray telescopes. During daytime, multiple mirrors of those plants follow the Sun and focus solar light on a solar tower. At night, photodetectors can be installed on the tower and the mirror control system may be used for monitoring different sources. Experiments of that kind have been conducted at solar power plants, for example, STACEE (Solar Tower Atmospheric Cherenkov Effect Experiment) in New Mexico and Solar II in Barstow, CA; it is worth mentioning as well the experiments CELESTE (ChErenkov Low Energy Sampling and Timing Experiment) in France and GRAAL in Spain. However, this method failed to yield any significant results, so that the solar power plants cannot compete with dedicated telescopes.

5. Prospects and new projects

It is expected that the sensitivity of planned Cherenkov telescopes of the next (fourth) generation will be an order of magnitude higher than that of existing telescopes. The major and most advanced project in this area is CTA [3]. It is noteworthy that two of the four third-generation telescopes (VERITAS and MAGIC) are located in the Northern Hemisphere, and two (HESS and CANGAROO III) in the Southern Hemisphere. This configuration enables the sky to be completely scanned. In CTA, within the same project, two arrays of Cherenkov telescopes will be concurrently deployed in the Northern and Southern Hemispheres. Their location has for a long time been a subject of discussions, but in 2017 it was finally decided that the northern part of CTA will be located in the Canary Islands and its southern part in the Atacama Desert (Chile). The CTA's northern and southern parts significantly differ: 19 telescopes will be deployed in an area of 0.5 km^2 in the Canary Islands (energy range from 20 GeV to 20 TeV), and 99 telescopes will be deployed in an area of over 4 km^2 in Chile (energy range from 20 GeV to 300 TeV). In the project, mirrors of different sizes will be used (the largest mirrors are 23 m in diameter). Mirrors for the project have already been manufactured, and the first telescopes are under testing in Europe. Infrastructure work at the locations of future observatories is already in progress.

However, it is not only Cherenkov telescopes that are currently under design for very high-energy gamma-ray astronomy. Figure 4 shows the HAWC (High Altitude Water Cherenkov) observatory operated in Mexico [4]. It represents both a Cherenkov array and a gamma-ray telescope; however, it is quite different from the facilities described above. Consisting of water Cherenkov detectors (each water tank is 7.3 m in diameter and 4.5 m high), it detects charged EAS particles at a rather high observation level (4100 m above sea level). Notice that this is the implementation, in its purest form, of Cocconi's idea on which Zatsepin's approach was based. In this way, the history of gamma-ray astronomy shows that, like any other history, it develops on a helix. The old idea being recalled became possible because some countries do not hold back money to finance major projects (Fig. 4 shows the large scale of the facility, allowing one to easily guess what the cost of deploying this facility in the mountains was). However, the HAWC observatory is not the first shower facility whose program involves studies in gamma-ray astronomy. An older facility, Tibet-ASγ (where AS is the abbreviation for air showers), combines in its name both atmospheric showers and gamma-radiation. A future facility of the LHAASO (Large High Altitude Air Showers Observatory) project [15] that is currently under development in China, will be the largest device of that type. High count rate (high statistical accuracy) and significantly improved angular accuracy will make it possible to detect point-like sources (gamma-radiation) against a uniform background of isotropically distributed cosmic rays (protons and nuclei). In order to detect diffuse gamma-ray radiation of space origin, proton and gamma-ray showers are to be separated. In relation to this, methods like the detection of muon-poor showers (the Kover 3 project currently being implemented by the Baksan Neutrino Observatory of the Institute for Nuclear Research, Russian Academy of Sciences [16]) are regaining importance. Wherever this selection is possible, imaging Cherenkov telescopes are included as a component of larger hybrid projects like TAIGA-HiSCORE (Tunka Advanced Instrument for cosmic ray and Gamma Astronomy–Hundred Square km Cosmic ORigin Explorer) in the Tunka valley [17]. However, the advantage of Cherenkov telescopes lies not only in utilizing the imaging technique. They are still beyond competition at low-energy thresholds. By now, the energy threshold for registering gamma-quanta of the best Cherenkov-method-based facilities comes close to 20 GeV. This means that the energy ranges of satellite- and ground-based gamma-ray telescopes are already overlapping to a significant extent.

Thus, despite progress in other methods of ground-based observations of cosmic gamma-quanta, the Cherenkov method is maintaining its importance and is developing very successfully. In addition to the aforementioned CTA project, which is now being actively developed, it is noteworthy that the HESS collaboration has recently built a telescope with a mirror 28 meters in diameter (HESS II), in addition to the already existing four telescopes. The ALEGRO (Atmospheric Low Energy Gamma-Ray Observatory) project [12], which has been elaborated in detail but has not yet obtained

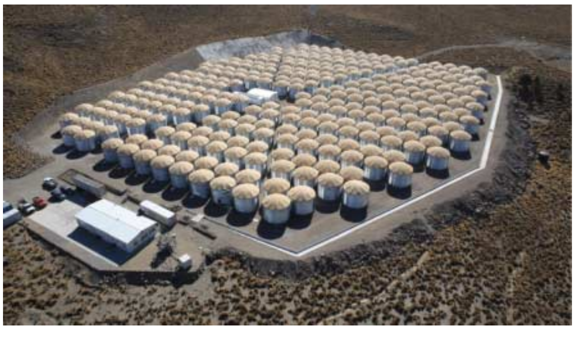


Figure 4. HAWC facility near Pueblo, Mexico located at an altitude of 4,100 m above sea level (Sierra Negro volcano). Individual detectors are water-filled tanks for registering Cherenkov radiation of EAS particles. It is essentially an implementation of Cocconi's idea dated 1959 [4].

Figure 5. View of an optical system with two mirrors (the Schwarzschild–Couder telescope) designed for the AGIS project.

financing, also belongs to the next generation, like the AGIS (Advanced Gamma-ray Imaging System) project [18], which has been at the discussion stage for quite a long time. An interesting feature of that project is an attempt to employ more complex optics, in addition to simple mirrors, for individual telescopes. Similar to CTA, telescopes will be used in the AGIS project that have mirrors of various diameters. Larger-diameter mirrors (18 to 20 m) will be used in Davies-Cotton reflectors, while mirrors 7 or 12 meters in diameter (the final selection seems not to have been made yet), combined with smaller-diameter mirrors, will be exploited in the Schwarzschild–Couder telescope (Fig. 5). In total, 50 to 100 such telescopes will be located on a site about 1 km^2 in area. The recording camera of each telescope will consist of 5,000 to 10,000 pixels. The list of candidates to host the observatory includes Chile, Argentina, and Mexico. Active cooperation with CTA project facilities is planned.

The ALEGRO project is also of interest because mirrors of larger diameter (about 30 m) will be installed at high altitudes. The creators of the project intend to additionally reduce in this way the energy threshold, lowering it to a value of about 5 GeV. The very idea of locating Cherenkov mirrors at high altitudes has already been implemented in an Indian project MACE (Major Atmospheric Cherenkov Experiment) [19]. This project stands somewhat apart from next-generation telescopes, since it has only one mirror 21 meters in diameter (currently the world's second largest), which is installed at an altitude of 4,270 m above sea level.

There are also other projects that are still at the discussion stage. However, although not all of the aforementioned projects will be implemented, it is clear that the method proposed by Zatsepin and Chudakov has created a new and fairly independent area of astronomy. The start of the method was not easy (the first positive results were only obtained many years after the pioneering experiments), but now it is developing in a very dynamic way. This method is of special interest for astrophysics, since it enables studying the objects that generate fluxes of the most energetic nonthermal radiation in the Universe. Among those objects belonging to the TeV range, about 20% are unidentified sources and about 40% are each galactic and extragalactic sources. A full list of the sources may be found in the TeVCat online catalog (http://tevcat.uchicago.edu). The types and features of those sources are beyond the subject of this paper, which is devoted to the method and its evolution.

Unfortunately, many present-day researchers working in this area are virtually unaware of the pioneers of the science and founders of the method. No more than 20 years ago, when the number of discovered sources was quite small, a detailed review on Cherenkov gamma-ray astronomy was published [20]. The review contained about 400 references to publications; however, the names of Chudakov and Zatsepin were not mentioned. This complete oblivion is sometimes combined with a twisting of the historical picture, as discussed at the beginning of this article. The goal of this publication consists in paying tribute to prominent scientists: to restore, at least to some extent, justice and fill in the gap in the knowledge of present-day scientists about the history of gamma-ray astronomy.

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