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Advances in Space Research xxx (xxxx) xxx

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Aragats high-altitude research station – 80 years of continuous cosmic ray monitoring ☆

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Received 3 March 2025; received in revised form 28 April 2025; accepted 30 April 2025

Abstract

The Cosmic Ray Division (CRD) of the Yerevan Physics Institute is a premier center for high-energy astrophysics, space weather research, and atmospheric physics. Operating at an altitude of 3,200 m, the Aragats Research Station provides a unique environment for continuously monitoring cosmic and atmospheric radiation. The SEVAN (Space Environment Viewing and Analysis Network) particle detector array stretches from Aragats to mountain peaks throughout Eastern Europe and Germany, promoting studies in solar physics, geophysics, and cosmic-ray interactions with Earth's atmosphere.

CRD has significantly contributed to high-energy astrophysics, enhancing our understanding of galactic cosmic rays (GCR origin and acceleration mechanisms) and detecting the highest-energy solar protons. The division has also been instrumental in identifying Thunderstorm Ground Enhancements (TGEs) and their connection to atmospheric electric fields, linking cosmic ray physics with atmospheric electricity.

Beyond traditional cosmic ray studies, CRD has pioneered AI-driven data analysis techniques that enhance gamma-ray purification in atmospheric Cherenkov imaging and reconstruct the primary cosmic-ray composition in extensive air shower experiments. Integrating machine learning, multivariate analysis, and real-time monitoring has significantly improved the accuracy of cosmic ray and space weather models.

With 80 years of continuous operation, Aragats is one of the world's longest-running cosmic ray monitoring stations. It plays a vital role in interdisciplinary research at the intersection of astrophysics, geophysics, and atmospheric science.

Keywords: Solar Physics; High-energy astrophysics; Atmospheric Physics; Thunderstorm Ground Enhancements (TGEs); Cosmic ray physics; Space weather research

1. Introduction

The Aragats Cosmic Ray Station, established in 1943 during the challenges of World War II, has been at the forefront of particle and cosmic ray physics. Located at an altitude of 3,200 m, the station sits beneath the south peak of Mt. Aragats, approximately 100 km from the biblical Mt. Ararat (Fig. 1). The Aragats northern summit, reaching 4,090 m, overlooks a vast volcanic crater formed by an eruption approximately 1.5 million years ago, covering half of Armenia with tuff and basalt. The research station is located on a high-altitude plateau, adjacent to the frigid Kari Lake at 40.4713 N and 44.1819E.

Research on cosmic rays at Aragats began in 1934 when an expedition from the Leningrad Physical-Technical Institute, with support from Norair Kocharian of Yerevan State University (Kocharian et al., 1940; 1957), studied

☆ This article is part of a special issue entitled: 'Astrophysics of cosmic rays' published in Advances in Space Research.

https://doi.org/10.1016/j.asr.2025.04.080
0273-1177/

Please cite this article as: Z. Asaturyan and A. Chilingarian, Aragats high-altitude research station – 80 years of continuous cosmic ray monitoring, Advances in Space Research, https://doi.org/10.1016/j.asr.2025.04.080

Fig. 1. Aragats Research Station. Ararat Mountain is in the background.

East-West cosmic ray anisotropy. The results sparked the interest of Artem and Abraham Alikhanyan, leading them to organize an expedition to Aragats in 1942. Despite the difficulties of war, economic hardships, and technological limitations, cosmic ray research at Aragats has continued uninterrupted for 80 years, overcoming funding shortages, electricity crises, and regional conflicts.

From its early years, the Aragats station pioneered cosmic ray research, unveiling fundamental insights into the nature of high-energy particles and their interactions. The study of cosmic rays opened a window into the universe's deepest mysteries and laid the foundation for new areas of physics. Today, Aragats contributes to high-energy astrophysics, solar physics, and space weather research, broadening our understanding of galactic and solar cosmic rays, atmospheric electricity, and thunderstorm-related particle acceleration. With its long history and ongoing technological advancements, the Aragats station remains a key observatory for cosmic ray studies, bridging the gap between historical discoveries and modern space science.

2. Detection and spectrometry of cosmic ray species

Research at Mt. Aragats has progressed through distinct phases throughout its history. The initial phase, known as the mass-spectrometric era**,** lasted about 15 years and is detailed in Chilingarian et al. (2009a). During this foundational period, the Alikhanyan brothers developed a mass spectrometer to measure the momentum and absorption length of charged particles, which facilitated effective mass analysis and led to the Identification of protons within the cosmic ray flux (Alikhanyan et al., 1945).

Furthermore, this method provided some of the earliest indications of particles with masses between the muon and the proton. While not all observed peaks in the mass distributions were later confirmed as genuine particles, a few were identified as K-mesons and π-mesons**.** The discussion surrounding intermediate-mass particles**,** referred to as "varitrons" (Alikhanyan and Alikhanov, 1951), inspired numerous experimental and theoretical studies. This debate attracted global interest in elementary particle physics and helped establish the Aragats station as a key research hub for cosmic ray studies.

Even today, distinguishing real particle peaks in one- and two-dimensional distributions remains a demanding task in high-energy physics. Despite advancements in mathematical techniques, precise identification requires sophisticated data analysis and experimental validation (Chilingarian, 2023).

The years from 1958 to 1970 witnessed significant advancements in the calorimetric measurement of cosmic rays (CR). In 1958, Naum Grigorov and his team from the Institute of Nuclear Physics at Moscow State University, along with physicists from the Yerevan Physics Institute, installed a pioneering ionization calorimeter at the

Aragats station (Grigorov et al., 1958). Their work shed light on the energy dependence of hadron-nuclei inelastic cross-sections, a finding later confirmed by direct measurements in experiments on Proton satellites and through accelerator experiments (Grigorov et al., 1970).

Further enhancements came in 1968–69 with the execution of two pivotal experiments. PION, led by Vahram Avakyan (Alikhanyan et al., 1974), measured the vertical fluxes of cosmic ray hadrons, while MUON, led by Tina Asatiani (Asatiani et al., 1980), focused on measuring fluxes of horizontal muons. PION experiment used a transition radiation detector for particle identification, developed by Albert Oganesian's group. Experiment results in measuring the cross sections of proton, pion, and neutron inelastic interactions with lead and carbon nuclei at energies between 0.5 and 5.0 TeV. The muon magnetic spectrometer's coordinate measuring system, including wire and wide-gap spark chambers, provided the maximum measurable momentum of 2.5 TeV. These experiments were the first to use the soviet computers, M220, and Armenia's minicomputer, NAIRI-2, for data acquisitions and analysis.

The 1970s marked the beginning of solar physics research at Aragats. Under Khachik Babayan's direction, neutron monitors of type 18HM64 were installed at both the Aragats and Nor-Amberd research stations. These installations laid the groundwork for further research in solar physics and space weather in its new history.

3. Development of the multivariate nonparametric analysis methods

In the 1980s, a groundbreaking AI-based nonparametric multivariate data analysis methodology was developed to address the CR inverse problem: deducing primary particle types and energies from diffuse, smeared EAS data (Chilingarian, 1989; Chilingarian and Zazyan, 1991a, 1991b; Chilingaryan, 1994).

The optimal solutions in astrophysics are sought through simulations of physical processes and experimental methods. As representatives of alternative hypotheses (i.e., types of primary nuclei, atmospheric electric fields, images in the matrices of photodetectors, etc.), simulated datasets form a theoretical basis for comparisons with experimental data. As we deal with multivariate distributions with a high level of statistical variability, it isn't easy to find an appropriate family of analytic functions that correctly describe the alternative hypothesis. In cosmic ray and accelerator physics, very sophisticated models mimic a stochastic mechanism through which data are generated. These models provide us with a wide range of outcomes from input variable sets, known as "labeled" or "training" samples. These events with known membership represent the general nonparametric mode of *a priori* information. To draw reliable and significant conclusions about the investigated physical phenomenon, a unified theory of statistical inference based on nonparametric models was developed at CRD (Monte-Carlo Statistical Inference, MCSI, Chilingarian, 2004). Two statistical approaches, Bayesian decision-making and neural network models, were coherently employed and compared within the developed theoretical scheme. The key points in MSCI are feature selection, which involves reducing the multivariate measurements metric space; nonparametric density estimation modes that offer the fastest convergence to the theoretically achievable Bayesian limit; and fast, random-search-based neural network training methods. The collection of multivariate nonparametric methods was implemented in the ANI software package (ANI, 2025). The first version of ANI software was developed in the early 80 s and has been continually enhanced and used extensively in the cosmic ray physics community since then.

In the ANI package, traditional nonparametric models, such as the Parzen window and K Nearest Neighbor (KNN), were modified to ensure uniform choices of method parameters across the entire distribution support range (Chilingarian, 1989). The resulting median estimate method provides better estimates than those obtained with any fixed value, such as the size of the Parzen window or the number of nearest neighbors. The ANI Neural Network toolbox uses the stochastic learning paradigm to offer various training scenarios. It employs evolutionary algorithms that consist of random variations and survival-of-the-fittest principles to solve optimization problems. The search for "good" solutions occurs in the weight space of feed-forward neural networks, implementing different modifications of evolutionary algorithms. The network's performance is continuously monitored during training, allowing for the formulation of stopping rules to avoid overtraining.

The ANI package was initially employed to estimate the upper limit of the iron nuclei fraction based on the γ-family characteristics observed in the PAMIR experiment. Our results supported the normal composition hypothesis and refuted the idea of iron nuclei dominance in PCR at energies greater than 10 PeV.

Then, it enabled the derivation of partial energy spectra for distinct nuclear groups—light, intermediate, and heavy—and was first implemented in the analysis of data from the MAKET-ANI experiment (Chilingarian et al., 2004) and later applied to the KASCADE experiment (Antoni et al., 2002). Fig. 2a demonstrates the two-way classification of primary nuclei by the neural network into light and heavy classes. Fig. 2b presents energy spectra of classified nuclei. It reveals a pronounced 'knee' in the energy spectrum of the light component, which consists of protons and alpha particles, and a lack of such a feature in the heavy component spectrum up to approximately 30 PeV (Chilingarian et al., 2007). These findings, highlighting a rigidity-dependent knee position, align with SNRs as probable sources of GCR and suggest Fermi-type acceleration as the primary mechanism for proton and nuclei acceleration.

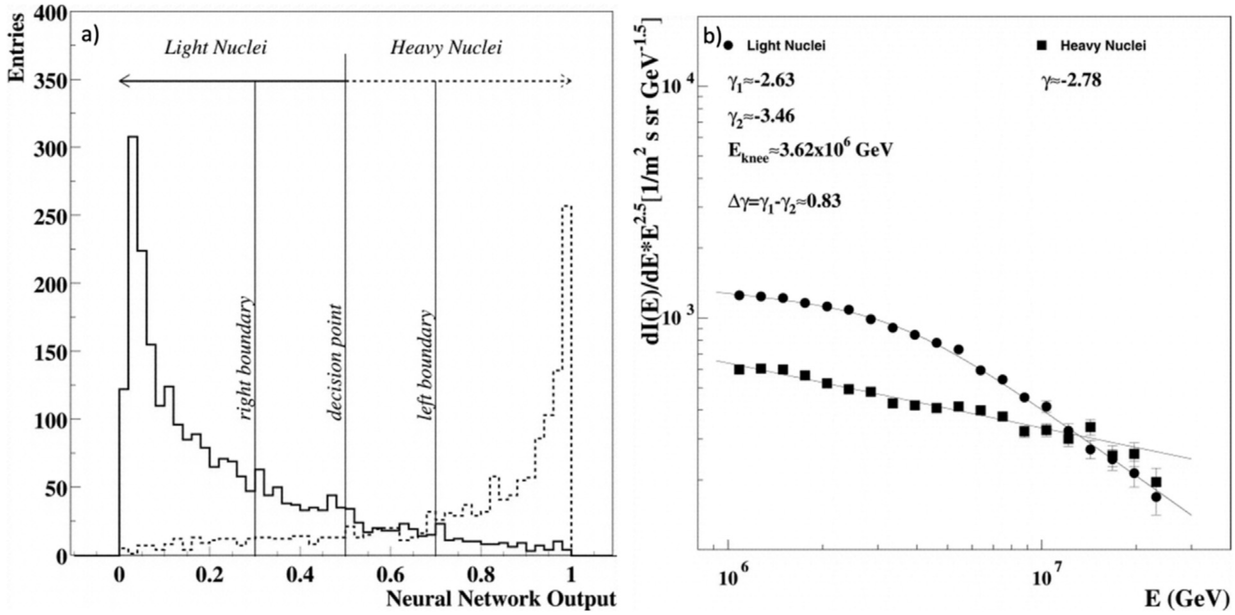

Fig. 2. (a) The output of the Neural Network trained to distinguish "light" and "heavy" nuclei (from Chilingarian et al., 2004); (b) Energy spectra of light and heavy nuclei obtained by neural classification and energy estimation. The EAS characteristics used are shower size and shape (age parameter).

Another implementation of the developed methods involved "purifying" the Cherenkov images, i.e., rejecting the background of hadronic images in registering very high-energy gamma rays from point sources by atmospheric Cherenkov telescopes (ACTs). In the atmosphere, a primary, very high-energy gamma-ray from the celestial object is multiplied millions of times in the electromagnetic cascade. Collecting low-energy Cherenkov photons generated by relativistic electrons with large mirrors and projecting them onto a matrix of photomultipliers has made it feasible to detect very weak fluxes from exotic objects in the Universe. The main obstacle of the Cherenkov Atmospheric Telescopes (ACT) techniques is the overwhelming background of cosmic ray protons, which far exceeds the expected flux of gamma rays from point sources.

The image purification technique was developed by the Whipple collaboration operating ACT on Mt. Hopkins in Arizona (Cawley et al., 1990). They register the "ON" sample, consisting of the number of events obtained with telescope axes continuously oriented in the direction of the gamma-ray source, and the "OFF" sample, obtained by pointing the telescope axes in the direction of the same celestial coordinates but after the source has already left the destination (no source). The estimate was obtained as the difference (DIFF) between both: N_{on}–N_{off}. In Table 1, we present the results of the famous detection of the Crab Nebula, now accepted as a "standard candle" due to its large intensity and stability. The comparison of different background suppression methods is shown in Table 1, where DIFF = $N_{on}{}^{*} - N_{off}{}^{*}$ is the estimate of the signal, DIFF/$N_{off}{}^{*}$ is the estimate of the signal-to-noise ratio, $N_{on}{}^{*}/N_{off}{}^{*}$ is the estimate of background suppression by the technique used. In the first row, we present the initial data that gives hope for the first point source due to its large significance ($\sigma = 4.8$). In the second row, we display the results obtained with the best one-dimensional parameter (see details on the selection of Cherenkov image parameters in Hillas, 1985), which combined the image's orientation and shape. However, this was not the best signal selection method, as many background events remain. The implementation of multivariate techniques, i.e, the multidimensional geometrical cut (Wedgecut, Chilingarian, and Cawley, 1991), Supercut (Punch et al.,1991), and finally, the nonlinear graphical cut (Chilingaryan, 1994) finally achieved a maximum significance of 35,8σ, while retaining a relatively large number of signal events – 3420 compared to the initial sample of 4878.

The Neural Network techniques were also applied to the hadron separation in the PION experiment on Aragats, second generation ACTs (Magic on Canarias islands, Baixeras et al., 2004), showing the best image purification (Bock et al., 2004) and planned ACTs for operation in the 100 GeV energy range (Konopelko et al., 2006).

For collider experiments, a "dimensionality" analysis (Renyi dimensions) technique was proposed for model separation in the multidimensional phase space (Chilingarian, 1992).

The MCSI-based methodology also proved useful beyond astrophysics. For example, the Multistart Random Search with Early Stop (MRSES) algorithm was applied to DNA microarray data (Schena et al., 1995). MRSES identified gene ensembles—not just individual markers—linked to aggressive colon tumors, marking one of the earliest coherent ensemble-based genome classification models (Chilingaryan et al., 2002).

Table 1
Comparison of the different background rejection methods on the dataset of WIPPLE detection of Crab Nebula, 1988–1989.

	N^*_{on}	N^*_{off}	σ	DIFF	DIFF/N^*_{off}	N^*_{off}/N_{off}
Raw	506,255	501,408	4,8	4847	0.01	
Azwidth	14,622	11,389	20.4	3233	0.28	0.0227
Wedge cut*	6017	3381	27.2	2636	0.78	0.0067
Supercut**	4452	1766	34.3	2686	1.52	0.0035
Neural*** 4::5::1	6278	2858	35.8	3420	1.20	0.0057

The MCSI/ANI predated and anticipated many core ideas of today's machine learning, such as simulation-trained classifiers, evolutionary optimization, and robust nonparametric inference. Developed in the context of cosmic ray physics, it remains one of the earliest and most comprehensive domain-specific AI toolkits in high-energy astrophysics.

4. Galactic cosmic ray research

In the 1980s, comprehensive cosmic ray studies required large detectors to measure various species of cosmic rays across extensive energy ranges. This realization led to the design of the ANI experiment (Danilova et al., 1982), conceptualized by YerPhI (Erik Mamijanyan) in collaboration with the Lebedev Physics Institute of the USSR Academy of Sciences (Sergey Nikolsky). The ANI experiment aimed to detect Extensive Air Showers (EASs, Auger et al., 1939), including their electromagnetic and hadronic components. The proposed setup included a large hadron calorimeter covering an area of 1,600 m^2, a 40 m^2 underground magnetic spectrometer capable of detecting muon momentum up to 20 TeV/c, and 200 m^2 of scintillators in the experimental hall located beneath 15 m of soil and concrete to detect muons with energies above 5 GeV. Three concentric rings of scintillation detectors were used to detect EAS particles with energies above 10^{15} eV, and seven ACTs were planned to precisely detect the position of stellar sources. It was one of the first attempts to detect stellar sources of cosmic rays by selecting "muon-poor" showers generated by ultra-high-energy (UHE) gamma rays in the terrestrial atmosphere. However, due to the dissolution of the USSR, the complete ANI complex was never finished. Only recently, at the HAWC (Albert et al., 2024) and LHAASO (Cao et al., 2024a) observatories, have galactic PeVatrons been discovered. Nonetheless, despite the very difficult years of establishing Armenia as an independent state, two surface arrays emerged from the unfinished ANI experiment, significantly contributing to high-energy cosmic ray physics: MAKET-ANI (Fig. 3), led by Vitaly Romakhin and Gagik Hovsepyan, and GAMMA, led by Romen Martirosov (Fig. 4, Garyaka et al 2002).

Launched in 1997, the MAKET-ANI surface array, comprising approximately 100 plastic scintillators with areas of 1 and 0.25 m^2, was designed to precisely select EAS cores from a detection area of about 3000 m^2, achieving an efficiency exceeding 95 % for EASs initiated by primary particles with energies greater than 5×10^{14}. Due to its low energy threshold, this compact array, consisting of continuously calibrated detectors, was well-suited for measuring energy spectra and cosmic ray composition at the "knee" of the cosmic ray spectrum. Over a million EASs recorded between 1999 and 2002 were meticulously analyzed, significantly contributing to the estimation of energy spectra for both light and heavy nuclei groups within the energy range of 5×10^{14}–3×10^{16} eV.

MAKET-ANI and GAMMA completed their operations in the early 2000s. Nonetheless, their legacy continues through ongoing cosmic ray research at Aragats and Nor Amberd. Many technological developments pioneered in these experiments have influenced later projects, including the SEVAN detector network and upgrades to high-altitude cosmic ray monitoring facilities. The data obtained from the arrays contributed to studies on cosmic ray interactions with the Earth's atmosphere. They provided a foundation for examining transient atmospheric phenomena, such as Thunderstorm Ground Enhancements (TGEs). This link between cosmic ray physics and atmospheric electricity has since become a critical area of research, leading to further experiments at Aragats and other high-altitude observatories.

In addition to advancing high-energy cosmic ray studies, these experiments contributed to interdisciplinary research, particularly in atmospheric physics. MAKET-ANI and GAMMA represented a significant step forward in cosmic ray data processing, being among the first experiments in the area to integrate computer-assisted data analysis. Early Soviet computers, such as the M220 and Armenia's mini-computer NAIRI-2, were utilized for data collection and storage, paving the way for modern machine-learning approaches now applied in high-energy physics. These early digital methods offered a framework for real-time event reconstruction, significantly enhancing future alerting systems for violent solar activity events.

5. Solar physics and space weather research with ASEC and SEVAN networks

The Aragats Space Environmental Center (ASEC) was established in 2000, focusing on solar physics and space weather research (Chilingarian et al., 2003, 2005). Using neutron monitors and scintillation detectors from the MAKET-ANI and GAMMA arrays, ASEC has played a crucial role in tracking CR fluxes modulated by frequent

Fig. 3. MAKET-ANI detector researching physics around the "knee", first observation of the light and heavy Galactic nuclei energy spectra.

Fig. 4. The GAMMA detector of the ANI experiment registers "muon-poor" showers for selecting PeV energy gamma rays.

solar events during the very intense 23rd activity cycle, which lasted from 1996 to 2008. Its capabilities were particularly highlighted during the peak of the 23rd solar activity cycle between 2000 and 2003, where it precisely captured ground-level enhancements (GLEs), and Forbush decreases (FDs, Chilingarian and Bostanjyan, 2009b, 2010).

In 2001, ASEC pioneered the early warning alert system for extreme solar energetic particle (SEP) events, characterized by hard spectra that pose risks to satellite electronics and the health of the Space Station crew (Gevorgyan et al., 2005). The data shown in Fig. 5 compares ArNM count rates (left Y-axis) with the 'hard' (>50 MeV) solar proton fluxes detected by GOES spectrometers (right Y-axis) for four major SEP events of the 23rd solar cycle. For all events, the intensification of harmful 'hard' particles lags behind the neutron bursts recorded by ArNM. This indicates that the most energetic solar ions triggering GLEs arrive ≈30 min before the peak intensity of ≈50 MeV solar protons. Detecting these early-arriving relativistic ions through GLE measurement serves as a forewarning of impending hazardous solar particle fluxes. By continuously synchronizing data from ASEC's solar monitors and analyzing correlations between various secondary cosmic rays, ASEC can provide timely alerts regarding

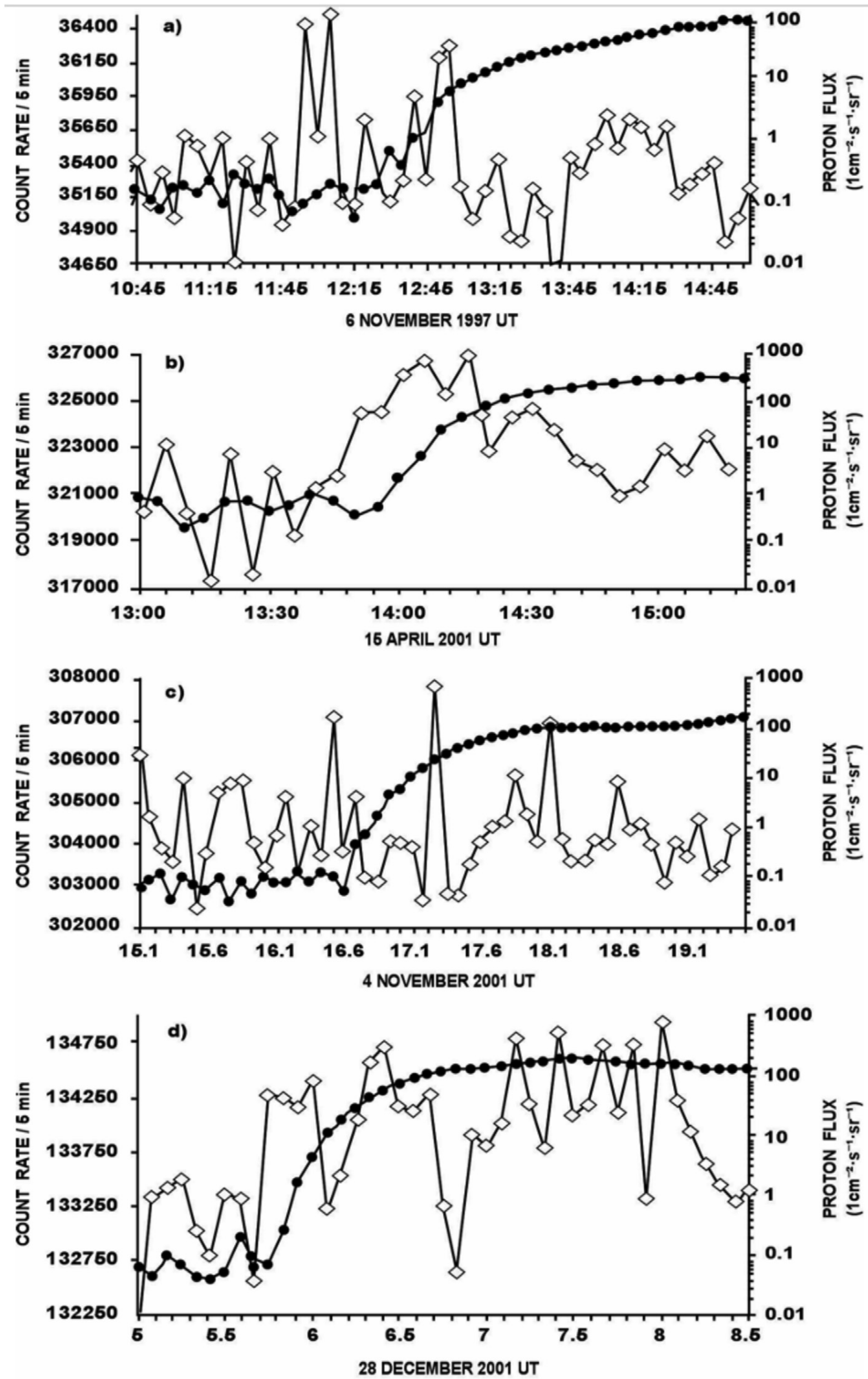

Fig. 5. Comparison of neutron count rates measured by ArNM and proton fluxes measured by facilities of the GOES satellite for the most severe SEPs of the 23rd solar activity cycle.

dangerous radiation events. An email alert system, established by Babayan et al. (2001), notifies subscribers within minutes of a sudden increase in count rate, giving satellite operators the critical window needed to implement protective measures. Subsequently, a methodology was developed to allow rapid recovery of the energy spectra of GLE ions (Chilingarian and Reymers, 2008; Zazyan and Chilingarian, 2009) to evaluate upcoming hazards of SEP events.

Recent developments in Sun activity monitoring systems include the recovery of the energy spectra of secondary particles (neutrons and muons) related to solar events (Chilingarian et al., 2024a).

The Aragats Solar Neutron Telescope (ASNT, Fig. 6) has been operational at the Aragats research station since 1997. It is part of a global network coordinated by Nagoya University's Solar-Terrestrial Laboratory, led by Yasushi Muraki (standing near the ASNT assembly). While the primary aim of ASNT is to monitor direct neutron flux from the Sun (Muraki et al., 1995), its capabilities also extend to tracking charged and neutral fluxes of atmospheric origin, as well as selecting four trajectories of horizontal muons: three from open space and one that passes through the massive Aragats mountain (Chilingarian et al., 2022a).

A landmark discovery at Mt. Aragats was the observation of solar protons with the highest energies ever recorded (Bostanjyan et al., 2007; Chilingarian, 2009c). On January 20, 2005, an intense X-ray burst erupted near the western edge of the Sun, with the X7.1 flare beginning at 06:36 UT and peaking at 07:01 UT. The most rapid

Fig. 6. Aragats Solar Neutron Telescope for detecting neutrons from violent solar bursts, a global network coordinated by Nagoya University and led by Professor Yasushi Muraki (seen in the Figure). The first measurement of the energy spectra of atmospheric runaway electrons was performed in 2009 by ASNT.

Fig. 7. On January 20, 2005, the GAMMA experiment's underground AMMM muon detector recorded the highest energy proton flux from solar accelerators (greater than 20 GeV).

GLE of solar cycle 23 was detected just minutes after the flare's onset. The GLE began at 06:48 UT, and the South Pole neutron monitor registered a staggering 5000 % increase in intensity, the largest ever recorded by neutron monitors. Between 07:00 and 08:00 UT, ASEC detectors measured unusually high count rates. Subsequently, from 07:02 to 07:04 UT, the Aragats Multichannel Muon Monitor (AMMM, Fig. 7) marked the first detection of a significant increase (4σ) in the flux of muons greater than 5 GeV. The differential energy spectra of solar protons showed a pronounced 'turn-over' at 700–800 MeV. Remaining exceptionally steep, the energy spectrum exhibited a power index of about −1 up to 800 MeV and extended into the tens of GeV range with a power index between −5 and −6. A meticulous statistical analysis of the peak suggested that the solar energetic event included protons with energies exceeding 20 GeV.

6. Solar physics research at the maximum of the 25th activity cycle with the SEVAN network

In 2007, the CRD inaugurated the SEVAN detector network (Space Environment Viewing and Analysis Network, Chilingarian et al., 2009d), marking a significant advancement in global particle flux monitoring. This initiative, part of the United Nations Basic Space Science (UNBSS) activities, was supported by the International Heliophysical Year 2007 and the UN Office for Outer Space Affairs, which led an instrument deployment program in developing countries. CRD experts developed a new class of hybrid particle detectors capable of measuring neutral and charged particles and high-energy muons. The primary goal of the SEVAN network is to monitor and measure the fluxes of various secondary cosmic ray species, effectively creating a comprehensive tool for investigating particle acceleration and propagation in the corona and interplanetary space. The network's initial rollout included installations in Croatia, Bulgaria, and India. Expansion continued with the installation of SEVAN detectors in Slovakia, Germany (Hamburg and Berlin), the Czech Republic, and atop Zugspitze, Germany's highest peak in 2023, as illustrated in the map, Fig. 8. Groups operating local SEVAN units establish a scientific community for collaborative research in solar physics and high-energy atmospheric physics by analyzing neutrons and muons modulated during SEPs and geomagnetic storms and recording increased fluxes of electrons and gamma rays during thunderstorms.

CRD's advanced particle detector system is underscored by the development of sophisticated data acquisition (DAQ) systems. Under the leadership of V. Danielyan and later Davit Pokhsraryan, the electronics group has designed and implemented versatile microcontroller-based DAQ systems (Chilingaryan et al., 2008). These systems

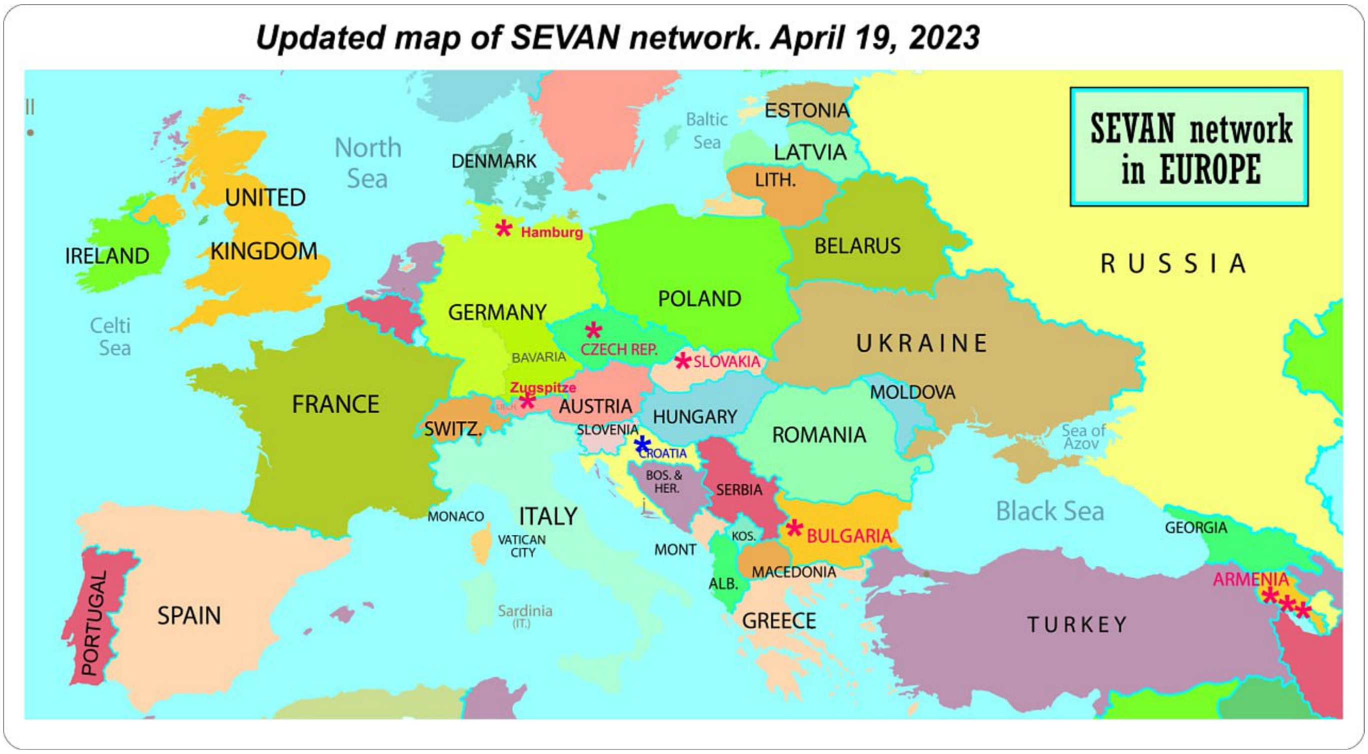

Fig. 8. Red asterisks show the hosts of the Space Environment Viewing and Analysis Network (SEVAN).

are tailored to meet the rigorous demands for stability and efficiency within multi-channel, multi-detector setups. A network of hundreds of channels captures the dynamic fluxes of secondary particles, yielding critical data on solar modulation effects during major solar events (Arakelyan et al., 2009; Pokhsraryan, 2016).

The deployment of advanced software for data analysis, triggering, and rapid data transfer facilitates the aggregation of time series of cosmic ray flux count rates within the CRD's central databases (Chilingaryan et al., 2010). These databases serve as reservoirs for comprehensive multidimensional visualization and statistical analysis, proving indispensable tools for scrutinizing experimental data, conducting collaborative research, and preparing scientific publications.

Data integration from local and international detector networks into the MySQL database at CRD headquarters in Yerevan is streamlined through the ADEI platform (Chilingaryan et al., 2008), which offers advanced visualization and statistical analysis capabilities. ADEI enables users to quickly analyze data, create figures and presentations, collaborate on data analysis with remote teams, test scientific hypotheses, and derive physical interpretations. Databases, visualization tools, and statistical analysis software are free and include detector descriptions with parameters such as efficiencies and energy thresholds calculated by the GEANT4 code.

Furthermore, alert systems that send email notifications can monitor thunderstorm events in real time. The ADEI database includes a time series of neutral and charged particle count rates, data on near-surface electric field (NSEF) disturbances measured by an array of Boltek EFM-100 electric field mills, and meteorological conditions recorded by automatic weather stations from Davis Instruments. Consolidating these diverse datasets allows users to visualize and conduct multivariate correlation analyses between particle fluxes and various environmental factors.

ASEC upholds a longstanding educational tradition through its high-energy physics schools, an initiative started by A. Alikhanyan in the 1960s at Nor Amberd. The SEE-2005 (Solar Extreme Events) and FORGES-2008 (Forecasting Of Radiation and Geomagnetic Storms) conferences were significant events that brought together diverse groups of scientists and students from various countries. These gatherings continue to foster collaboration and learning in the dynamic fields of solar physics and space weather research.

7. Solar physics research with the SEVAN network

After an unusually quiet 24th solar cycle, the Sun exhibits a marked increase in activity that resulted in a relatively intense 25th cycle, peaking in 2024–2025. This uptick produced numerous violent coronal mass ejections that impacted Earth, leading to geomagnetic storms and SEP events. The complex interaction between the turbulent interplanetary magnetic fields and Earth's geomagnetic field cause diverse phenomena, ranging from damaging satellite electronics to generating awe-inspiring Auroras. In this dynamic context, understanding the influence of large magnetized solar ejections on the near-Earth environment is crucial. Cosmic rays serve as messengers, carrying essential information about these multifaceted processes. Ground-based particle detector networks, which include the latest installations at Aragats and Zugspitze, offer valuable data that complement observations from space agencies like NOAA, NASA, and ESA.

On November 5, 2023, particle detector networks at middle latitudes and mountaintops observed a rare magnetospheric effect (ME). The newly installed SEVAN detector at Zugspitze (Chilingarian et al., 2024e; see Fig. 9) and the SEVAN light detector on Aragats provide the first measurements of the energy spectrum of particles responsible for this magnetospheric phenomenon. With its critical role in validating the RREA-TGE theory of particle bursts, the SEVAN network is also a major instrument for the solar activity research, capturing the energy spectra of GLEs, FDs, and magnetospheric effects, thereby continuing the legacy of the solar physics research conducted by the CRD during the 23rd solar cycle two decades ago.

The geomagnetic storm classified as G5 occurred on May 10–11, 2024, marking one of the most powerful storms in the observation's history (for an in-depth examination, refer to Hayakawa et al., 2025). This phenomenon commenced with notable FD and transitioned into GLE #74 during FD's recovery phase. Ground-based neutron monitors (Mavromichalaki et al., 2011) validated a GLE started at ≈02 UTC on May 11, 2024, following an X.5.8 flare that peaked at 01:23 UTC. Fig. 10 presents time series of the precise correlated counts from the

Fig. 9. Johannes Knapp, Till Rehm, Tigran Karapetyan, and Balabek Sargsyan after installing the SEVAN light detector at the Environmental research station Schneefernerhaus (Zugspitze, 2650 m).

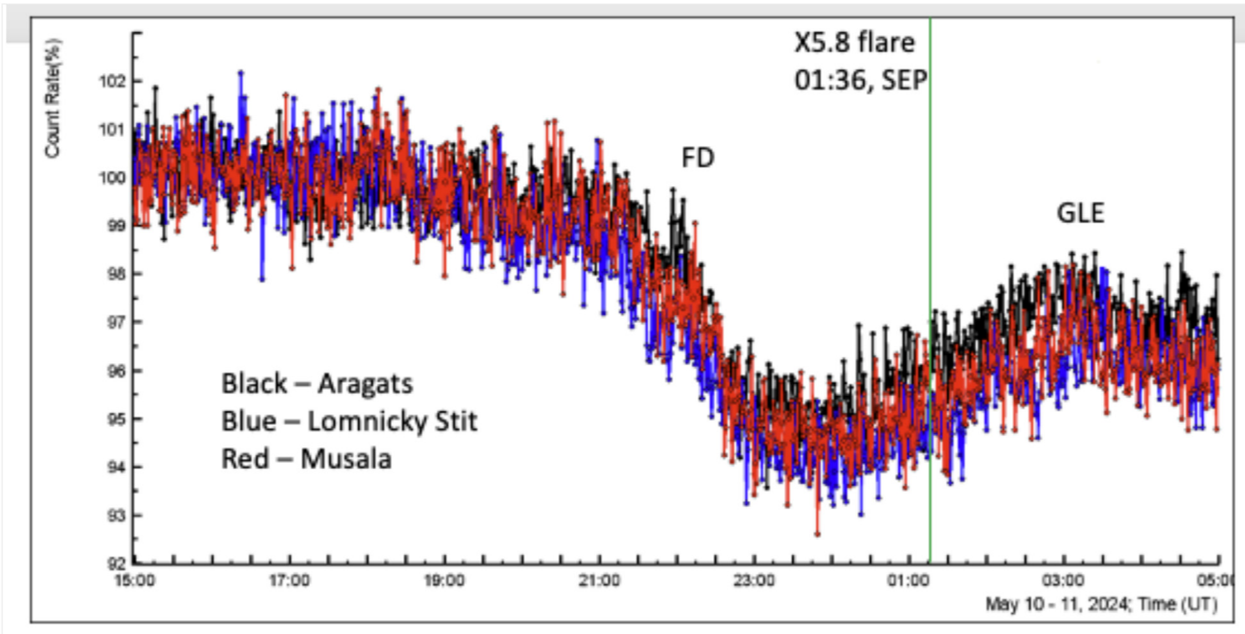

Fig. 10. Observation of FD and GLE by SEVAN network's Aragats, Lomnicky Stit, and Musala detectors.

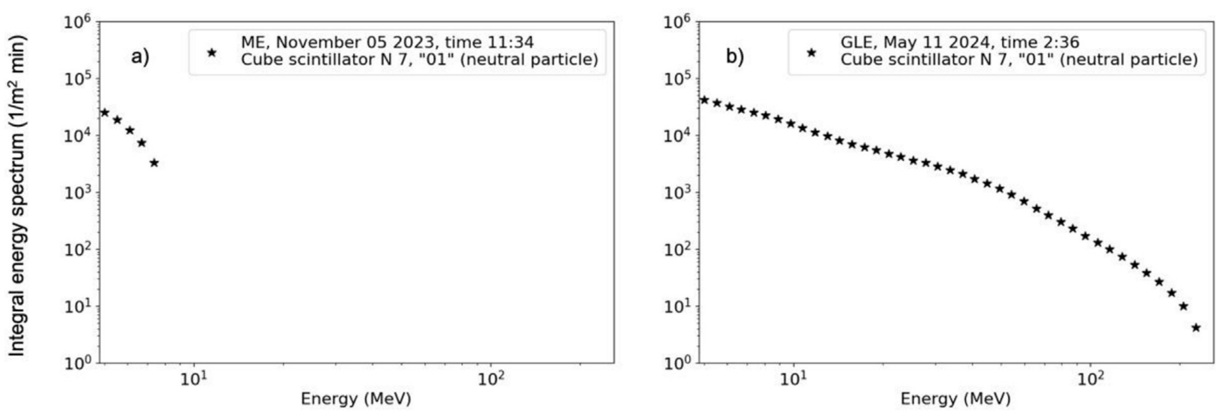

Fig. 11. The integral energy spectra of ME particles (a), and GLE particles (b) measured by the spectrometer on Aragats.

5-cm-thick, one m^2 area SEVAN upper scintillators located on Mts. Aragats (40.25°N, 44.15°E, altitude 3200 m), Musala (42.1°N, 23.35°E, altitude 2930 m), and Lomnicky Stit (49.2°N, 20.22°E, altitude 2635 m).

Fig. 11 illustrates the energy spectra of GLE and ME obtained from energy release histograms, measured using a scintillation spectrometer with a thickness of 20 cm and an area of 0.25 m^2. The maximum energy of the ME energy spectrum on November 5, 2023, is limited to 10 MeV, indicating low-energy primary protons contributing to this solar event. The GMS-induced weakening of geomagnetic shielding enables primary GCR with energies below the geomagnetic cutoff rigidity to penetrate the atmosphere and produce particle cascades reaching mountain tops on middle latitudes. In contrast, the energy of secondaries from SEP on May 11 extends beyond 100 MeV, as shown in Fig. 11b. As we demonstrated in Bostanjyan et al. (2007) and Chilingarian and Bostanjyan (2009b), the energies of solar protons can reach 20 GeV or more. Therefore, during GLE, SCR generates secondaries with energies significantly larger than those during ME. Unlike ME, which we associate with galactic protons having energies below the cutoff rigidity, SCR can achieve energies above 10 GeV.

8. High-energy physics in the atmosphere

Following the most intense GLE event in 2005, solar activity transitioned into the notably calm 24th cycle without significant events. Correspondingly, research on Aragats focused on planetary science, complementing its traditional methods with high-energy physics instrumentation. A new emerging field is integrated under High Energy Physics in Atmosphere (HEPA, Chilingarian, 2024; Dwyer et al., 2012). HEPA examines cosmic ray flux modulation in Earth's atmosphere by measuring various species of cosmic rays on Earth's surface, atmosphere, and space with advanced particle detectors. One of the most important achievements in HEPA was the discovery of TGEs on Aragats in 2009. TGEs are characterized by a sudden increase in the fluxes of electrons, gamma rays, and neutrons that occur during thunderstorms, highlighting the intricate relationship between atmospheric processes and cosmic ray fluxes and emphasizing the impact of cosmic rays on our planet (Chilingarian et al., 2010, 2011; Chilingarian, 2014). TGEs are driven by the relativistic runaway electron avalanche (RREA) mechanism, which occurs in strong atmospheric electric fields (AEFs, Babich et al., 2001; Gurevich et al., 1992; Alexeenko et al., 2002; Dwyer, 2003). TGE research has led to a significant expansion of the experimental infrastructure on Mt. Aragats, where a variety of new particle detectors, weather stations, lightning detectors, and electric field sensors have been established on the slopes of Aragats and in Yerevan (see the details of new scientific infrastructure in Chilingarian et al., 2024b).

The experimental facilities include a network of seven NaI spectrometers to collect extensive statistics for gamma-ray energy spectrometry within the 0.3–50 MeV range. Additionally, the site features three STAND1 detectors, each consisting of three stacked 1-cm-thick, 1 m^2 area scintillators and a separate 3 cm thick standalone scintillator surveying a 50,000 m^2 area. These detectors are integrated into a rapid data synchronization system capable of capturing time series with a 50-ms sampling rate, precisely aligned with atmospheric discharges at nanosecond precision. Sixteen plastic scintillators of the MAKET-ANI surface array continue to record EASs and electron avalanches originating from overhead thunderclouds. The ASNT remains a cornerstone in high-energy atmospheric physics, measuring the TGE electron energy spectrum in the 10–50 MeV energy range (Chilingarian et al., 2023).

Thunderstorms generate extensive electric fields that permeate the areas within and around the storm system. These fields, indicated by red arrows in Fig. 12, form oppositely charged dipoles. They arise from charge separations within the clouds resulting from warm air updrafts and the dynamic interaction of different hydrometeors.

Pioneering research by Joachim Kuettner at Zugspitze (Kuettner, 1950) revealed the complex tripole charge structure within thunderclouds. According to the tripole model, atmospheric electrical fields (AEFs) comprise upper and lower dipoles that accelerate free electrons toward the atmosphere and the Earth's surface.

The upper dipole (first dipole) consists of the main negative and positive charge layers in the middle and top of a thundercloud. Electrons create avalanches in the upper

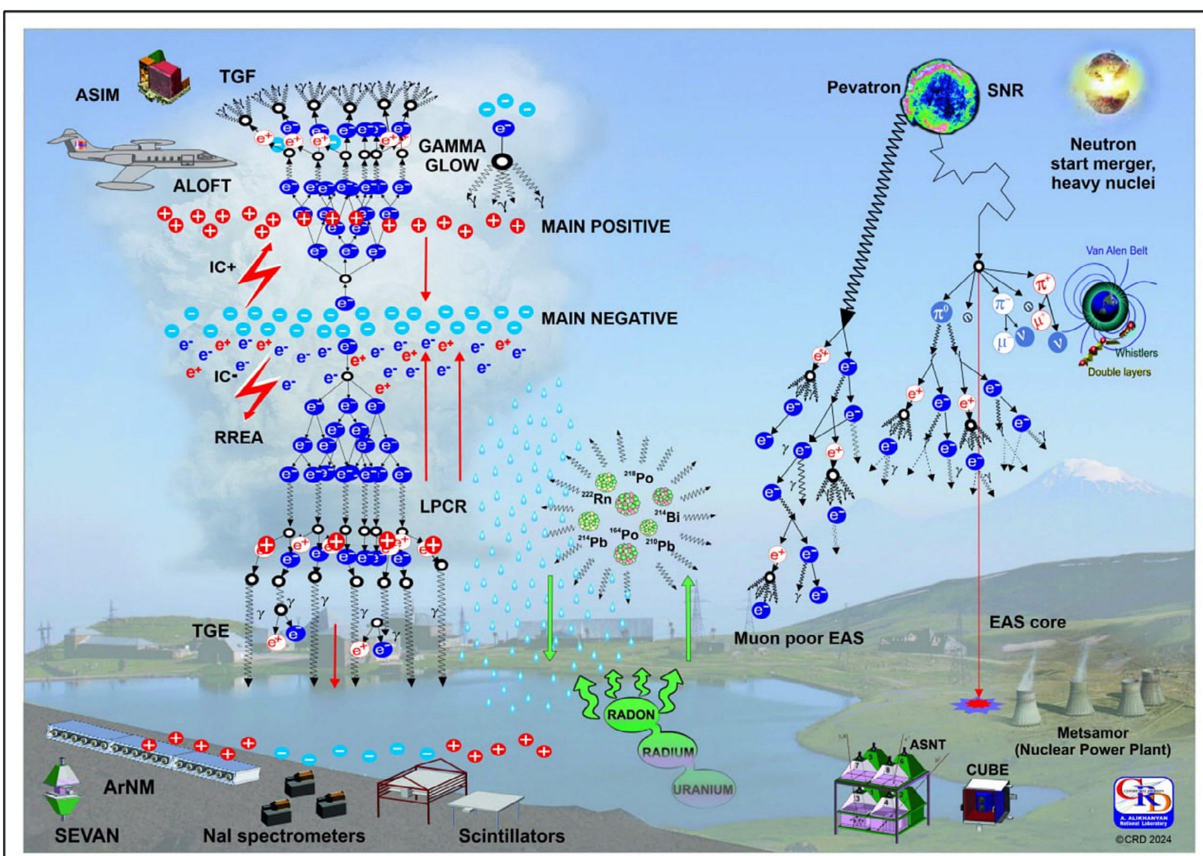

Fig. 12. The flux of secondary particles from space and atmospheric accelerators, as well as gamma radiation from ^{222}Rn progeny. The illustration also shows the charge structure of a thundercloud, the direction of electric fields, lightning strikes, and various measuring instruments both on the surface and in space. Additionally, we can identify the sources of primary cosmic rays. In the background, the Aragats cosmic ray station is visible, located at 3,200 m, and equipped with various particle detectors and spectrometers.

atmosphere, producing bremsstrahlung gamma rays. The gamma-ray glows, generated in the upper atmosphere, are detected by airborne experiments flying above thunderstorms (Kelley et al., 2015; Ostgaard et al., 2019; Marisaldi et al., 2024; Helmerich et al., 2024). The most energetic gamma rays occasionally reach orbiting gamma observatories 400–700 km from the source. Orbiting gamma observatories register microsecond bursts of particles known as terrestrial gamma flashes (TGFs, Fishman et al., 1994; Mailyan et al., 2016). Gamma glows, originating in upper atmospheric dipoles, exhibit different characteristics from TGEs. The high altitude, thinner air, and larger charges in the main positive layer of the upper atmosphere create distinct conditions for RREA development. Therefore, reserving the term "gamma glow" for particle fluxes observed in the upper atmosphere and "TGE" for particles observed on the Earth's surface is appropriate. Several groups call "gamma glows" also gamma-ray enhancements registered on the Earth's surface (Wada et al., 2021). However, despite their different locations, these two phenomena—both powered by RREA—share similarities and would likely resemble each other if measured at the same distance from the source. Recent findings from the ALOFT mission support this conclusion (Marisaldi et al., 2024).

The lower, second dipole consists of a main negative layer in the middle of the cloud, balanced by an opposing charge in the Earth. A third dipole forms between the main negative layer and a transient lower positive charge region (LPCR) associated with descending graupel (snow pellets coated in ice). Electrons accelerated by the lower dipole can trigger electron-gamma ray avalanches, observed on the ground as TGEs, consisting of numerous gamma rays, electrons, and neutrons. In addition, a fourth dipole between the LPCR and its counterpart in the Earth accelerates positrons and positive muons while slowing down electrons and negative muons (Chilingarian and Sargsyan, 2024c, 2024d).

Balloon experiments conducted in New Mexico (Marshall et al., 1995; Stolzenburg et al., 2007) and TGEs registered on Aragats (Chilingarian et al., 2019, 2022b), Zugspitze (Chilingarian et al., 2024e), and Lomnicky Stit mountains (Chum et al., 2020) highlight the relationship between particle fluxes and AEFs. Observations confirm that intense electric fields above particle detectors promote the development of RREA (Chilingarian et al., 2023). Simulations with CORSIKA and GEANT4 codes support these findings, showing large particle avalanches when the electric field exceeds critical thresholds.

Lightning flashes reduce electric field strength in the lower dipole below the RREA initiation threshold. This consequently stops RREA. However, even after the near-surface electric field strength returns to fair-weather levels, TGEs can persist due to the Radon circulation effect (Chilingarian et al., 2020). This occurs because unstable Radon chain isotopes ^{214}Pb and ^{214}Bi are lifted into the atmosphere, increasing natural gamma radiation (see the central part of Fig. 12). TGE can last up to 2–2.5 h for energies below 3 MeV, controled by the half-lives of approximately 27 and 20 min for the isotopes ^{214}Pb and ^{214}Bi, respectively.

The diagram on the right illustrates EAS development from primary gamma rays and protons interacting with atmospheric atoms. These primary particles are produced during cataclysmic cosmic events, such as supernova explosions and neutron star mergers, occurring in our galaxy and beyond. When EASs reach the Earth's surface, they can cover several square kilometers. EAS core, marked by the red circle in the diagram, contains the most energetic secondary particles that create brief, intense bursts. At altitudes exceeding 4,000 m, the observation of muon-poor EAS events suggests the presence of PeVatrons, celestial accelerators capable of propelling protons to energies up to 10^{15} eV. Additionally, the diagram indicates a nuclear power plant as a potential source of radioactive contamination, and the Van Allen radiation belt from which MeV electrons are directed to the Earth's surface.

Over the past fifteen years, physicists at the Cosmic Ray Division have significantly advanced HEPA research. The latest breakthroughs, reported in 2023, illustrate the dynamic nature of this research. Previous data indicate that impulsive enhancements in particle flux at Aragats usually range from 10 % to 20 %, with rare instances surpassing 100 %. In Fig. 13, we present the distribution of TGEs by the percentage of count rate enhancement. The particle flux enhancement was measured by a 3-cm-thick plastic scintillator with an area of 1 m^2 and an energy threshold of 7 MeV. In 2023, five TGEs exceeded the 100 % limit, one of which exhibited an unprecedented enhancement of 1800 % (energy threshold 0.8 MeV, Chilingarian et al., 2024f, see inset to Fig. 13).

A total of 487 TGEs documented between 2013 and 2024 reveal a distinct seasonal pattern: the majority, including all significant events, occurred during Spring and Autumn (accounting for 83 % of all TGEs) at outside temperatures between −2 °C and +2 °C. Approximately 12 % of TGEs occurred in Summer when outside temperatures are positive and thunderclouds are high above the surface, and 5 % in Winter. During 2008–2012, when meteorological and electricity sensors were not yet installed, 277 TGE events were observed. Thus, the total number of TGE events reaches 764. Including the TGEs recorded by the SEVAN network at the mountaintop in Eastern Europe and Germany, the total number of TGEs exceeds 1,000. The TGEs were selected if three independent particle detectors demonstrate simultaneous peaks in the count rate, larger than 3σ, and the NSEF absolute value exceeds 3 kV/m. All TGE candidates were carefully examined to exclude possible artifacts.

An unprecedentedly large TGE was recorded on May 23, 2023, at Aragats Mountain. This event showcased a maximum flux intensity surpassing 3 million particles per minute per square meter for energies above 0.4 MeV. Distinctively, the fluence of the event was measured at approximately ≈700 particles/cm^2.

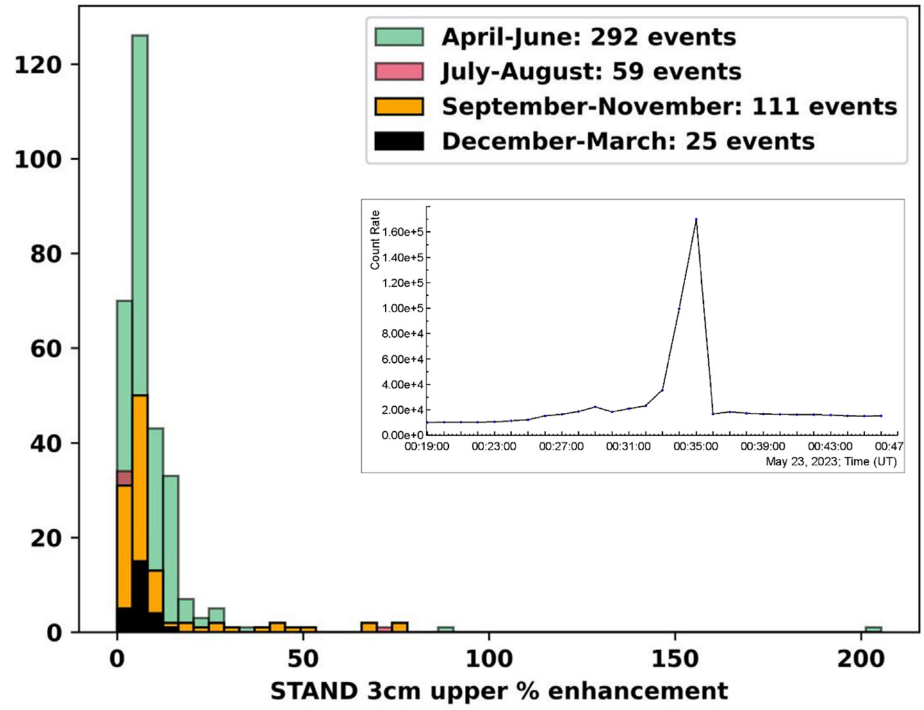

Fig. 13. The season-dependent histogram of the 369 TGEs in percent. The 3 cm-thick and 1 m^2 area plastic scintillator was used for the relative enhancement calculation. The inset shows the 1-minute time series of the 1-cm-thick outdoor scintillator's count rate measured on May 23, 2023 (energy threshold 0.8 MeV, maximum flux was at 00:34 – 00:35).

Outstanding events at mountaintops can be attributed to the proximity of the accelerating electric field to the detectors, the large electric field strength, and the site's geography. On Aragats, the thundercloud sometimes hovers so low over the station that the area becomes shrouded in thick fog. The installation of SEVAN detectors at mountaintops in Eastern Europe and Germany has greatly enhanced TGE detections. The sharp peak of Lomnicky Stit can occasionally lie within the thundercloud, i.e., directly inside the RREA. On June 10, 2017, the number of registered TGE particles exceeded ≈200 times the fair-weather level (Chum et al., 2020). Significant TGEs are also registered on Musala mountain in Bulgaria (Chilingarian et al., 2021). Newly installed SEVAN detectors are recording TGEs at Zugspitze in Germany (Chilingarian et al., 2024E) and Mileshovka in the Czech Republic (Šlegl et al., 2024).

To gain further insight into the largest TGEs, we investigated the stability of the particle flux at its maximum values. Fig. 14 presents four 50-ms time series of TGE count rates along with the time series measured at the same time but on the previous day during fair weather. TGE time series are up to 10-fold higher than the fair-weather ones (see details in Chilingarian et al., 2024d). The legends describe the selected TGE intervals (ranging from 30 s to 1 min), count rate means, standard and relative errors, percentage of enhancements, and significance measured in standard deviations above the mean of fair weather.

As shown in Fig. 14a–d, the TGE flux is very stable – the relative errors for all 4 TGEs are smaller than the ones calculated for the ambient cosmic ray flux at fair weather (a day earlier). Thus, despite the fast-changing atmosphere environments, electron accelerators sustain a stable particle flux over at least 50,000 m^2 (the area covered by the STAND1 network). It pointed to yet unknown beam stabilizing mechanisms in the operation of the "thundercloud" electron accelerators.

9. Synergy of atmospheric physics and high-energy astrophysics

Free electrons from small and large EASs serve as seeds (similar to electron guns in man-made accelerators) for the accelerators that develop in thunderclouds. However, it is not a single link between cosmic rays and atmospheric accelerators. In turn, processes within the terrestrial atmosphere affect the observations of galactic cosmic rays and the recovery of their energy. The EAS-TOP detector (Aglietta et al., 1989), the ARGO-YBJ experiment (Axikegu et al., 2022), and the LHAASO observatory (Aharonian et al., 2023) noted a significant rise in EAS trigger frequency during thunderstorms. These and other surface arrays recorded a substantial increase in electron flux during thunderstorms, frequently occurring at high-altitude sites.

Based on the MAKET-ANI EAS detection, CRD physicists classified surface array triggers into "genuine" EASs and TGEs (Chilingarian et al., 2011). During thunderstorms on September 19, 2009, and October 4, 2010, the MAKET trigger rate was enhanced by ≈250 %. This

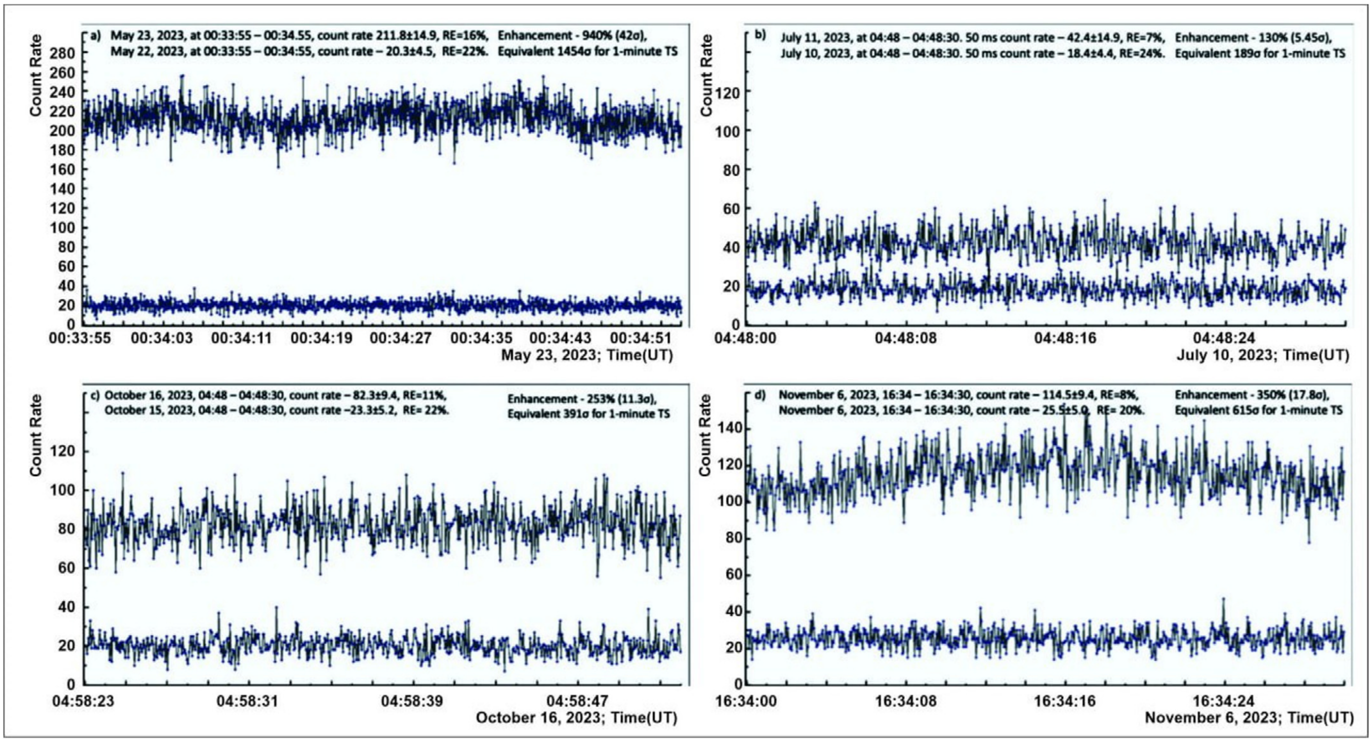

Fig. 14. 50 ms time series of count rates of the STAND1 detector's upper scintillator. The lower curve in each frame corresponds to the count rate measured in fair weather at the same time one day before TGE. The legend includes each TGE's mean count rates, standard errors, and significance.

significant influence of atmospheric processes on galactic cosmic ray observations was never anticipated. The primary particle energy in EAS experiments is estimated by the number of shower electrons, Ne, and an increase in Ne naturally leads to an overestimation of primary particle energy. Recent research by CRD physicists suggests a potential 10-fold overestimation of the primary gamma-ray energy recorded at the LHAASO observatory (Chilingarian and Zazyan, 2024g). Fig. 15 illustrates the behavior of EAS particles in the strong AEF. Panel 13a depicts EAS development during fair weather, while panel 13b shows the effects of electron multiplication in the AEF.

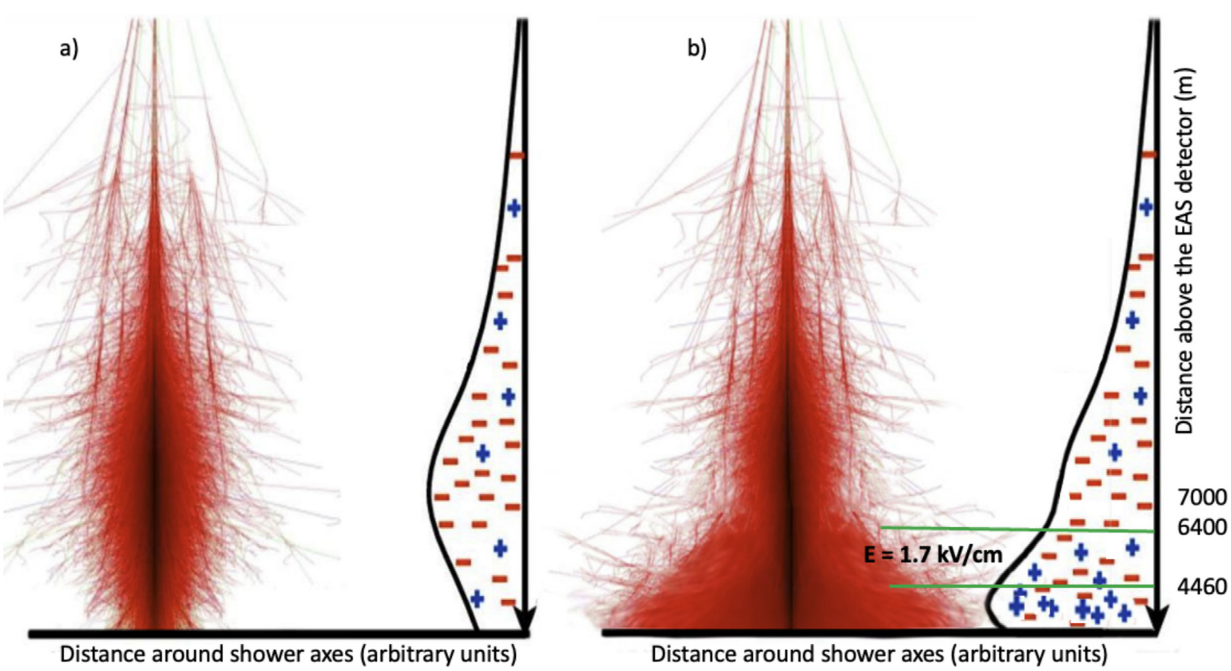

Fig. 15. EAS propagation in AEF. During fairweather (a) and thunderstorm (b). Adopted from Chilingarian and Zazyan (2024g).

Numerous theoretical papers based on UHE gamma-ray observations discuss the origin of the Galactic PeVatrons, gamma-ray propagation in the galaxy, and the possibilities of their detection (see, for instance, Sudoh and Beacom, 2023). Phenomenological models that combine leptonic and hadronic fluxes from various galactic sources have been developed to explain the detected gamma rays in the energy ranges of 10 GeV–10 TeV and 10 TeV–1 PeV, respectively. While several classes of stellar objects in the Milky Way appear capable of accelerating hadrons to energies of many tens of TeV, it remains unclear which ones can achieve PeV energies. During the 1,441 days of LHASSO operation to gather data for the first catalog (Cao et al., 2024b), 200 thunderstorms occurred. Hence, carefully considering climatic conditions is essential to confirm the PeVatron detection, considered the most intriguing discovery in cosmic ray physics today.

10. Conclusions

Investigating cosmic ray modulation in the Earth's atmosphere enhances our understanding of radiation bursts that lead to changes in atmospheric chemistry and the dynamics of thunderstorm charge structures, which are critical for the global electrical circuit. The complex relationship between cosmic rays and AEFs is vital for identifying the types and energies of primary particles. A comprehensive approach that combines particle detection with atmospheric physics instrumentation has revealed the factors contributing to high-energy and atmospheric physics.

At the forefront of solar physics, space weather, and high-energy atmospheric physics, the CRD has positioned itself as a leading global institution. The SEVAN network, extending from Armenia to Eastern Europe and Germany, is a versatile platform for atmospheric and solar physics research. CRD's contributions to high-energy astrophysics include clarifying GCR origins and acceleration mechanisms and identifying the upper limits of solar proton acceleration.

Since 2010, the experimental facilities on Aragats have continuously monitored the fluxes of charged and neutral particles, electrical and geomagnetic fields, lightning locations, meteorological parameters, and the skies above the station. Recently, smaller-scale monitoring centers were established at two locations on the slopes of Aragats and in Yerevan, making Aragats a major center for interdisciplinary research on cosmic rays and geophysical phenomena. Among the most significant discoveries in recent years is the measurement of electron and gamma-ray

Fig. 16. Participants of the TEPA-2019 (Thunderstorms and Elementary Particle Acceleration) conference on Aragats.

energy spectra of TGEs, providing key evidence for RREA development in the thunderous atmosphere (Star, 2024). Research at Aragats also reveals the synergy of atmospheric and Galactic particle accelerators, advancing our understanding of cosmic ray phenomena (Kwan, 2024).

CRD's commitment to collaborative scientific progress is evident through its active participation in international conferences and its leadership in organizing the annual TEPA (Thunderstorms and elementary particle acceleration) meetings at the Nor Amberd International Conference Center, the Department of Radiation Dosimetry at the Nuclear Physics Institute of the Czech Academy of Sciences, and the Skobelzin Nuclear Physics Institute of Lomonosov University. These events foster dialogue and partnerships in the growing field of high-energy atmospheric physics (see Fig. 16).

In 2024, CRD declared an open competition for a project in HEPA to be performed on Aragats, a unique location for HEPA research. In May-June and September-October, intense TGEs cover the particle detectors with millions of electrons and gamma rays. Proposals for solar physics, space weather, atmospheric, and environmental physics experiments are also welcomed. Integrating data from CRD and partner detectors will be accomplished through a multivariate analysis of physical phenomena, measuring all relevant parameters. This competition reflects how researchers propose to utilize the laboratory facilities specially built for this competition. The laboratory, with a 9 m ^{2} area, is equipped with 1 cm thick, 1 m ^{2}, and 0. 25 m ^{2} area, 25 cm thick plastic scintillators, an electric field sensor, a weather station, and two all-sky cameras (see Fig. 17). These facilities will be provided to the

Fig. 17. Experimental Laboratory provided to the winner projects.

winning projects for multivariate research in HEPA, including the registration of TGEs, air glows, electric fields, lightning occurrences, natural gamma radiation, and other environmental studies. Researchers and students can add particle detectors, photometers, high-speed cameras, and other equipment for their experiments. CRD will provide the Internet connection, database, and analysis platform for storing and accessing data online. In 2024, three expeditions from France, the Czech Republic, and Russia successfully installed their detectors, and data registration is ongoing. The 2025 competition is already attracting new projects.

Beyond traditional research, CRD has pioneered AI-driven data analysis methods, enabling multivariate correlation analysis with applications ranging from astroparticle physics to genomic studies. Data from Aragats and international networks are available online through free-access databases and Mendeley datasets (Chilingarian et al., 2024h).

In 2025, we will continuously monitor geophysical and radiation parameters at Mt. Aragats (currently at four stations) and in Yerevan, utilizing existing and new sensors. We will collect energy spectra of TGE electrons and gamma rays using four particle spectrometers (ASNT, SEVAN, CUBE, NaI) across a wide energy interval from 300 keV to 100 MeV. The network of RT56 gamma spectrometers (energy range 0.3–50 MeV) produced by Geordies' firm (Czech Republic) will provide precise measurements of natural gamma radiation and its variations on the slopes of Aragats and in Yerevan (Chilingarian and Sargsyan, 2024). We also plan to conduct atmospheric muon and neutron research, investigate the charge structure of thunderclouds, and study new types of optical glows in the lower atmosphere.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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