Annual Report, Cosmic Ray Division of Artem Alikhanyan National Lab (AANL) 2024

SHORT DESCRIPTION OF PAST ASEC RESEARCH PROGRAM

One of the world's largest high-altitude cosmic-ray research stations is on the slopes of Mt. Aragats, 3200 m and 2000 m above sea level. Since 1942, physicists of the Cosmic Ray Division (CRD) of YerPhI have been studying Cosmic Ray fluxes on Mt. Aragats with various particle detectors: mass spectrometers, calorimeters, transition radiation detectors, and huge particle detector arrays detecting particle cascades initiated by protons and nuclei accelerated in most energetic explosions in the Galaxy. The latest research at Mt. Aragats adds to traditional fields of Space Weather, Solar accelerators, and high-energy physics in the atmosphere. From 2008 to 2022, particle detectors at Aragats continuously registered fluxes of charged and neutral particles using various particle detectors. ASEC detectors measure particle fluxes with different energy thresholds and Extensive air showers (EASs) initiated by primary protons and nuclei with energies above 50–100 TeV. Thunderstorm activity on Aragats is extreme in May - June. Long-lasting light flashes sometimes occur near the station, and lightning activity lasts an hour or more. Thunderclouds are usually below the southern peak (i.e., not higher than 500 m above ground level) and sometimes only 25–50 m above the station. Therefore, most energetic Thunderstorm ground Enhancements (TGEs) contain many avalanche electrons, like the one that occurred on 19 September 2009, which triggered the MAKET surface array 100 times, proving that avalanche electrons are distributed over areas of thousands of square meters.

Most of the particle detectors are located in the MAKET experimental hall. First, the Aragats Solar Neutron Telescope (ASNT) remains the main detector in high-energy atmospheric physics, measuring the flux of electrons and gamma rays in the 10-100 MeV energy range. In the same hall are the Aragats Neutron Monitor (ArNM), type 18HM64, and the space environment viewing and analysis network (SEVAN) particle detector, which records charged and neutral particle fluxes. Sixteen plastic scintillators of the MAKET-ANI surface array record EASs and avalanches unleashed by runaway electrons originating in the thunderclouds above.

After the first years of TGE research, the experimental complex at Aragats was significantly expanded. Numerous new particle detectors were installed at an altitude of 3200 m. A network of 7 spectrometers (based on NaI crystals of 12 x 12 x 24 cm^3 size was established in the SKL experimental hall. The low energy threshold (~ 300 keV) provides extensive statistics (~ 50,000 counts per minute) for reconstructing gamma ray differential energy spectra from 0.3 to 50 MeV. A network of 3 STAND1 detectors (three stacked scintillators with a thickness of 1 cm and an area of 1 m^2 and one stand-alone with a thickness of 3 cm) is located at Aragats station premises with a spacing of ≈250 m. The network is connected to the fast data synchronization system that can capture time series with a sampling time of 50 ms, which allows one to study the relation of the TGE development to atmospheric discharges.

The largest TGEs registered by SEVAN network units at Mt. Musala (Bulgaria), and Mt. Lomnicky Stit (Slovakia), by NAI scintillators in Finland, as well as the results obtained on the Eastern coast of Japan and recent measurements at Zugspitze, prove that TGE isn't only a specific Aragats feature but a universal characteristic of thunderstorms over high-altitude experiments. The measured energy spectra allow us to gain insight into the thundercloud's charge structure and clarify the role of the lower positively charged region (LPCR) in the development of the TGE.

Data from local and international networks are transferred to the MySQL database at the CRD headquarters in Yerevan and are available through the ADEI multidimensional visualization and statistical analysis platform. ADEI allows users to analyze data quickly, prepare figures and slides, perform joint data analysis with remote groups, test hypotheses, and draw physical inferences. Alerts and forewarnings sent by e-mail to service subscribers make it possible to follow the progress of thunderstorm events in real time. ADEI database contains a time series of neutral and charged particle count rates together with data on disturbances of the NSEF measured by a network of Boltek EFM-100 electric field mills and meteorological conditions from automatic weather stations from Davis Instruments. Placing these data in one database allows the visualization and multivariate correlation analysis of particle fluxes and numerous environmental parameters.

The simulation of the development of Relativistic runaway electron avalanches (RREA) supported measurements of TGEs in the atmospheric electric field above detectors with GEANT4 and CORSIKA codes and spectrometric measurements of Radon progeny gamma radiation. By making multiple simulations with different electric field strengths and elongation, we outline plausible parameters of the electric field that give rise to TGEs and define the main charge structures supporting their origination.

Other discoveries made on Aragats include the registration of the atmospheric neutrons observed during thunderstorms, originating from the photonuclear reactions of the RREA gamma rays; the discovery of the Radon circulation effect; the uncovering of the muon stopping effect and positron flux modulation; the estimation of the largest electric voltage (potential difference) at mountain peaks; and the observation of transient luminous events (TLEs) in the lower atmosphere.

In the following sections, we will highlight the most important results of TGE physics.

STAFF

The total number of CRD employees at the beginning of 2025 was 31, including a professor, 5 PhDs, 2 Ph.D. students, five engineers, seven technicians, three electrical technicians, two drivers, four cocks, a WEB designer, an accountant, a secretary, and an assistant. Additionally, a senior scientist works in another YerPhI department (Hovsepyan Gagik); a Ph.D. student works primarily at UCLA (Aslanyan Davit), USA, and a data analysis consultant works at KIT, Karlsruhe, Germany (Chilingaryan Suren).

CONFERENCES

1. ISWI Steering Committee Annual Meeting

2024 February 5-6

Online participation, Vienna

Update of the SEVAN network

2. Cosmic Ray Workshop 2024 RSVP

11th - 14th March 2024
at Georgia State University, Atlanta, GA, USA
Online participation

T. Karapetyan

European network of particle detectors for Solar physics,

Space weather and Atmospheric research

A.Chilingarian

Cosmic Ray Navigation System (CRoNS) for Autonomous Navigation in GPS-Denied Environments

3. Common Meeting Virtual Alpine Observatory (VAO) and Alpine Convention, March 19-20 2024, Innsbruck, Austria

A.Chilingarian: Scientific goals and potential synergies (neutron detectors at Kugelalm/UFS)

4. 16th Workshop Solar Influences on the Magnetosphere, Ionosphere and Atmosphere,

3-7 June 2024, Primorsko, Bulgaria.

Chilingarian A., Approaching the maximum of the 25th solar activity cycle: as seen by particle detectors' networks

5. 38 Russian conference on cosmic rays

1 to 5 July 2024 Lebedev Physics Institute, Moscow, RF.

Ashot Chilingarian

Регистрация сетью детекторов СЕВАН солнечных событий 25 цикла.

Широкие атмосферные ливни и атмосферные электрические поля. #49 (03.07 16:30)

PUBLICATIONS

1. *PHYSICAL REVIEW D (2024) 109, 062003*

Atmospheric positron flux modulation during thunderstorms

A. Chilingarian and B. Sargsyan
A I Alikhanyan National Lab (Yerevan Physics Institute), Yerevan 0036, Armenia

We have discovered a new phenomenon in high-energy atmospheric physics involving an increased fraction of ground-level positrons during a thunderstorm. This increase is linked to developing a lower positively charged region (LPCR) at the thundercloud bottom. When the electric field strength in the lower atmosphere exceeds a critical value, seed electrons from cosmic rays accelerate and multiply, creating relativistic runaway avalanches of millions of electrons and gamma rays with energies up to 50 MeV. The emerging LPCR changes the polarity of the electric field nearly to the Earth's surface, causing electrons to decelerate and positrons to accelerate, increasing the flux of 511 keV "annihilation" gamma rays. By measuring these gamma rays, we can reveal the formation of the LPCR and follow the dynamics of the charge structure in the lower part of the thundercloud. Our previous measurements demonstrate that the atmospheric electric field during thunderstorms modulates fluxes of cosmic ray electrons and gamma rays, muons, and neutrons. This research shows that the emerging charged structures in the thundercloud also modulate positron flux.

2. *Advances in Space Research (2024) 74, 4377. doi.org/10.1016/j.asr.2024.02.041*

Enormous impulsive enhancement of particle fluxes observed on Aragats on May 23, 2023

A.Chilingarian, G. Hovsepyan, B. Sargsyan, T. Karapetyan, D. Aslanyan, L. Kozliner
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An unprecedented thunderstorm ground enhancement (TGE) event was recorded on May 23, 2023, at Aragats Mountain, the highest peak in Armenia. This event showcased a maximum flux intensity surpassing 3 million particles per minute per square meter for energies above 0.4 MeV. Distinctly, the fluence of the event was measured at approximately ≈700 particles/cm^2. The comprehensive instrumentation at the Aragats research station, including a suite of spectrometers and detectors, enabled precise cross-correlation of measurements. The electron flux at energies exceeding 10 MeV was observed at roughly ≈55,000 particles per minute per square meter. Additional measurements, including cloud base heights and corona discharge detections, validated the intensity of the electric field, reaching approximately 2.1 kV/cm at elevations 50–100 m above ground level. Our observations confirm that TGE is a universal and significant atmospheric event, contributing a substantial flux of high-energy electrons to the global electrical circuit. Integrating such TGE phenomena into Earth's numerical models is imperative, considering their impact on aviation and aerospace operation safety.

3. *Advances in Space Research (2024) 74, 4388. doi.org/10.1016/j.asr.2024.03.013*

Extensive air showers and atmospheric electric fields. Synergy of Space and atmospheric particle accelerators.

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Various particle accelerators operate in the space plasmas, filling the Galaxy with high-energy particles (primary cosmic rays). Reaching the Earth's atmosphere, these particles originate extensive air showers (EASs) consisting of millions of elementary particles (secondary cosmic rays), covering several km^2 on the ground. During thunderstorms, strong electric fields modulate the energy spectra of EAS secondary particles, changing the shower size (number of EAS electrons) and altering the primary particle's estimated energy and frequency of the surface array triggers. Impulse amplifications of particle fluxes (the so-called thunderstorm ground enhancements, TGEs) manifest themselves as large peaks in the time series of count rates of particle detectors located on the Earth's surface. Free electrons are abundant at any altitude in the atmosphere, from small to large EASs. These electrons serve as seeds for electron accelerators, which operate in the thunderous atmosphere and send particle avalanches in the direction of Earth's surface and into space (terrestrial gamma flashes, TGFs). EAS cores randomly hitting arrays of particle detectors also generate short bursts of relativistic particles. For years, particle detectors, electric field sensors, and lightning locators have gathered information about the complex interactions of secondary particle fluxes, electric fields, and lightning flashes. This information is crucial for establishing a field of high-energy physics in the atmosphere.

4. *Journal of Environmental Radioactivity (2024) 274, 107409. doi.org/10.1016/j.jenvrad.2024.107409*

The causes of the abrupt enhancement of the natural gamma radiation in the thunderous atmosphere on the mountain tops

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The study presented the relationship between sudden Natural Gamma Radiation (NGR) increases related to enhanced atmospheric electric fields. We pinpoint Thunderstorm Ground Enhancements (TGEs) as the primary source of abrupt and significant NGR spikes. These TGEs, which are transient, several-minute-long increases in elementary particle fluxes, originate from natural electron accelerators within thunderclouds. The more pro- longed, yet less pronounced, increases in NGR, persisting for several hours, are attributed to the gamma radiation from radon progeny and enhanced positron fluxes. This radon, emanating from terrestrial materials, is carried aloft by the Near-Surface Electric Field (NSEF). To measure NGR at Aragats Mountain, we use an ORTEC detector and custom-built large NaI (Tl) spectrometers, employing lead filters to discriminate between cosmic ray fluxes and radon progeny radiation. Our analysis differentiates between

radiation enhancements during positive and negative NSEF episodes. The resultant data provide a comprehensive measurement of the intensities of principal isotopes and positron flux during thunderstorms compared to fair weather conditions.

The global emergence of strong electric fields within the Earth's atmosphere during thunderstorms implies that the observed NGR enhancements are widespread phenomena. Due to their significant planetary i2mpact, these effects warrant inclusion in the numerical models of Earth's atmospheric processes.

5. ***EPL- A letter Journal Exploring Frontiers of Physics (2024) 146, 24001 https://creativecommons.org/licences/by-nc-nd/3.0***

Increase in the count rates of ground-based cosmic-ray detectors caused by the heliomagnetic disturbance on 5 November 2023

A. Chilingarian[1], T. Karapetyan[1], B. Sargsyan[1], M. Zazyan[1], J. Knapp[2], M. Walter[2] and T. Rehm[3]

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The unexpected surge in solar activity in fall 2023 following a period of the calm sun during the previous relatively small 24th solar activity cycle indicates the approach of the solar maximum of the 25th cycle expected in 2024. The nonlinear interplay between disturbed interplanetary magnetic and geomagnetic fields yields diverse effects, from damage to satellite electronics to fascinating Auroras. In these circumstances, it is increasingly important to understand the effects of large magnetized clouds ejected from the Sun on near-Earth environments. Cosmic rays are direct messengers, conveying crucial information about these intricate processes. Networks of particle detectors continuously monitoring cosmic ray flux on the Earth's surface provide valuable insights complementary to spaceborne detectors operated by NOAA, NASA, and ESA. Our letter unveils a rare Magnetospheric Effect observed by particle detector networks at middle latitudes on mountaintops. Additionally, we present, for the first time, the energy spectrum of the particles causing the observed count rate enhancement, shedding light on the solar-magnetospheric interaction.

6. ***Physics Open (2024) 18, 100202. doi.org/10.1016/j.physo.2023.100202***

Space-temporal structure of the thunderstorm ground enhancements (TGEs)

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We analyzed the structure of the Thunderstorm Ground Enhancement (TGE) using a particle detector network on Aragats. We performed a statistical analysis of the particle arrival time series on a nanosecond time scale using the largest TGE event on record, which occurred on May 23, 2023. Our findings confirm that the TGE is a mixture of multiple runaway electron avalanches that arrive independently and provide stable particle flux. The electron accelerator, operated by the dipole that emerges in the lower part of the thundercloud, sends copious electrons and gamma rays toward the Earth's surface that sustains for minutes. The experimental results are supported by simulations of electron multiplication and acceleration in strong atmospheric electric fields. We compare TGEs and Terrestrial Gamma Flashes (TGFs), which are brief bursts observed by gamma-ray detectors in orbit and are thought to be associated with atmospheric discharges.

On 23 May 2023, the RREA in the thundercloud above Aragats produced a stable ten times higher particle flux than the ambient cosmic ray flux during fair weather. The count rate of TGEs shows a smaller relative error compared to the flux of the ambient population of cosmic rays during fair weather. TGE particles arrive uniformly and randomly, according to the Poisson process.

7. *Astroparticle Physics (2024) 156, 102924. doi.org/10.1016/j.astropartphys.2024.102924*

Energy spectra of the first TGE observed on Zugspitze by the SEVAN light detector compared with the energetic TGE observed on Aragats

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The energy spectra of Thunderstorm ground enhancement (TGE) electrons and gamma rays are the key evidence for proving the origin of enhanced particle fluxes from thunderclouds. Till now, the electron energy spectrum was measured only by the Aragats large scintillation spectrometer ASNT. We changed the electronics board of the SEVAN detector installed at the Umwelt-Forschungs-Station (UFS, Schneefernerhaus, 2650 m asl) to allow these vital measurements near the top of the Zugspitze. The new electronics of the SEVAN detector, supplied with logarithmic ADC, for the energy release measurements up to 50 MeV (the thickness of the spectrometric skintiller is 25 cm). Thus, by measuring energy releases well above 3 MeV, we unambiguously separate Radon progeny gamma radiation from the electrons and gamma-ray relativistic runaway avalanches. Using the different energy release histograms allows for separating charged and neutral particles, enabling the disentangling of electron and gamma-ray energy spectra. On May 23, 2023, the first TGE was registered on Zugspitze by the SEVAN detector. The gamma-ray flux enhancement was 44%, corresponding to the observed count rate peak enhancement of 44σ. The gamma-ray energy spectrum was recovered, maximum energy is 60 MeV. On the same day, a large TGE was observed on Aragats. The TGE maximum flux overpasses the fair-weather flux by 207%, equivalent to a 1-minute peak significance of 400σ. Maximum energy of electrons is 50 MeV, gamma rays – 45 MeV. In this context, we will explore and explain the new capabilities of the SEVAN detector installed on Zugspitze and the rearranged similar detector on Aragats. We also present and compare electron and gamma-ray energy spectra from Aragats TGE and gamma-ray energy spectrum from Zugspitze.

The new possibilities offered by SEVAN detectors give a unique opportunity for high-energy atmospheric physics and solar physics research. The recovered spectra, coupled with the ability to estimate the height and strength of intracloud electric fields, significantly advance high-energy atmospheric physics research.

8. *Mendeley Data, V1, (2024) doi: 10.17632/z4ry54hccb.1https://data.mendeley.com/datasets/z4ry54hccb/1*

"Extreme thunderstorm ground enhancements registered on Aragats in 2023

Chilingarian, Ashot; Karapetyan, Tigran; Aslanyan, Davit; Sargsyan, Balabek (2024),

We present the catalog of thunderstorm ground enhancements (TGEs) collected by 24/7 monitoring of various particle fluxes, environmental parameters, and near-surface electric fields on the slopes of Mt. Aragats in Armenia in 2023. Previously, we published the catalog of TGE events registered in Mendeley in 2013-2022. The posted dataset shows 12 parameters of 55 TGEs observed in 2023. All multivariate measurements from the hundreds of registration channels are available from the links to each TGE event. We present our measurements on a user-friendly site, allowing further correlation analysis by colleagues worldwide. The users are provided with multivariate data to continue the research and come to new interesting physical results. The survey of TGE physics and TGE selection procedure users can be found in the paper attached to the dataset, the details of Aragats station facilities, and data analysis methods in the WiKI section of ADEI, accessible from links in the dataset.

9. *Atmospheric Research, (2024) 304, 107403. doi.org/10.1016/j.atmosres.2019.104713*

Corrigendum to "Termination of thunderstorm-related bursts of energetic radiation and particles by inverted intracloud and hybrid lightning discharges", Atmospheric Research, 233 (2020), 104713-104720.

A. Chilingarian, Y. Khanikyants[1], V. Rakov

The authors would like to apologize for any inconvenience caused by our conclusion on the frequency of lightning flashes of different types terminated by Thunderstorm Ground Enhancements (TGEs) and that TGEs associated with inverted IC flashes and hybrid flashes caused relatively small particle flux drops (Chilingarian et al., 2020). We recently analyzed different types of lightning flashes that terminate TGEs using a significantly enlarged data sample (163 TGE events instead of 49) observed from 2012 to 2021 (Soghomonyan et al., 2021). Our analysis of this three times larger dataset has led to results that do not support some of our previous conclusions based on smaller statistics. Therefore, we present a new analysis of the expanded database and compare our previous and current findings on the relationship between particle fluxes and lightning discharges.

10. *Pure and Applied Geophysics, Springer Nature Switzerland (2024) 181, 1963. /doi.org/10.1007/s00024-024-03481-5*

Measurements of Particle Fluxes, Electric Fields, and Lightning Occurrences at the Aragats Space-Environmental Center (ASEC)

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To catalyze transformative advancements in High- energy Physics in the Atmosphere (HEPA), a comprehensive understanding of particle fluxes, electric fields, and lightning occurrences across atmospheric layers is imperative. This paper elucidates the instrumentation and capabilities of the Aragats Space-Environmental Center (ASEC), which encompasses measurement tools for various cosmic ray species, near-surface electric fields, and lightning events integrated across high-mountain research stations at slopes of Mt. Aragats and the highest mountains of Eastern Europe and Germany. Through these measurements, we aim to elucidate models of particle acceleration mechanisms and the charge distribution within the lower atmosphere. We introduce an Advanced Data Extraction Infrastructure (ADEI) integrated with sophisticated statistical analysis tools to facilitate rapid access to this wealth of data. Despite the significance of these atmospheric processes, the intricate interplay between thundercloud electrification, lightning activity, wideband radio emissions, and particle fluxes remains poorly understood. A particularly compelling avenue of inquiry lies in exploring the relationship between high-energy atmospheric phenomena, intracloud electric fields, and lightning initiation. Furthermore, investigations into accelerated structures within geospace plasmas hold promise for shedding light on particle acceleration processes, potentially extending to higher energies within analogous structures in cosmic plasmas. This paper also examines practical methodologies for extracting meaningful physical insights from temporal datasets, such as correlating surges in particle flux intensity with variations in near-surface electric field strength and precipitation patterns. Additionally, we explore the utility of wideband field and interferometer antenna signals in this context, offering valuable avenues for further research and analysis. Through these endeavors, we aim to deepen our understanding of high-energy atmospheric processes and their broader implications for terrestrial and cosmic phenomena.

11. Radiation Physics and Chemistry (2024) 222, 111819.

An enormous increase in atmospheric positron flux during a summer Thunderstorm on Mount Aragats

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On July 11, 2023, we observed a remarkable 500% increase in positron flux, coinciding with a significant Thunderstorm Ground Enhancement (TGE). The enhanced flux of electrons and gamma rays was attributed to relativistic runaway electron avalanches (RREAs) generated within the dipole formed between the main negatively charged layer in the middle of the thundercloud and the Lower Positively Charged Region (LPCR) at the bottom of the thundercloud. Concurrently, a substantial enhancement in the 511 keV gamma-ray flux resulting from electron-positron annihilation was recorded. This surge is intricately linked to the LPCR within the thundercloud.

The emergence of the LPCR induces a polarity change in the atmospheric electric field (AEF) below the LPCR (fourth dipole), leading to the deceleration of electrons and the acceleration of positrons. Particle flux measurements were conducted using scintillation and NaI(TL) spectrometers. To mitigate the contamination of natural gamma radiation and refine the 511 keV flux measurements, the ORTEC spectrometer
was shielded with a 4 cm thick lead filter. CORSIKA simulations corroborate the observed positron flux enhancement. Highlighting the synergy between high-energy physics in the atmosphere and astroparticle physics, we introduce a new scenario to elucidate the enigmatic large flux of galactic positrons measured by the Alpha Magnetic Spectrometer (AMS) aboard the International Space Station (ISS).

12. Data in Brief 54 (2024) 54, 110554

Dataset on extreme thunderstorm ground enhancements registered on Aragats in 2023

A. Chilingarian, T. Karapetyan, B. Sargsyan, D. Aslanyan, S. Chilingaryan[a,b]
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Studying atmospheric electric fields (AEF) and cosmic ray fluxes as an interconnected system is crucial to advance high-energy atmospheric physics. At Mt. Argats, simultaneous measurements of particle fluxes, electric fields, weather conditions, and lightning locations have significantly enhanced the validation of models that describe the charge structures
of thunderclouds and the mechanics of internal electron accelerators. In 2023, observations of the five largest thunderstorm ground enhancements (TGEs) revealed electric fields
exceeding 2.0 kV/cm at elevations just tens of meters above ground—potentially hazardous to rockets and aircraft during launch and charging operations. Utilizing simple yet effective monitoring equipment developed at Aragats, we can mitigate the risks posed by these high-intensity fields. The Mendeley dataset, comprising various measured parameters during thunderstorm activities, enables researchers to perform advanced correlation analysis and uncover complex relationships between these atmospheric phenomena. This study underscores the critical importance of integrated atmospheric studies for ensuring the safety of high-altitude operations and advancing atmospheric science.

13. *Journal of Atmospheric and Solar-Terrestrial Physics (2024) 262, 106305*

The Forbush decrease observed by the SEVAN particle detector network in the 25th solar activity cycle by the SEVAN particle detector network in the 25th solar activity cycle

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The temporal variations of cosmic-ray intensity, measured by ground-based detectors at various latitudes, longitudes, and altitudes, are related to the geophysical and solar phenomena. The latter are interplanetary coronal mass ejections and fast solar wind from coronal holes, which cause interplanetary magnetic field (IMF) abrupt variations near Earth. Interacting with the magnetosphere, they cause worldwide sudden decreases (Forbush decreases, FDs) of intensity followed by gradual recovery. The amplitude of the flux depletion depends on the type and energy of the registered particle, which in turn depends on geographical coordinates and the detector's energy threshold and selective power. SEVAN particle detector network with nodes in Europe and Armenia selects three types of particles that demonstrate coherent depletion and recovery and correspond to different energy galactic protons interacting with disturbed magnetospheric plasmas.

On November 3–4, 2021, an interplanetary coronal mass injection (ICME) hit the magnetosphere, sparking a strong G3-class geomagnetic storm and auroras as far south as California and New Mexico. All detectors of the SEVAN network have registered an (FD) of ≈5% depletion in a 1-min time series of count rates. Approaching the maximum solar activity cycle, large variations of the particle flux intensity were registered on February 27, March 23, 2023, and March 24, 2024.

In this work, we present measurements of these FDs performed on mountain altitudes on Aragats (Armenia), Lomnicky Stit (Slovakia), Mileshovka (Czechia), and at sea level DESY (Hamburg, Germany). We compared FD measurements made by SEVAN detectors and neutron monitors located on Aragats and Lomnicky Stit and made a correlation analysis of FD registration at different locations.

14. ***Physical Review D (2024) 110, 063043.***

Extreme thunderstorm ground enhancements registered on Aragats in 2023

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In 2023, our research team on Mount Aragats in Armenia detected a series of dramatic surges in particle fluxes linked to thunderstorms, with intensities rising to ten times more than on a clear day. This boost is due to strong electric fields in the clouds that act like natural accelerators, speeding up electrons to create Relativistic Runaway Electron Avalanches (RREAs). When they reach the Earth's surface, these avalanches manifest themselves as Thunderstorm Ground Enhancements (TGEs), large peaks in the time series of electrons, gamma rays, and neutrons registered by particle detectors.Our findings revealed a clear pattern of TGEs initiated by RREAs, shedding light on the conditions for their formation. Surprisingly, thunderstorm-related electric fields can be as strong as ≈2.0 kV/cm at heights as low as below 50 meters above the ground. This observation and the consistent power of these natural electric field accelerators during thunderstorms unveil a new level of structured behavior in atmospheric electric fields that we hadn't recognized before.

15. ***Europhysics Letters, EPL 148, 19001. doi:10.1209/0295-5075/ad7e4c***

Influence of Interplanetary Coronal Mass Ejections on Terrestrial Particle Fluxes Through Magnetosphere Disturbances

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This study investigates the modulation of particle fluxes at the Earth's surface influenced by the intensity and orientation of the Interplanetary magnetic field (IMF) carried by the Coronal Mass Ejecta (ICME). We examine how IMF and its Bz component, opposing the magnetosphere, significantly enhance geomagnetic activity through magnetic reconnection. This reconnection facilitates increased penetration of solar wind particles into the magnetosphere, thus amplifying the fluxes registered by terrestrial particle detectors and enhancing particle fluxes through reduced cutoff rigidity (magnetospheric effect, ME). Conversely, the orientation of the Bz component is less crucial for a Forbush decrease (FD); instead, the strength of the ejecta's scalar magnetic field (B) predominates, potentially triggering a significant FD. The study explores how magnetic field variations influence the flux of neutrons and muons, effectively modifying the observed rates of cosmic ray influx. Comprehensive data from the WIND magnetometer and Aragats spectrometers underline the direct relationship between ICME magnetic configurations and variations in ground-level particle fluxes.

Moreover, we discover that the energy spectra of additional particles during ME are limited to 10 MeV due to the low energy of solar protons entering the terrestrial atmosphere. In contrast, the energy spectra of the “missing” FD particles can extend up to 100 MeV, demonstrating that magnetic traps and cradles formed by interactions between ejecta and Earth's magnetic fields can also deflect medium-energy solar protons. These insights advance our understanding of geomagnetic modulation of particle fluxes and bolster predictive models of space weather impacts on particle detection technologies.

16. *Letters of Solar Influences on the Magnetosphere, Ionosphere and Atmosphere (2024) 100(11), 1517.*

The Solar Modulation Events of the 25th Solar Activity Cycle as Seen by Particle Detectors' Networks

A. Chilingarian
A. Alikhanyan National Lab (Yerevan Physics Institute)

Cosmic rays are direct messengers, conveying crucial information on solar-terrestrial relations. Networks of particle detectors continuously monitoring cosmic ray flux on the Earth's surface provide valuable insights complementary to spaceborne detectors operated by NOAA, NASA, and ESA. The ongoing deployment of new particle detectors at mountain altitudes, particularly spectrometers measuring energy release spectra of charged and neutral particles, is a strategic choice for understanding the cause of global count rate variations and their relation to the solar energetic particles (SEP) and intricate interactions between colliding magnetic fields. The energy spectra of particles reaching the detectors during violent solar events allow a direct comparison of the measured energy release spectrum with what is expected under different hypotheses on the

type of solar event and SEP energy spectrum. The importance of using advanced measurement techniques of astroparticle physics to study solar-induced phenomena is underscored by the presented analysis of solar events of the 25th cycle. We apply the SEVAN network's spectrometers and developed spectra recovery techniques to characterize the Forbush decreases of 4 November 2011 and May 10, 2024, the magnetospheric effect of 5 November 2023, and the 74th GLE of May 11. We also formulate a refined definition of the magnetospheric effect to distinguish the magnetospheric effect from other solar events.

17. ***The Astrophysical Journal Letters (2024) 975, L39. Overestimation of Astrophysical Gamma-Ray Energies during Thunderstorms: Synergy of Galactic and Atmospheric Accelerator***

A. **Chilingarian, M.Zazyan**
A. Alikhanyan National Lab (Yerevan Physics Institute)

Particle accelerators abound in space plasmas, saturating the cosmos with fully stripped nuclei and gamma rays, with energies surpassing the capabilities of human-made accelerators by orders of magnitude. Upon reaching Earth's atmosphere, these particles trigger extensive air showers (EASs), generating millions of secondary cosmic rays of lower energies. Free electrons from EASs developing in the atmosphere are seeds for atmospheric electron accelerators. Strong atmospheric electric fields (AEFs) evolving during thunderstorms act as accelerators, amplifying the intensity of electrons many times, significantly enlarging the EAS size (number of electrons). Thus, the energy of the primary cosmic ray recovered by EAS size can be significantly overestimated. Recently discovered by high-altitude EAS arrays, PeVatron candidates (ultra–high-energy (UHE) astrophysical gamma-ray sources) must be carefully examined according to the atmospheric conditions during EAS detection. Large High Altitude Air Shower Observatory and High-Altitude Water Cherenkov Observatory arrays are located in regions of frequent thunderstorms, and an AEF's strength can reach and surpass the critical strength to start relativistic runaway electron avalanches. A few registered UHE gamma rays from stellar sources can be registered at just this time when the AEF highly enhances the EAS size. Thunderstorm ground enhancements are copiously registered at mountain peaks of Eastern Europe, Germany, and Armenia, with energies well above the threshold energy of EAS array scintillators. Thus, the overestimation of the energy of primary particles is not an exotic process but a consequence of already well-established physical phenomena. Consequently, a report on each registered UHE gamma ray should include the recorded time and corresponding weather conditions.

18. ***International Journal of Radiation (2024) 100(11), 1517. doi.org/10.1080/09553002.2024.2396378***

Korogodina V., Arakelyan V., Chilingarian A., et al.

Purpose: To study the adaptation of bacteria to the natural γ-background of mountains and anthropogenic emissions from nuclear power plants; to establish the main factors of variability and speciation of bacteria. Method: Analysis of materials on the radiation background and its impact on living organisms in the landscape of Armenia, calculation of the absorbed dose by microbes due to rock radiation. Results: The review shows the death, reproduction, radioresistance and speciation of bacteria in changing conditions of low variable natural and anthropogenic γ-background.

Conclusion: We assume that γ-rays from rocks activate cellular epigenetic mechanisms that regulate genome expression, signaling and, ultimately, variability of bacteria. Some of them have already been studied, others require research.

19. COSMOS Encyclopedia (in Russian), Chapter: Радиационные условия в нижней части атмосферы Земли

А. А. Чилингарян

Разнообразные ускорители в космической плазме наполняют Галактику высокоэнер- гичными частицами. При входе в атмосферу они создают широкие атмосферные ливни (ШАЛ), состоящие из миллионов вторичных частиц, доходящих до поверхности Земли. Атмосферные электрические поля, которые действуют как крупномасштабные уско- рители электронов, инициируют электрон-фотонные лавины, значительно увеличивая поток космических лучей от ШАЛ. Современные эксперименты по регистрации ШАЛ расположены в высокогорных районах с частыми грозами, создающими сильные атмо- сферные электрические поля (англ. Atmospheric electric field, AEF) над установками. Эти поля модулируют энергетические спектры, значительно увеличивая количество и энергии электронов и гамма-квантов, увеличивая размер ШАЛ, что приводит к завы- шенным оценкам энергии первичных частиц.

MOST CITED CRD PAPERS

(December 30 2024)

KASCADE experiment

KASCADE measurements of energy spectra for elemental groups of cosmic rays: Results and open problems

T Antoni, WD Apel, AF Badea, K Bekk, A Bercuci, J Blümer, H Bozdog, ...
Astroparticle physics 24 (1-2), 1-25

867 citations

A non-parametric approach to infer the energy spectrum and the mass composition of cosmic rays

T Antoni, WD Apel, F Badea, K Bekk, K Bernlöhr, H Blümer, E Bollmann, ...
Astroparticle Physics 16 (3), 245-263

112 citations

MAGIC experiment

Variable very high energy γ-ray emission from Markarian 501

J Albert, E Aliu, H Anderhub, P Antoranz, A Armada, C Baixeras, JA Barrio, ...

The Astrophysical Journal 669 (2), 862

786 citations

Methods for multidimensional event classification: a case study using images from a Cherenkov gamma-ray telescope

R.K. Bock, A. Chilingarian, M..Gaug, F. Hakl, T. Hengstebeck, M. Jiřina, ...
Nuclear Instruments and Methods in Physics Research Section A: Accelerators ...

339 citations

Aragats experiments

Ground-based observations of thunderstorm-correlated fluxes of high-energy electrons, gamma rays, and neutrons

A Chilingarian, A Daryan, K Arakelyan, A Hovhannisyan, B Mailyan, ...
Physical Review D 82 (4), 043009

295 citations

Particle bursts from thunderclouds: Natural particle accelerators above our heads

A Chilingarian, G Hovsepyan, A Hovhannisyan
Physical Review D 83 (6), 062001

165 citations

Correlated measurements of secondary cosmic ray fluxes by the Aragats Space-Environmental Center monitors

A Chilingarian, K Arakelyan, K Avakyan, V Babayan, N Bostanjyan, ...
Nuclear Instruments and Methods in Physics Research Section A: Accelerators ...

106 citations

Recovering of the energy spectra of electrons and gamma rays coming from the thunderclouds

A Chilingarian, B Mailyan, L Vanyan
Atmospheric Research 114, 1-16

98 citations

Neutron bursts associated with thunderstorms

A Chilingarian, N Bostanjyan, L Vanyan
Physical review D 85 (8), 085017

80 citations

Thunderstorm ground enhancements—Model and relation to lightning flashes

A Chilingarian
Journal of Atmospheric and Solar-Terrestrial Physics 107, 68-76

68 citations

Statistical decisions under nonparametric a priory information

A.A. Chilingarian
Computer Physics Communications 54 (2-3), 381-390

66 citations

Aragats Space-Environmental Centre: status and SEP forecasting possibilities

A Chilingarian, K Avakyan, V Babayan, N Bostanjyan, S Chilingarian, ...
Journal of Physics G: Nuclear and Particle Physics 29 (5), 939

64 citations

Role of the lower positive charge region (LPCR) in initiation of the thunderstorm ground enhancements (TGEs)

A Chilingarian, H Mkrtchyan
Physical Review D 86 (7), 07200

59 citations

Multivariate approach for selecting sets of differentially expressed genes

A Chilingaryan, N Gevorgyan, A Vardanyan, D Jones, A Szabo
Mathematical Biosciences 176 (1), 59-69

58 citations

Types of lightning discharges that abruptly terminate enhanced fluxes of energetic radiation and particles observed at ground level

A Chilingarian, Y Khanikyants, E Mareev, D Pokhsraryan, VA Rakov, ...
Journal of Geophysical Research: Atmospheres 122 (14), 7582-7599

48 citations

On the initiation of lightning in thunderclouds

A Chilingarian, S Chilingaryan, T Karapetyan, L Kozliner, Y Khanikyants, ...
Scientific reports 7 (1), 1371

46 citations

Study of extensive air showers and primary energy spectra by MAKET-ANI detector on mountain Aragats

A Chilingarian, G Gharagyozyan, S Ghazaryan, G Hovsepyan, ...
Astroparticle Physics 28 (1), 58-71

46 citations

Structures of the intracloud electric field supporting origin of long-lasting thunderstorm ground enhancements

A Chilingarian, G Hovsepyan, S Soghomonyan, M Zazyan, M Zelenyy
Physical Review D 98 (8), 082001

41 citation

Thunderstorm ground enhancements: Gamma ray differential energy spectra

A Chilingarian, G Hovsepyan, L Kozliner
Physical Review D 88 (7), 073001

41 citations

Lightning origination and thunderstorm ground enhancements terminated by the lightning flash

A Chilingarian, G Hovsepyan, G Khanikyanc, A Reymers, ...
Europhysics Letters 110 (4), 49001

39 citations

Remarks on recent results on neutron production during thunderstorms

A Chilingarian, N Bostanjyan, T Karapetyan, L Vanyan

Physical Review D 86 (9), 093017

34 citations

Structure of thunderstorm ground enhancements

A Chilingarian, G Hovsepyan, T Karapetyan, G Karapetyan, L Kozliner, ...
Physical Review D 101 (12), 122004

33 citations

Investigations of the response of hybrid particle detectors for the Space Environmental Viewing and Analysis Network (SEVAN)

A Chilingarian, A Reymers

31 citations

On the production of highest energy solar protons at 20 January 2005

NK Bostanjyan, AA Chilingarian, VS Eganov, GG Karapetyan
Advances in Space Research 39 (9), 1454-1457

31 citations

Termination of thunderstorm-related bursts of energetic radiation and particles by inverted intracloud and hybrid lightning discharges

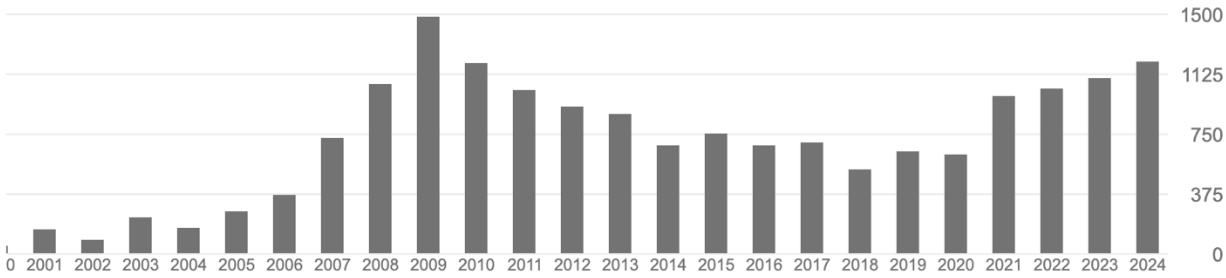
A Chilingarian, Y Khanikyants, VA Rakov, S Soghomonyan

Atmospheric Research 233, 104713

31 citations

GOOGLE Citation summary ***(https://scholar.google.de/citations?user=_hOAVu4AAAA***

	All	Since 2019
Citations	17956	5620
h-index	62	38
i10-index	193	117



LAST PRESS RELEASES

PR 54 **26.09.2024**

Yerevan State University Students Visit Aragats and Nor Amberd Research Stations

On September 24, 2024, 30 Yerevan State University (YSU) students went on an educational excursion to the Aragats and Nor Amberd research stations. The excursion aimed to enhance the students' understanding of ongoing atmospheric and solar physics research at the Aragats research station by introducing them to cutting-edge research in the Cosmic ray division (CRD) of YerPhI.

At Aragats research station, Dr. Tigran Karapetyan led an informative tour of the monitoring facilities, introducing the students to the advanced particle detectors and field meters used for cosmic ray astrophysics and studies of high-energy physics in the atmosphere. Students gained valuable insights into modern experimental physics's technical and scientific aspects.

Following visiting Aragats, students proceeded to the Nor Amberd research station. They attended a lecture by Prof. Ashot Chilingarian, who presented the latest advancements in cosmic ray and atmospheric physics, emphasizing their significance in understanding fundamental problems of cosmology. He also discussed the ongoing research on solar activity and its impact on Earth's environment, offering students a glimpse into the future of space weather issues.

The excursion provided YSU students with a unique opportunity to witness advanced scientific research in action, interact with experts in the field, and explore the practical applications of their studies. Both the Aragats and Nor Amberd research stations are crucial in advancing scientific knowledge in Armenia and internationally, contributing to global efforts in understanding the cosmos and Earth.

Figure 1. Students at the seminar hall of Nor Amberd Research Station with Prof. Chilingarian and Dr. Tigran Karapetyan

Figure 2. Prof. Chilingarian delivered a lecture on the latest advancements in cosmic ray and atmospheric physics

Figure 3. Dr. Tigran Karapetyan introduces the students to the Aragats Research Station facilities

PR 55 **1.10.2024**

A new powerful source of atmospheric ionization was presented at the Biosphere conference in Prague.

On October 1, 2024, Prague Metrology Institute organized a training course on the influence of extraterrestrial radiation on the biosphere. A. Chilingarian delivered a lecture on an overlooked atmospheric ionization source discovered on Aragats. Occasionally, the day before, ScienceAlert hizhlighted the recent CRD paper recommended by APS. We share this issue with you.

Figure 1. A.Chilingarian introduces powerful electron accelerators operated in thunderclouds.

Overlooked Weather Phenomenon Produces Gamma Rays in Our Atmosphere

PR 56 **28.10.2024**

TEPA Conference in Yerevan

The 14th annual meeting “Thunderstorms and Elementary Particle Acceleration” (TEPA, Yerevan, Armenia, October 14-17, (http://www.crd.yerphi.am/TEPA_2024) was organized by the Cosmic Ray Division (CRD) at the Yerevan Physics Institute. In addition to the traditional topics of observations of particle fluxes on Earth’s surface, in the troposphere, and in space, the detection of solar events abruptly increased with the approached maximum of the 25 solar activity cycle and high-energy cosmic ray physics has been added. The conference highlighted the synergy between cosmic ray physics and high-energy atmospheric physics, particularly through the interrelation of galactic and atmospheric particle accelerators. Galactic accelerators supply atmospheric ones with seed electrons from extensive air showers (EASs) initiated by high-energy protons and nuclei entering the terrestrial atmosphere. Conversely, atmospheric electron accelerators significantly increase the number of electrons detected by surface arrays, thereby introducing biases in primary particle energy estimation.

Since the inception of Thunderstorm Ground Enhancement (TGE) research in 2009, the CRD has consistently organized international conferences to explore intriguing problems in high-energy atmospheric physics and to advance collaborative studies.

The Aragats Cosmic Ray Research Station remains the premier institution for TGE research. TGEs occur through relativistic runaway electron avalanches (RREA) in atmospheric electric fields (AEF). Particle bursts, when registered on the surface, are called TGEs. In the atmosphere, they cause gamma glows. When seen on orbiting gamma observatories ≈500 km from their origin, they are called TGFs.

In 2009, the CRD initiated TGE research on Aragats and established the SEVAN particle detector network to monitor TGEs across Eastern Europe, Germany, and Armenia. The atmospheric electron accelerators produce copious particles with energies of tens of MeV, covering vast atmospheric volumes and expansive areas on Earth's surface. This substantial flux of electrons and gamma rays has coexisted with life on Earth for billions of years, undoubtedly influencing various aspects of the geospace and biosphere.

In 2023, at Aragats, several episodes of minute-long stable electron fluxes spanning 50,000 square meters were observed. A massive electron beam emerged within the thundercloud, triggering gigantic avalanches of electrons, photons, and neutrons. This newly identified source of energetic radiation from thunderclouds represents a significant factor in geophysics and warrants inclusion in comprehensive Earth models.

During the discussion was mentioned that particle fluxes above and below thunderclouds originate from RREA, which produces the same distribution of arriving particles coming uniformly or in patches (gamma glows measured several km above source by detectors on aircraft, and TGF several hundred km above source measured by orbiting gamma observatories). The duration and intensity of observed fluxes are contingent upon the distance of the detector from the source, yet they share the same underlying physical processes. Consequently, conference participants strongly advocated for a community-wide discussion on clarifying the terminology to describe these phenomena. This revision aims to eliminate confusion in future research and agree on a proper citation practice in publications.

During an excursion to the Aragats Research Station at 3200 m, participants visited new facilities and particle detectors from various countries hosted at this prime location.

- A Czech Group from the Nuclear Physics Institute in Prague installed a new detector at Aragats.
- A group from the French National Centre for Space Studies (CNES) will shortly bring their detector in November.
- The following year, European European groups plan to deploy particle spectrometers and photometers.

The joint operation of these detectors at Aragats ensures that detectors for future balloon, aircraft, and space missions will be calibrated using the detectors and facilities on Aragats. The station registered tens of TGEs annually, with the strongest events exhibiting significant electron content.

The 14th Annual TEPA Meeting underscored the critical interplay between cosmic ray and atmospheric physics, particularly TGEs, EASs, and RREAs. The conference facilitated international collaborations, showcased new results at the Aragats Research Station, and emphasized the need for standardized terminology to streamline future research endeavors. The continued efforts of the CRD and its partners promise significant advancements in our comprehension of high-energy atmospheric phenomena and their broader impacts on Earth's geospace.

PR 57 **6.11.2024**

Synergy of Galactic and Atmospheric Accelerators Unveiled

One of the most intriguing challenges in astrophysics is identifying extreme particle accelerators capable of pushing protons to PeV (10^{15} eV) energies, known as ‘PeVatrons.’ Recently, high-altitude detectors like LHAASO in China and HAWC in Mexico have observed gamma rays well exceeding 300 TeV. Yet, questions remain on how such ultrahigh-energy particles are generated by astrophysical sources.

The "knee" in the cosmic-ray spectrum at 3–4 PeV suggests an upper limit to proton energies that supernova remnants (SNRs) can achieve. Gamma rays resulting from proton-proton collisions are expected to reach up to ~300 TeV in such environments. However, despite ongoing research, ground-based Imaging Atmospheric Cherenkov Telescopes (IACTs) have detected gamma rays at only about 100 TeV.

LHAASO's recent catalog of ultra-high-energy (UHE) sources—compiled from data between January 2020 and September 2022—lists 43 potential PeVatron candidates. This catalog relies on detailed statistical models of particle interactions within Earth's atmosphere. However, one significant factor—the influence of atmospheric electric fields (AEFs)—was not included in the analyses.

In the last decade, researchers have found that AEFs during thunderstorms can act as natural electron accelerators, amplifying particle showers and potentially leading to overestimating primary gamma-ray energies. As cosmic-ray electrons enter AEF, they gain energy, runaway, and emit additional gamma rays through bremsstrahlung, triggering electron-photon avalanches that multiply the electron count by orders of magnitude. This cascade effect can significantly inflate the estimated energy of the initial gamma ray. As illustrated in Figure 1, this multiplication effect can increase the electron count by **1 to 2 orders of magnitude**, significantly inflating the estimated energy of the primary gamma-ray. The left side of the figure shows the normal evolution of a particle shower, while the right side illustrates the expanded shower in a strong AEF.

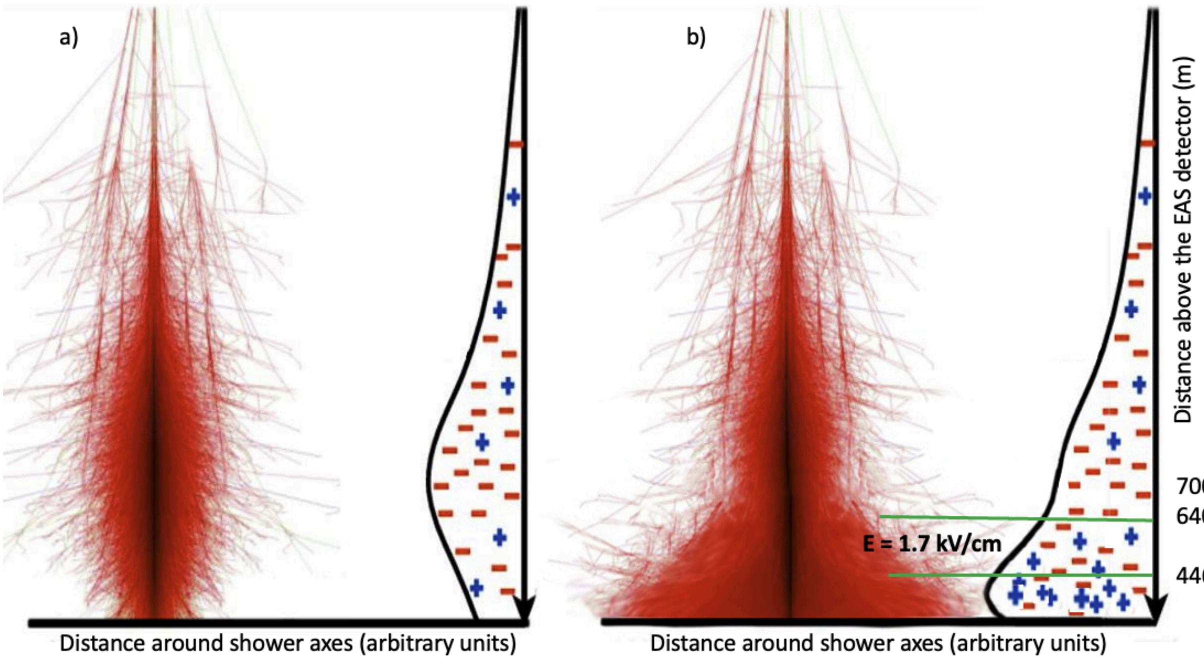


Figure 1. EAS propagation in AEF. During fairweather (a) and thunderstorm (b). The 1.7 kV/cm electric field was introduced at heights 4460-6400 above LHAASO detectors.

A recent study published in *Astrophysical Journal Letters* [1] reveals this atmospheric effect's impact on energy measurements of cosmic rays, noting that during LHAASO's 1,441-day data collection, over 200 thunderstorms were recorded. This suggests that several high-energy detections may actually be lower-energy events magnified by AEFs. Consequently, examining the atmospheric conditions for each UHE event is essential to accurately identify true PeVatrons, marking an exciting convergence of space and atmospheric sciences.

This new insight could reshape the hunt for PeV photon sources and call for further interdisciplinary collaboration to enhance our understanding of cosmic ray phenomena.

[1] A. Chilingarian, M. Zazyan, *Overestimation of Astrophysical Gamma-Ray Energies During Thunderstorms: Synergy of Galactic and Atmospheric Accelerators*, **Astrophysical Journal Letters** 975 (issue 2), L39. DOI: 10.3847/2041-8213/ad85e1

PR 58 **8.11.2024**

Two leading scientific publications featured discoveries made by Armenian physicists working at the Aragats Cosmic Ray Station.

In an article titled *"Mountaintop Observations of Gamma-ray Glow Could Shed Light on Origins of Lightning,"* Jacklin Kwan from *Physics World* emphasizes the station's role in understanding lightning formation. She writes, "Research done at a mountaintop cosmic-ray observatory in Armenia has shed new light on how thunderstorms can create flashes of gamma rays by accelerating electrons. Further study of the phenomenon could answer important questions about the origins of lightning." For more details, see the full article: Physics World article.

Similarly, Michelle Starr from *Science Alert* highlights the surprising electric field strength observed near Aragats in her article, *"Overlooked Weather Phenomenon Produces Gamma Rays in Our Atmosphere."* She states, "The electrical effects of a thunderstorm are not confined just to high up in the atmosphere. Close to the ground, Earth's atmosphere hums with intense electric fields that accelerate particles, flinging electrons in ways that force atoms to glow with gamma rays." The full article is available here: Science Alert article.

These findings were published in *Physical Review D* in the original research paper by Chilingarian A., Sargsyan B., Karapetyan T., et al. (2024), *Extreme Thunderstorm Ground Enhancements Registered on Aragats in 2023, Physical Review D* 110, 063043.

Below is a recent photograph (by Anahid Margaryan) of the Aragats station taken on November 6, in the background, Mount Ararat, situated 100 km from Aragats.

NATURE 30 September 2024

By MICHELLE STARR

https://www.sciencealert.com/overlooked-weather-phenomenon-produces-gamma-rays-in-our-atmosphere

The electrical effects of a thunderstorm are not confined just to high up in the atmosphere. Close to the ground, Earth's atmosphere hums with intense electric fields that accelerate particles, flinging electrons in ways that force atoms to glow with gamma rays.

From atop a mountain in Armenia, scientists have taken a close look at this mysterious meteorological phenomenon.

At the Alikhanyan National Science Laboratory's cosmic ray facility on Mount Aragats, physicist Ashot Chilingarian and his colleagues have been working to understand Thunderstorm Ground Enhancements, or TGEs.

This electromagnetic enhancement, Chilingarian says, has been overlooked in thunderstorm research – but it could be a piece of the puzzle in our understanding of the physical Universe, from thunderstorms here on Earth, to the cosmic rays that travel vast distances across space.

"Each day, 40,000 thunderstorms occur. Numerous networks detecting atmospheric discharges and satellites with precise optical instruments are monitoring lightning flashes. Still, when we started TGE research, nobody monitored the huge flux of mega-electronvolt (MeV) electrons bombarding our planet and space above it," he told ScienceAlert.

"We established the SEVAN particle detector network ten years ago to monitor TGEs in Eastern Europe, Germany, and Armenia. Electron accelerators with energies of tens of MeV cover vast volumes in the atmosphere and many square kilometers on the Earth's surface.

"This huge flux is accompanied by life on Earth through its billion years of evolution and surely influences all aspects of the geospace and biosphere."

TGEs consist of electric fields in the atmosphere, generated by thunderstorms. Within these electric fields, electrons are accelerated to high speeds – speeds approaching that of light in a vacuum, or relativistic speeds.

These are known as relativistic runaway electron avalanches, propelled by the electric field both towards the ground and upward into the atmosphere. It's these electrons that produce the radiation.

When they decelerate suddenly, deflected by a collision with an atomic nucleus in the atmosphere, the loss of energy manifests as gamma rays – a form of radiation known as bremsstrahlung radiation.

Using their network of detectors, Chilingarian and his colleagues collected data on thunderstorms across Europe in 2023, performing detailed measurements of the electrons and the gamma radiation that occurred during the 56 intense TGEs they recorded.

The most intense TGEs mostly took place from May to July, and the most powerful was recorded on Mount Lomnický štít in Slovakia in May. For this one event, the particle flux was 100 times the normal, fair-weather level. In total, there were seven events that exceeded the fair weather flux by more than 75 percent.

"We measure the stable electron flux on Earth's surface, covering a hundred thousand square meters. Some mechanism provides this stability for a minute or more," Chilingarian explained.

"A huge electron beam emerges in the thundercloud, where the charge structure changes on the second-time scale. Atmospheric discharges kill the potential difference, but the flux is stable. It was exciting to measure!"

Surprisingly, the researchers also found that the electric field is much closer to the ground than they expected to find. They measured a strong electric field strength down to 50 meters (164 feet) above ground.

"This discovery was astonishing to meteorologists, who didn't believe it until we presented exhaustive proof," Chilingarian noted.

The consistency of the acceleration, able to maintain particle flux for up to several minutes, as well as the low height of the electric field, reveals new details about the structure of atmospheric electric fields, and thunderstorms, that we didn't know before.

For example, TGEs might provide a pathway whereby lightning strikes can reach the ground. And their role in geophysics needs to be investigated. The researchers have made an open-access TGE database available for the scientific community to explore and analyze.

Their thunderstorm research is only part of the work performed on Aragats. This year, the Sun has reached a frenzy as it approaches solar maximum, the peak of its activity cycle, sending particles spewing into space powered by coronal mass ejections.

Chilingarian and his colleagues have also detected solar events with the mountaintop equipment, publishing three papers with a fourth on the way.

"Violent explosions in our galaxy also send ultra-high energy particles to the solar system.
Recently, Pevatrons, sources of 1015 eV gamma rays, were discovered. We critically analyzed this discovery based on our knowledge of atmospheric physics," Chilingarian told ScienceAlert.

"The synergy of atmospheric, space, and solar accelerators is important for understanding nature!"

The findings are published in Physical Review D.

Chilingarian A., Sargsyan B., Karapetyan T., D. Aslanyan , S. Chilingaryan , L. Kozliner, and Y. Khanikyanc (2024), Extreme thunderstorm ground enhancements registered on Aragats in 2023, Physical Review D 110, 063043.

HIGHLIGHTED ARTICLE in Science

December 20, 2024

Could thunderstorms be exaggerating the strength of mysterious gamma rays from outer space?

Storms may be confounding measurements at high- altitude observatories of the universe’s highest energy light

In 2021, astronomers at a remote observatory in Tibet won acclaim for detecting the universe’s highest energy light: a handful of gamma ray photons reaching energies of more than 1 petaelectronvolt (PeV). Not only did the gamma rays hint at the existence of cosmic particle accelerators thousands of times more powerful than any atom smasher on Earth, but

they could also be traced back on the sky to identify the engines’ locations in the galaxy.

But astrophysicist Ashot Chilingarian worries China's Large High Altitude Air Shower Observatory (LHAASO) was getting fooled by something rather less cosmic: thunderstorms. The observatory doesn't capture gamma rays directly; instead, it detects showers of subatomic particles generated when an ultra–high-energy gamma ray slams into the upper atmosphere. In a study published last month in *The Astrophysical Journal Letters*normal, Chilingarian says the powerful electric fields of a thunderstorm can intensify those particle showers, causing LHAASO astronomers to overestimate the energy of the original gamma ray.

"I'm not saying that all these PeV events are from thunderstorms, but I'm just saying, please consider that it could be a possibility," says Chilingarian, director of the Aragats Cosmic Ray Research Station. He wants LHAASO to release weather data associated with their gamma ray claims, to show that thunderstorms aren't confounding the measurements.

LHAASO scientists say they can already rule out thunderstorm effects. But Johannes Knapp, an astroparticle physicist at DESY, a particle physics laboratory in Germany, says the effects are plausible and astronomers at LHAASO and other high-altitude gamma ray observatories should take care to account for them. "If by chance some of these events happen during a thunderstorm, shower particles could be amplified by a factor of 10 or 100," Knapp says.

The gamma rays in question are the offspring of cosmic rays—protons and other atomic nuclei, that bombard Earth at nearly the speed of light. Their sources have not been pinned down because the particles are charged, enabling interstellar magnetic fields to bend their paths on their way to Earth. However, as cosmic rays collide with clouds of gas surrounding their sources, they emit gamma ray photons, usually about one-tenth as energetic as the cosmic rays themselves. Photons, because they are uncharged, follow a straight path to Earth, where they slam into

air molecules to produce the secondary particles that observatories such as LHAASO can detect. From the intensity and size of the air showers, astronomers can infer the energy of the gamma rays, whereas the shape of the showers gives a handle on the direction of the gamma rays. Astronomers have traced them back to sources that may include the remnants of supernovae, spinning neutron stars called pulsars, and winds in stellar nurseries.

However, the electric fields in thunderstorms can also accelerate charged particles to relativistic speeds, causing them to emit flashes of gamma rays known to atmospheric physicists as the "gamma glow." Like gamma rays from across the cosmos, these photons can also collide with air molecules, creating particle showers that might be picked up by LHAASO's detectors.

Based on an analysis of 56 thunderstorms at a mountaintop observatory in Armenia, Chilingarian and colleagues in September presented evidence that electric fields in thunderstorms could be stronger than previously thought. In the new study, he and his colleague Mary Zazyan of the Yerevan Physics Institute modeled the effect of such an electric field on a particle shower at LHAASO. They found it significantly boosted the number of high energy particles, which would cause researchers to hugely overestimate the energy of the gamma ray source.

However, LHAASO spokesperson Zhen Cao says his team already monitors the weather and deploys antennas to measure atmospheric electric fields. He says he sees no "obvious connection" between the PeV gamma ray events and thunderstorms. “We have a team of more than 10 researchers dedicated to working on this topic,” he says, adding that thunderstorms are relatively rare in the mountains of Tibet.

At Mexico’s High Altitude Water Cherenkov Observatory (HAWC), which has detected gamma rays nearly as energetic as those at LHAASO, researchers also monitor electric fields and take care to cross-check their data for confounding storms, says Kelly Malone, a scientist at Los Alamos National Laboratory (LANL) and member of the HAWC collaboration.

“Ultra–high-energy gamma rays are evenly distributed in time throughout our data, which would not be true if they were attributed to thunderstorms,” she says.

A more mundane reason to doubt that thunderstorms are contaminating HAWC’s gamma ray events is that the team often doesn’t save data during severe weather, says Pat Harding, a LANL scientist who leads the HAWC collaboration. “The biggest reason for that, honestly, is that our experiment often breaks during thunderstorms,” he says.

But Harding doesn’t mind LHAASO’s record-setting detections getting some extra scrutiny. “In cases where there’s just one or two specific events creating a lot of excitement,” he says, “you have to open it up as much as possible to let people try and poke at it.”

CRD Project: INSTALL YOUR DETECTOR ON MOUNT ARAGATS in 2025 (Open Competition)

The Cosmic Ray Division of A. I. Alikhanyan National Laboratory, the world’s biggest high-altitude cosmic ray research station for monitoring cosmic ray fluxes, declares open competition for a project in High-energy Physics in the Atmosphere (HEPA) to be performed on Aragats, see Fig.1. Aragats is a unique place for HEPA research. Each year, in May-June and September-October, tens of intense TGEs (Thunderstorm ground enhancements) covered the particle detectors with millions of electrons and gamma rays (rarely by neutrons). However, proposals for solar physics, space weather, atmospheric and environmental physics experiments will also be considered. We will approach this through a multivariate, multidisciplinary analysis of physical phenomena, measuring all relevant parameters. The scientific plans of CRD for 2025 are attached.

The competition mirrors how researchers propose to use the laboratory facilities specially built for this competition. The laboratory (9 m^2 area) is equipped with an electric field sensor, a weather station, and two all-sky cameras, see Fig. 2. The mentioned facilities will be provided to the winning projects for multivariate research of Atmospheric physics phenomena, including registration of the Thunderstorm ground enhancements (TGEs), air glows, electric fields, lightning occurrences, natural gamma radiation, and other environmental studies. Researchers/students can add particle detectors, photometers, high-speed cameras, and other equipment for their experiments. Standard data-acquisition (DAQ) electronics and online computers are anticipated to be a part of the installed facility. Multiple detectors and spectrometers, weather stations, and near-surface electric field monitoring systems operated at Aragats station can calibrate newly installed facilities. CRD will provide the Internet connection, database, and analysis platform for storing and accessing data.

The unexpected rise of solar activity points to reaching the solar maximum in 2024. After a long period of quiet Sun and a rather small 24^{th} solar activity cycle, research of near-earth environments affected by huge magnetized clouds ejected from the Sun again became relevant. The nonlinear interaction between disturbed interplanetary magnetic and geomagnetic fields causes various effects in geospace, ranging from damage to satellite electronics and some surface industries to the beautiful Aurora Borealis. The cosmic rays are messengers bringing direct information on these complex processes. Networks of particle detectors 24/7 monitoring the intensities of cosmic rays' incidents on the Earth's surface are an important addition to the spaceborne particle detectors operated by NOAA, NASA, ESA, and other space agencies. In 2024, we reported observing the very rear Geomagnetic effect, Forbush decreases (FD), and ground level enhancement (GLE) measured by particle detector networks operated on middle latitudes on mountain tops. For the first time, we measured the energy spectrum of the Geomagnetic effect, FD, and GLE, confirming their physical model and improving the classification scheme. Therefore, we also welcome Solar physics and Space weather research proposals.

Proposals will be judged based on motivation and creativity, and the winning team will have the chance to discuss and tune their project ideas with CRD researchers before installing their facilities on Aragats. They will be invited to spend one week at Aragats (in June-August) for their experiment, with the unique opportunity to join the CRD team. The results are supposed to be summarised in a report and presented at the upcoming TEPA conferences.

Projects in free format, including all proposed facility specifications, should be provided to CRD by 1 March 2024. All correspondence should go to Asaturyan Zara, zaraasaturyan.87@gmail.com. The winners will be declared on March 15, 2024.

Links to the CRD site and CRD publications:http://crd.yerphi.am/

http://crd.yerphi.am/crd_publications

Figure 1. All four peaks of Aragats, Kare Lake, and Aragats high altitude research station located at an altitude of 3200 m.

Figure 2. Experimental Laboratory provided to the winner projects