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Սարգսյան Բալաբեկ Սարգսի

Ամպրոպային վերգետնյա ավելացումների ժամանակ էլեկտրոնների և գամմա ճառագայթների էներգետիկ սպեկտրները 0.3 -100 ՄէՎ էներգիաների տիրույթում

Ա.04.16 - «Միջուկի, տարրական մասնիկների և տիեզերական ճառագայթների ֆիզիկա» մասնագիտությամբ ֆիզիկա-մաթեմատիկական գիտությունների թեկնածուի գիտական աստիճանի հայցման ատենախոսության

ՍԵՂՄԱԳԻՐ

ԵՐԵՎԱՆ -2024

A. I. ALIKHANYAN NATIONAL SCIENCE LABORATORY
(YEREVAN PHYSICS INSTITUTE)

Sargsyan Balabek

Energy spectra of electrons and gamma rays in the energy range of 0.3-100 MeV during Thunderstorm Ground Enhancements

SYNOPSIS

of Dissertation in 01.04.16 – "Nuclear, elementary particle and cosmic ray physics" for the degree of candidate in physical and mathematical sciences

YEREVAN – 2024

Ատենախոսության թեման հաստատվել է Ա. Ի. Ալիխանյանի անվան Ազգային Գիտական Լաբորատորիայի (ԵրՖԻ) գիտական խորհրդում:

Գիտական ղեկավար՝
Ֆիզ. մաթ. գիտ. դոկտոր — Աշոտ Աղասիի Չիլինգարյան (ԱԱԳԼ)

Պաշտոնական ընդդիմախոսներ՝
Ֆիզ. մաթ. գիտ. թեկնածու — Հրանտ Ռուբենի Գուլքանյան (ԱԱԳԼ)
Ֆիզ. մաթ. գիտ. դոկտոր — Պավել Ալեքսանդրի Կլիմով (Լոմոնոսովի անվան Մոսկվայի Պետական Համալսարան)

Առաջատար կազմակերպություն՝ — Երևանի Պետական Համալսարան

Ատենախոսության պաշտպանությունը կայանալու է 2025 թ. հունվարի 21-ին ժամը 14:00 -ին, ԱԱԳԼ-ում գործող ԲԿԳԿ-ի 024 «Ֆիզիկայի» մասնագիտական խորհրդում (Երևան, 0036, Ալիխանյան Եղբայրների փ. 2):
Ատենախոսությանը կարելի է ծանոթանալ ԱԱԳԼ-ի գրադարանում:
Սեղմագիրն առաքված է դեկտեմբերի 12-ին:

Մասնագիտական խորհրդի գիտական քարտուղար՝
Ֆիզ. մաթ. գիտ. դոկտոր — Հրաչյա Մարուքյան

The subject of the dissertation is approved by the scientific council of the A. I. Alikhanyan National Science Laboratory (YerPhI).

Scientific supervisor:
Doctor of ph-math. sciences — Ashot Chilingarian (AANL)

Official opponents:
Candidate of ph-math. sciences — Hrant Gulkanyan (AANL)
Doctor of ph-math. sciences — Pavel Klimov (MSU after Lomonosov)

Leading organization: — Yerevan State University, Yerevan, Armenia

The defense will take place on the 21 of January at 14:00 during the "Physics" professional council's session of HESC 024 acting within AANL (2 Alikhanyan brothers str., 0036, Yerevan, Armenia).

The dissertation is available at AANL library.
The synopsis is sent out on the 12 of December, 2024.

Scientific secretary of the special counsil:
Doctor of ph-math. sciences — Hrachya Marukyan

General description of the thesis

Importance of obtained results:

1. *Understanding Atmospheric Electrification and Natural Gamma Radiation (NGR)*
The discovery of new physical phenomena, such as Thunderstorm Ground Enhancements (TGE), is crucial for advancing our understanding of atmosphere electrification, lightning initiation, and the potentially dangerous consequences of severe weather events. These findings contribute to developing more accurate weather forecasting models and strategies for mitigating severe weather risks.
2. *Insights into Particle Acceleration Mechanisms in Atmospheric Plasmas:*

Elucidating mechanisms driving electron acceleration in atmospheric plasmas enhance our understanding of terrestrial phenomena and provide insights into much more energetic processes occurring in space plasmas. This knowledge can aid in studying phenomena such as supernova explosions, neutron stars, and black hole jets, contributing to advancements in astrophysical research.

3. *Utilization of Atmospheric Electric Fields for Monitoring and Safety Purposes:*

The revelation of large atmospheric electric fields, particularly those near the Earth's surface, presents opportunities for practical applications. Developed particle spectrometers can monitor these fields, providing early alerts and warnings during rocket launching and charging. This enhances safety measures and helps mitigate potential hazards associated with electrical discharges.

Thesis objective:

- *Analyze the natural radiation measured on Aragats research stations by precise spectrometers.*
- *Recover energy spectra of TGE electrons and gamma rays and Radon progeny spectrograms.*
- *Analyze the gamma-ray flux enhancements during thunderstorms, emphasizing the most pronounced spectral lines, 214Pb (0.352 MeV) and 214Bi (0.609, 1.12, and 1.76 MeV).*
- *Examine the Radon progeny correlations with disturbances of the near-surface electric field (NSEF).*
- *Measure NGR intensity during fair weather and large TGEs.*
- *Compare the concentration of different Radon isotopes in the rainwater and the air.*
- *Investigate the positron flux and asymmetry of the intensity of the 511 keV "annihilation" line at positive and negative NSEF.*

Scientific innovation:

1. Discovery of the radon circulation effect.
2. Discovery of amplification of NGR and positron flux during thunderstorms.
3. Registration of a new type of optical luminescence in the lower atmosphere.
4. Measuring the extension of the horizontal component of the atmospheric electric field over tens of kilometers.

Personal Commitment:

1. **Detector and Electronics:**
Active involvement in commissioning and installing particle detectors and modernizing their electronics at key locations such as Aragats (Armenia), Milechovka (Czech Republic), Hamburg, and Zugspitze (Germany). By ensuring the proper setup and calibration of detectors, reliability and accuracy were achieved during multiyear experiments.
2. **Experimental Work on TGE Registration:**
A hands-on role in conducting experiments on TGE registration, leveraging the SEVAN network and other particle detectors positioned on the slopes of Mt. Aragats.
3. **Data Analysis and Interpretation:**
The analysis of multivariate data obtained from networks of particle detectors provides meaningful physical insights into high-energy atmospheric processes.

Main points for defense:

1. **Elaboration of Thunderstorm Ground Enhancements (TGE) and electron energy spectra recovery:**

Electron and gamma-ray energy spectra measurements at the highest summits of Eastern Europe, Armenia, and Germany provided evidence for a new physical phenomenon known as Thunderstorm Ground Enhancements (TGE).

2. **Discovery of Radon Circulation Effect:**

Uncovered the Radon circulation effect, elucidating the phenomenon of aerosols lifting with attached Radon progeny into the atmosphere and subsequent return to the ground through precipitation events.

3. **Positron Flux Enhancement during Thunderstorms:**

Discovery of a 5-fold enhancement in positron flux during thunderstorms by forming a fourth dipole between the lower positively charged region and the ground.

4. **Amplification of Natural Gamma Radiation:**

Observed a large boost in natural gamma radiation levels during disturbances of the atmospheric electric field, shedding light on the relationship between atmospheric dynamics and radiation phenomena.

5. **Registration of Light Glows during TGE Events:**

Registrations of light glows during TGEs, a new optical phenomenon in the lower atmosphere

6. **Observation of Large-Scale Atmospheric Electric Field:**

Measuring large-scale atmospheric electric field, accelerating electrons at cosmic ray stations Aragats and Nor Amberd, 13 km apart.

7. **Methodological Developments:**

- *Developed methodologies for studying Radon progeny gamma radiation and estimating positron flux during thunderstorms.*
- *Modernized the SEVAN particle detector to enable precise energy spectra measurements of electrons and gamma rays separately*

Conferences:

The main results of the dissertation have been reported

- *Thunderstorms and Elementary Particle Acceleration (TEPA-2020),* ***October 12-15, 2020,*** *NorAmberd International Conference Centre of the Yerevan Physics Institute, Byurakan, Aragatsotn Province, Armenia*
- *TEPA_2022(THUNDERSTORMS & ELEMENTARY PARTICLE ACCELERATION),* ***October 17-20, 2022,*** *Nuclear Physics Institute of the CAS, Prague,Czechia.*
- *TEPA 2023,* ***October 2-5, 2023,*** *Conference Hall of the Czech Academy of Sciences, Národní 3, Prague, Czechia*
- *TEPA 2024,* ***October 14-17, 2024,*** *Conference Hall of the Cosmic Ray Division of Yerevan Physics Institute, Yerevan, Armenia.*

Publications:

Twelve scientific articles, the list of which is given at the end of the synopsis, have been published based on the thesis results.

Structure of the dissertation

The dissertation is 108 pages long and includes an introduction, six chapters, a conclusion, 134 references, 76 figures, and 11 tables.

Chapter 1

Chapter 1 describes the origin of Natural Gamma Radiation (NGR) and gamma spectrometers used on Aragats [1]. The TGE registration with both types of spectrometers allows us to measure and understand TGE composition and behavior at different time and energy scales. Various particle detectors and spectrometers at Aragats Space Environmental Center (ASEC) monitor 24/7 particle fluxes of almost all species of the secondary CR flux. We use the ORTEC-905-4 spectrometer for Natural gamma-ray radiation (NGR) spectroscopy. Fig. 1b. The relative energy resolution of FWHM (full width at half maximum) is approximately 8% at energy levels of 0.3-3 MeV. Also, we utilize a network of six large NaI spectrometers to observe TGE gamma radiation, Figure 1a. The sensitive area of each spectrometer is roughly 0.035m2 (11.5 x 30 cm) with a thickness of 11.5 cm, which is about six times larger than the ORTEC spectrometer's (a cylinder with a 3" length and diameter, cross-section of 0.0056 m^2). These NaI spectrometers provide ample statistics, with 50,000 to 60,000 counts per minute, to recover the TGE energy spectrum in the energy range of 0.3 – 50 MeV. However, the energy resolution of large NaI spectrometers is much worse than ORTEC's, and we cannot resolve the isotope spectral lines with it. Poor energy resolution turns discrete isotope energies into broad distributions. Combining ORTEC with large NaI spectrometers allows us to perform accurate isotope spectroscopy within the energy range of 0.3-3 MeV [4,5]. Additionally, we can retrieve energy spectra of up to 50 MeV for the most significant observed TGEs.

Figure 1. Large NAI spectrometer with lead filters above a); ORTEC spectrometers with lead filters from the sides and the bottom b).

To investigate hour-to-hour variations of Radon progenies and enumerate the spectral lines, we monitor the NGR from the Rn-222 daughter chain with an ORTEC firm spectrometer: NaI(Tl), type 905-4 (ORTEC), 3" x 3" (diameter and length), 1024 channels, very high stability, and relative energy resolution (FWHM ~ 7.7%).
The network of 5 large NaI spectrometers with size 12 x 12 x 30 cm continuously measure particle fluxes on Aragats from 2010.

Figure 2 shows the time series of count rates measured by NaI spectrometers N 2(upper curve) and N 4 (lower curve, 4 cm lead on the top) [2]. The disturbances of NSEF measured by electric mill EFM-100 are shown between these curves. In the insets to the left (a and c), we demonstrate a time series of maximal energies of the recovered differential energy spectra for each minute of TGE. In the right insets (b and d), we demonstrate the examples of these one-minute energy spectra for both spectrometers. 50 MeV peak near 21:00, seen in insets 2a and 2b, corresponds to high energy gamma rays from RREA developed in the thunderous atmosphere above the detector. The RREA process produced a near-vertical flux of gamma rays. The maximal energies measured by the spectrometer with lead on the top (isotropic gamma rays from radon progenies decay, see Figs. 2c and 2d) never exceed 2 MeV.

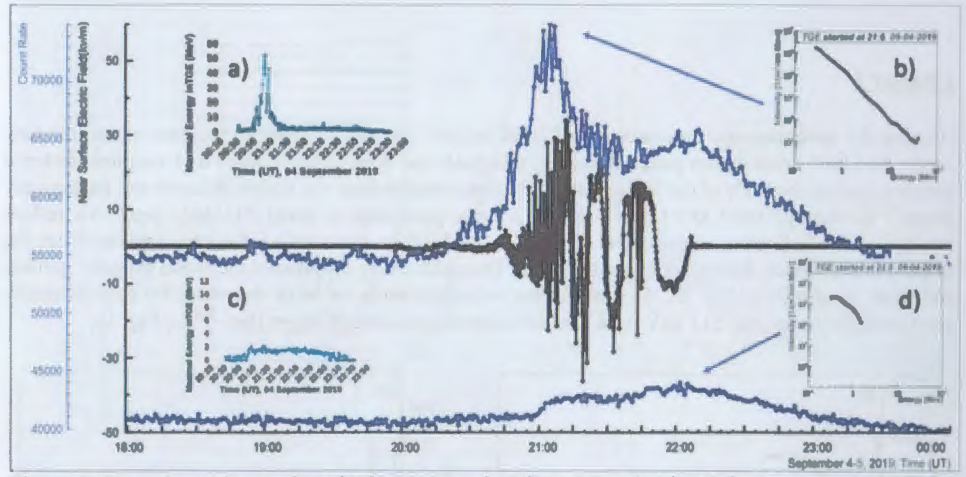


Figure 2. One-minute time series of TGE measured on September 4 c) by NaI spectrometers with the lead filter on top and without lead. The disturbances of the near-surface electric field are shown between these curves. In insets a) and c), we show the histogram of maximal energies of energy spectra measured each minute by both spectrometers and in insets b) and d) -examples of measured energy spectra.

Summarizing, we analyzed the TGE development according to the main physical processes responsible for TGE origination, namely RREA and Radon progenies radiation. We explain the impact of both processes on the TGE shape and energy spectrum. We conclude that TGE is a rather complicated phenomenon having roots in at least three physical processes related to thunderous atmospheres. Gamma radiation of Radon origin starts when the updraft of aerosols (with attached radiated isotopes) provides a sufficient concentration of gamma-ray emitters at heights above particle detectors. RREA radiation is near-vertical, whereas isotope radiation is isotropic and can be registered at large zenith angles [3].
Thus, the TGE time series are rather complicated and are controlled by the intracloud electric field and near-surface electric field, and by the decay time of most frequent 214Pb (0.354 MeV) and 214Bi (0.609 MeV), the shape of the TGE can be separated into three species:

- RREAs, providing up to a hundred percent peaks above the background, lasting a few minutes with particle energies reaching tens of MeV; lightning flash usually interrupts particle fluxes. Particles come from the near-vertical direction.
- Low energy Radon progeny radiation (< 2MeV), radiation continued as NSEF is high, never interrupted by lightning; particles come isotropic.
- The decay phase - decay of Radon progeny after the storm finished. The half-life time of TGE decay is consistent with the 214Pb (~300 keV peak) and 214Bi- (~600 keV peak) isotopes from the Radon chain.

Chapter 2

During the spectroscopic measurement of NGR in 2019 [1], we detected an increase in the intensity of the 511 keV annihilation peak. However, this peak had been contaminated by Compton scattered gamma rays (in the body of the NaI crystal) of higher energies from the Radon decay chain, particularly from ^{214}Bi isotope (609 keV), see Fig. 3a, a large peak near a small 511 keV peak. To reduce background interference, we utilized 4 cm thick lead bricks surrounding the spectrometer from the bottom and all sides, leaving only the top open. This effectively suppressed the radon progeny gamma radiation, as shown in Fig. 3b. As a result, the overall intensity of NGR decreased by approximately ten times. However, the 511 keV peak's relative size became much larger than ^{214}Bi, Fig. 3b.

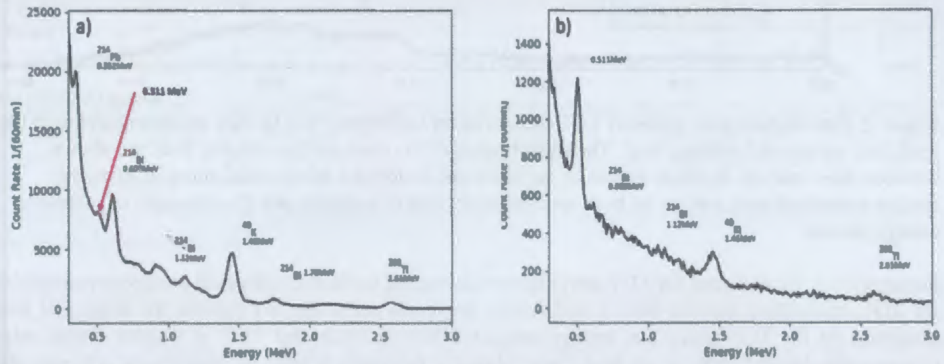


Figure 3. NGR spectrograms obtained with the ORTEC spectrometer during an hour exposition without a lead filter a) and a 4cm lead filter b). In frame a), the 511 keV peak is shown by the red arrow

After relatively small TGEs in June, a large TGE was registered on 11 July 2023[11]. In Fig. 4, we show the enhancement of particle flux measured by the 1 m^2 area scintillator of the STAND1 detector. The particle flux rises more than twice from 550 to 1250 per second. TGE duration was ≈5 minutes, and the flux maximum coincides with the positive NSEF, green lines in Fig. 4. Thus, we compare the enhancement of the positron flux (by its proxy 511 keV gamma rays) at positive and negative NSEF (denoted by yellow lines in Fig. 4)

Figure 5 shows one-second spectrograms of NGR measured by the ORTEC spectrometer at positive and negative ***NSEF***. The 511 keV annihilation line is much larger at positive NSEF than at negative NSEF.

Comparing count rates at positive and negative NSEF and "pure" TGE fluxes, we obtain the ratio of TGE to fine weather, reaching 500% for positive and 250% for negative NSEF.

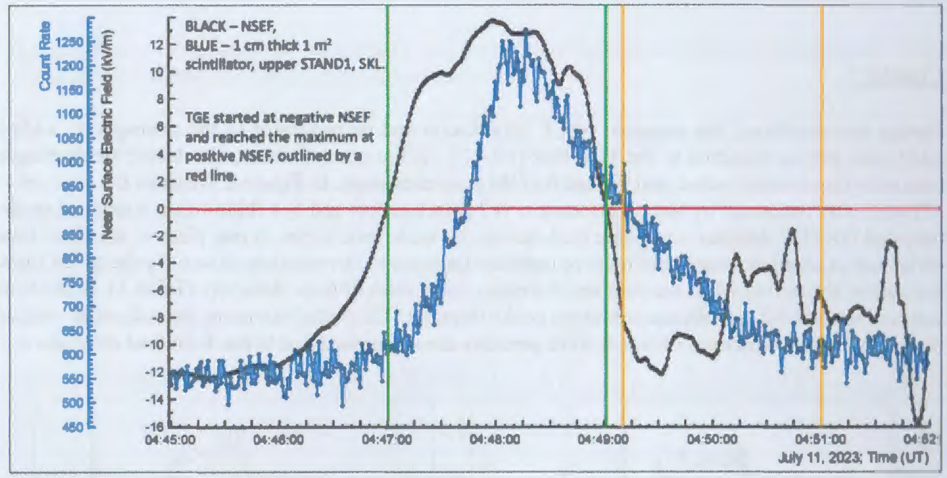


Figure 4. One-second time series of STAND1's upper scintillator near SKL hall (blue) and NSEF (black). Green and yellow lines indicate episodes of positive and negative NSEF.

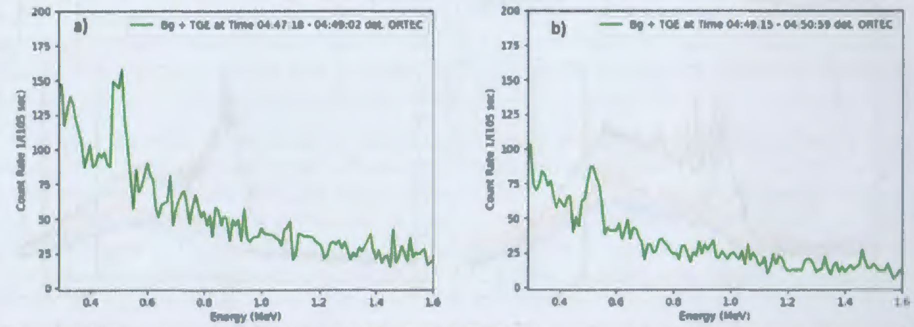


Figure 5. NGR spectrograms obtained with the ORTEC spectrometer during positive a) and negative b) NSEF, as indicated by lines in Figure 4.

This research shows that positron flux is modulated when a "graupel" dipole, discovered by Joachim Kuettner, emerges in the lower part of the thundercloud. The enhanced 511 KeV flux indicates positron acceleration in the dipole between the cloud base and the ground, accelerating positrons and positive muons in the direction of the Earth's surface. RREA (electron-gamma ray avalanche) is developing above this dipole in the much larger gap between the main negative layer in the middle of the cloud and LPCR. Thus, by the 511 keV gamma-ray flux measurements, we can confirm the scenario of the LPCR emergence and its role in cosmic ray flux modulation.

Chapter 3

During thunderstorms, the emerged NSEF lifts Radon and its progenies to the atmosphere, adding additional gamma radiation to the TGE flux [10, 12]. As the storm finishes, the electric field strength returns to fair-weather value, and the uplift of Rn progenies stops. In Figure 6, we show the time series of count rates measured by NaI spectrometers N 2 (black curve) and N 4 (blue curve, 4 cm lead on the top) and ORTEC detector count rate (red curve). To scale time series in one picture, we show time series not in absolute counts but relative numbers (percent to fair weather value). By the green lines, we outline the period when we compare the mean count rates of three detectors (Table 1). In the time series of the NaI N2, we can see prominent peaks from the TGE particles coming from the near-vertical direction. In the count rates of NaI 4, TGE particles are suppressed due to the 4 cm lead filter above.

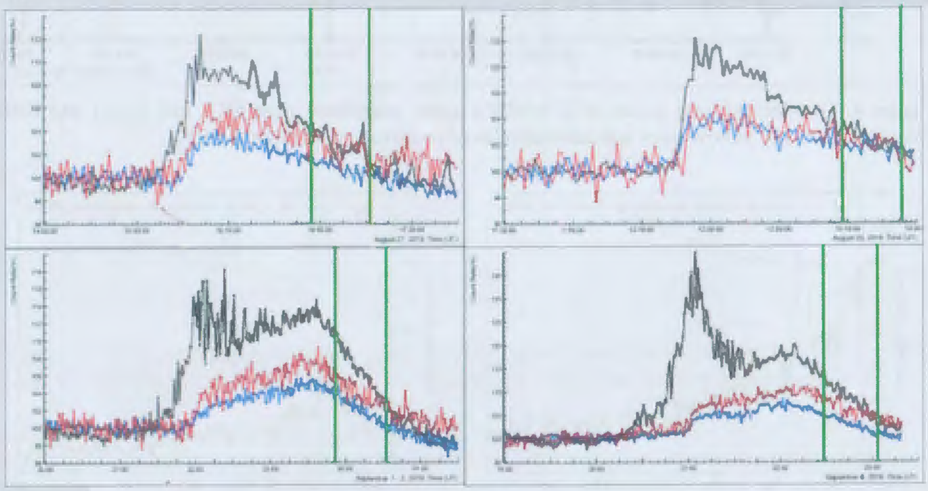


Figure 6. One-minute time series of count rates of NaI spectrometers N2 (black, energy threshold 0.3 MeV), N4 (blue, energy threshold 0.3 MeV, 4 cm lead filter on the top), and ORTEC spectrometer (red). Green lines show the time when the mean count was calculated.

Table 1 shows the mean count rates of 8 TGEs that occurred during one month in August-September 2019, measured by three spectrometers. The 1-minute count rates were averaged over time of the decay phase of TGE at fair weather when there were no disturbances of NSEF and high-energy TGE flux. The ratio of count rates of NaI N4 (second column) to ORTEC (fourth column) is very stable at 3.00±0.06, confirming that both spectrometers are measuring the same Radon progeny gamma radiation coming under large zenith angles. The ratio of counts NaI N2 to ORTEC is more vulnerate at 4.2±0.13, reflecting fluctuation of the near-vertical flux registered by the NaI N2. The last two columns show the recovered half-life time of the Radon progeny gamma radiation estimated by NaI (Tl) and ORTEC spectrometers.

Table 1. Mean count rates of 3 detectors measured after the storm at fair weather in the decay phase of TGE (radon progeny gamma radiation only).

2019	NaI 4	NaI 2	ORTEC	NaI4/ORT	NaI1/ORT	NaI_ $T_{0.5}$(min)	ORTEC $T_{0.5}$(min)
27/08	40841±318	57728±938	13435±130	3.04	4.30	52	51
30/08	41030±282	56882±571	13286±114	3.08	4.28	46	47
2/09	40800±382	57774±982	13755±153	2.97	4.16	50	50
4/09	43080±402	63024±403	14380±154	3.00	4.38	49	46
6/09	41771±296	58763±716	13663±160	3.06	4.30	48	49
11/09	39825±191	52746±371	13282±134	3.00	3.97	40	40
17/09	39724±271	55492±511	13185±112	3.0	4.21	50	48
28/09	38743±440	54061±690	13567±165	2.86	4.01	51	50
Mean	40727±230	57059±340	13569±140	3.00±0.06	4.2±0.13	46 ±4,5	47 ±3,3

To compare the NGR enhancement in positive (accelerated positrons in direction to Erath's surface) and negative (accelerated electrons in direction to Erath's surface) electric fields, we select four stormy events with both signs of NSEF. The NSEF values in kV/m were (5.6, 13.8, 9.8,17.5) and (-16.0, -14,8, -8.4, -6.0) correspondingly. An example of such an event that occurred on September 26, 2023, is shown in Figure 7. The disturbances of NSEF started at 9:15 and simultaneously increased ORTEC's count rate. The NSEF reached its maximum value of 5 kV/m at 10:05, and ORTEC's count rate rose from a fair weather value of ≈10,000 to x11500, i,e, by 15%. Afterward, the count rate smoothly decayed with decaying Radon progeny until 11:00; another enhancement, now due to negative NSEF, happened. NSEF reaches a minimum of 10 kV/m at 11:25 simultaneously with a maximum ORTEC count rate of 10900, surpassing the fair-weather value by 9%.

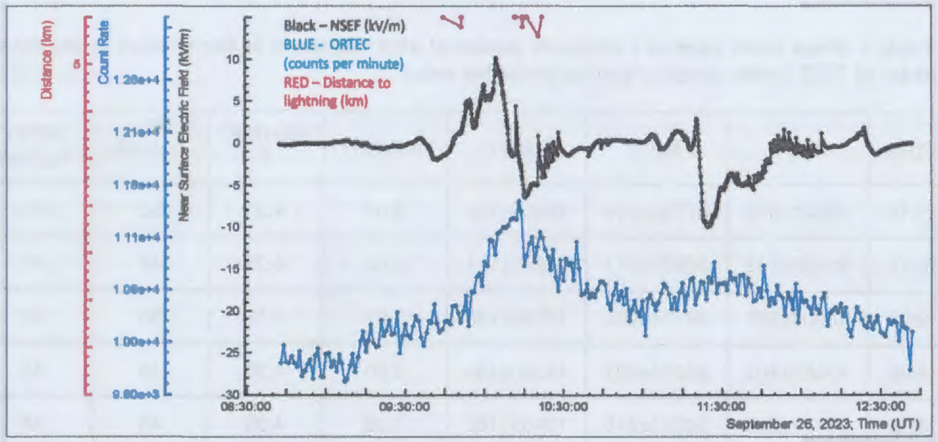


Figure 7. NGR enhancement measured by ORTEC spectrometer at positive and negative NSEF measured by BOLTEK's EFM 100 electric mill.

In summary, we measure and present two additional sources of NGR: TGEs and Radon progeny lifted into the atmosphere by NSEF during thunderstorms. TGEs can enhance NGR several times, Radon progeny – 20-30%. TGEs prolonged for several minutes, Radon progeny radiation 2-3 hours.

As strong electric fields emerge globally in the terrestrial atmosphere, measured enhancements of NGR are planetary effects and should be accounted for in the numerical models of Planet-Earth.

Chapter 4

Starting in 2014, we performed continuous (24/7) monitoring of the skies above the Aragats research station. The used ALL SKY CAM model produced by Moonglow Technologies is a circular fisheye system providing a 190° hemispherical field of view (FoV). The image sensor is a Color 1/3" Sony Super HAD CCD II with an effective pixel number across FoV of 546 × 457, with automatic exposure time (10^{-5} to 4 s) and high sensitivity in the visible wavelength band of 300-700 nm. The camera provides motion detection with video analysis. Using a software package provided by the firm, we upload image streams to the internet and store digital images in the ADEI database. We keep photos every second in strong storm conditions (when NSEF exceeds 5 kV/m)—otherwise, every minute.

The glow observed in April 2020 demonstrates a complicated pattern like multiple avalanches from runaway electrons (inset on the left of Figure 8) [7]. Aragats particle detectors prove the presence of electrons with energies above 20 MeV in the sky above Aragats at 17:05-17:19 (blue and red curves). The image at maximal flux resembles optical radiation from multiple runaway avalanches. For comparison, we put in the right inset a glow, possibly due to corona discharge that occurred after the electron flux was in the atmosphere. The pattern is different from the multiple avalanche lights in the left inset.

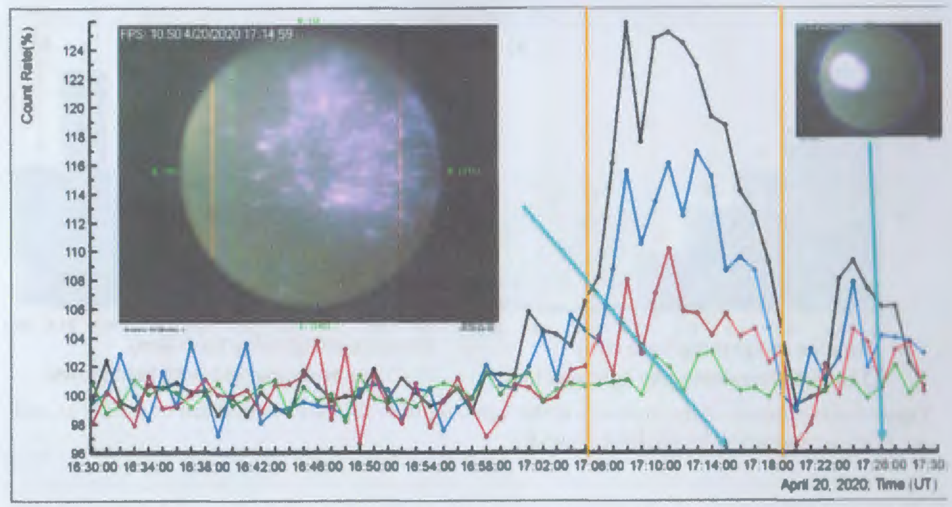
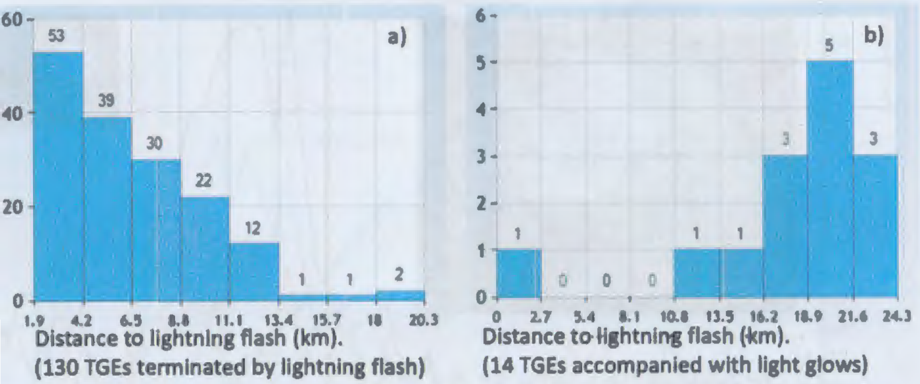


Figure 8. TGE registered on April 20, 2020. The black-green curves show the 1-minute time series of count rates of stacked scintillators of the STAND3 detector. In the insets, we offer the glow in the sky above Aragats; by blue arrows, we indicate when the panoramic camera took images. The yellow lines indicate the "glowing" time.

Our analysis shows that when the storm's active zone is 10 km or more away from particle detectors, the TGE extends for tens of minutes and smoothly terminates when the conditions of the atmospheric electric field fail to support RREA. In Figure 9a, we show the distribution of distances to lightning flashes abruptly terminated by the lightning flash. Figure 9b shows the same distribution for long-lasting TGEs, accompanied by light glows. It is apparent that these distributions belong to distinct classes; only the second class (presented in Figure 9b) supports the origination of light glows. Thus, electron acceleration occurred in both cases, and RREA particles covered large areas below thunderclouds. We conclude that the RREA can be unleashed in a very large spatial domain around the active lightning zone and many kilometers apart.

The light glows observed are not local corona discharges on metallic masts but a discharge in the atmosphere above the Aragats station that influences all electric field sensors. These discharges do not initiate lightning flashes, only large disturbances of the NSEF, and they produce light glows in the sky above the station.



gure 9. Distribution of the distances to the lightning flash for TGEs terminated by a flash a), and r TGEs accompanied by the light glows b).

hapter 5

ıe variabilities of the electric field during thunderstorms exhibit intricate patterns in both vertical and ›rizontal directions—large variability results from the constantly changing atmospheric conditions ıring thunderstorm development. Understanding variations of electric fields and their underlying .uses can be of great importance in meteorology, atmospheric sciences, and safety. Several mospheric processes, such as the separation of positive and negative charges within thunderstorm ouds, lightning discharges, and the interaction between charged particles and aerosols in the mosphere, influence the electric field in the atmosphere.

› get an idea of the atmospheric electric field over long distances, we installed in 2022 networks of aI spectrometers and electric field sensors on the slopes of Mount Aragats: at Aragats (3200 m a.s.l), Nor Amberd (2000 a.s.l.,13 km from Aragats), at Burakan (1600 a.s.l.,15 km from Aragats) [6,8]. uring a severe storm on the first of May 2022, NSEF disturbances occurred at Aragats and Nor mberd, reflecting the storm's enormous size. Figure 10 shows a 1-minute time series of count rates easured with plastic scintillators 5 cm thick and 1 m^2 square under a 0.8 mm thick iron roof at Aragats ıd Nor Amberd. Large count rate increases occurred at Aragats at 13:23-13:33 UT and Nor Amberd 12:30-13:23 UT. However, from 12:56 to 13:15, both Aragats and Nor Amberd stations significantly creased the count rate. During 1 hour of the enhanced particle flux, the NSEF varied from -23 to 8 /m at Aragats and from -25 to 25 kV/m at Nor Amberd. Aragats experienced the TGE during the ›ep negative electric field, while Nor Amberd experienced it during the positive NSEF. Despite the fferent conditions of the NSEF perturbations, the TGE was registered by the same type of detectors both stations. This indicates that electron accelerators were operational for an hour above both ations.

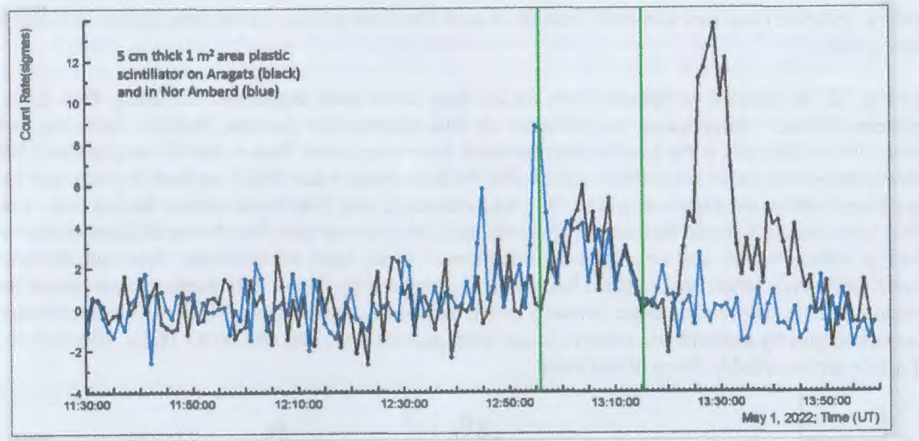


Figure 10. Disturbances of the NSEF (black); 1-minute time series of count rates of 5 cm thick and 1 m^2 area plastic scintillators (blue); and distances to lightning flashes (red) measured on Aragats a) and in Nor Amberd b).

Another large storm occurred on Aragats on September 6. Numerous lightning flashes accompanied it on both stations; see Figure 11a. The pattern of the NSEF disturbances was approximately identical on both stations. The particle flux enhancement started on both stations simultaneously at 15:59 UT, see Figure 11b. The maximum peak significances measured by two identical 5 cm thick, 0.64 m^2 area plastic scintillators were achieved in Nor Amberd at 16:01 UT and on Aragats at 16:08 UT. Thus, the storm induces a large electric field at both stations; although the maximum significances were achieved at different times, both stations share the overall TGE time.

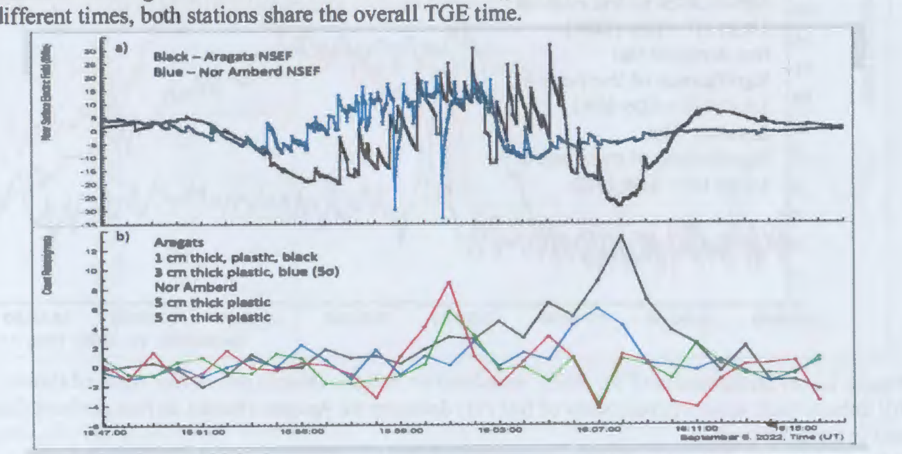


Figure 11. a) Disturbances of the NSEF measured on Aragats (black) and in Nor Amberd (blue); b)1-minute time series of count rates of 1 cm and 3 cm thick (both 1 m^2 area) plastic scintillators on Aragats

(black and blue) and two identical 5 cm thick and 1 m^2 area plastic scintillators in Nor Amberd (red and green).

In Fig. 12, we present an episode from a very long storm from September 22, 2022. This time, the pattern of NSEF disturbances was different on both stations. On Aragats, multiple lightning flashes were observed (black curve), and in Nor Amberd, there were a few flashes, but the amplitude of NSEF fluctuations was rather large (blue curve). The TGE occurred when NSEF on both stations was in the positive domain, see Figure 61a. The TGE was measured with NaI(Tl) detectors. At this time, a large flux was observed also in Burakan, 2 km away and 200 m lower than Nor Amberd. Close occurrences of flux enhancements and very large significances of peaks leave no doubt that this time, avalanches covered an even larger area than on September 6, extended by 15 km. Our measurements show that a strong electric field covers huge volumes in the thunderous atmosphere. Electrons are accelerated to large energies by atmospheric electric fields, born gamma rays, and end up as TGEs, allocated to the Earth's surface sizable doses of radiation.

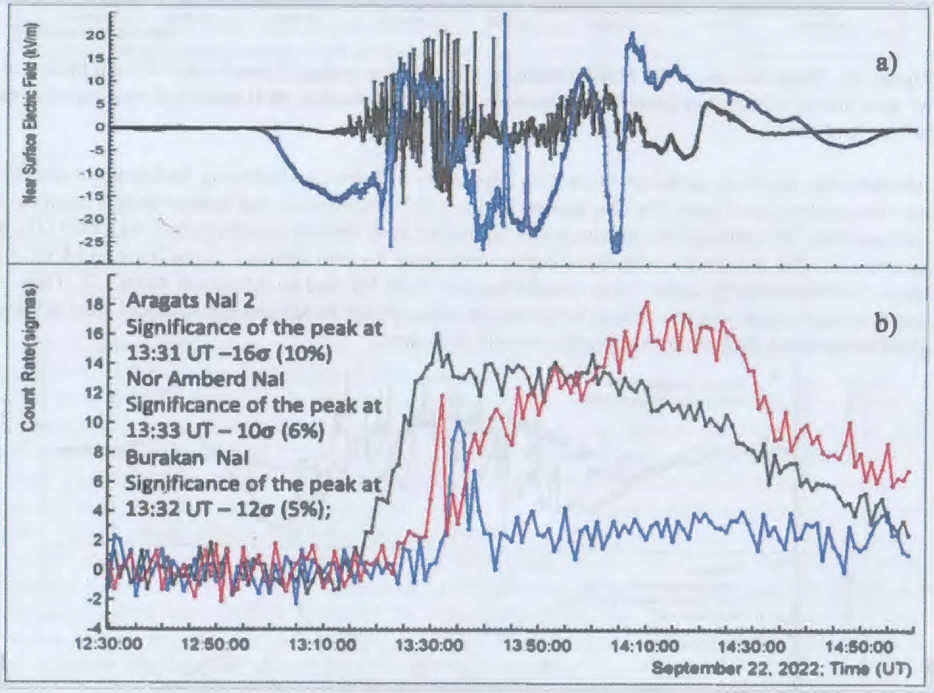


Figure 12. a) Disturbances of the NSEF measured on Aragats (black) and in Nor Amberd (blue); b)1-minute time series of count rates of NaI (Tl) detectors on Aragats (black), in Nor Amberd (blue), and in Burakan (red).

TGEs measured on Aragats in Nor Amberd and Burakan confirm that the atmospheric electric field unleashed TGEs in many cubic km of the atmosphere and square km of Earth's surface. This global high-energy electron and gamma-ray flux influence the Global Electric Circuit (GEC) and the Earth's

climate. This additional radiation should be introduced to weather forecasting models and global change. Remote sensing of electric fields in the lower atmosphere by measuring the fluxes of electrons and gamma rays reveals the large extension of the strong electric field both vertically and horizontally. Remote sensing can be done on the Earth's surface, distant from the storm, and it does not require balloon launches near the most intense weather. Surface detectors are stable and long-lasting, not moved by wind or destroyed by lightning. Several detectors can monitor multiple regions of interest simultaneously. The time resolution is in the order of seconds, and monitoring is performed 24/7, without a chance of missing violent storms. Especially important is the monitoring of the strong electric field just above the ground, which can reach very high values just tens of meters above the Earth's surface. The remote sensing of the atmospheric field can be used along with a field mill climatology, usually saturated at high electric fields, to minimize the risk of launching space vehicles during thunderstorms.

Chapter 6

SEVAN (Space Environment Viewing and Analysis Network) is a network of particle detectors located at middle to low latitudes, primarily on mountain peaks. It started as a project of the International Heliophysical Year (IHY-2007) and is currently operational as part of the International Space Weather Initiative (ISWI). For almost 15 years, the SEVAN detectors have measured the time series of charged and neutral particle count rates. In 2023, a new SEVAN light detector was installed at Zugspitze, the highest mountain in Germany [9]. Just after installation, on the morning of May 23, during a thunderstorm SEVAN light detector registered sizeable GLE in gamma-ray flux, see Fig. 13. At the maximum TGE flux, the enhancement of count rate reached 44%, and the peak statistical significance was 41σ. TGE started at 6:58 when the NSEF was in the positive domain +8 kV/m. Then, after briefly touching the negative domain, NSEF returned to the same positive value at was abruptly terminated at 7:06 by a normal polarity lightning flash that occurred at a distance ≈of 10 km.

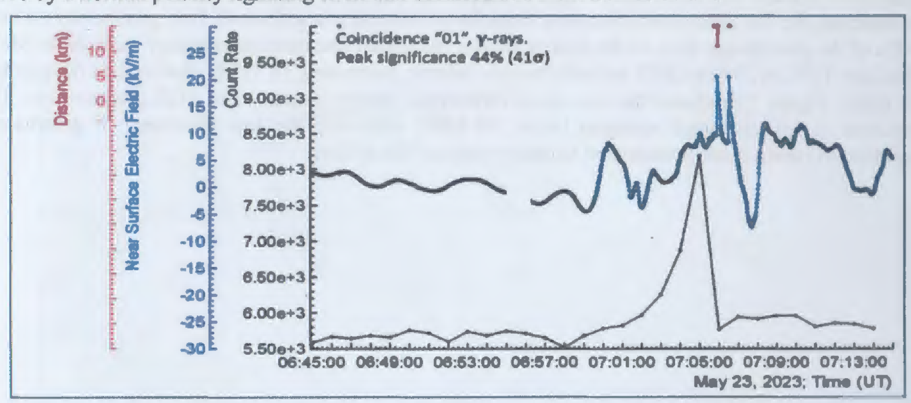


Figure 13. One minute time series of the "01" coincidence measured by SEVAN light on Zugspitze, black; One second time series of NSEF, blue, and distances to lightning flash, red.

During the same day at night of May 23, a significant TGE occurred on Aragats, see Fig. 14. The storm on Aragats was severe, and there were numerous nearby lightning flashes. The TGE began at 00:16

and finished at 00:35. Normal polarity lightning flashes at 00:25:06 (9 km distance) and 00:28:41 (3.8 km distance) interrupted its progression and slowed down count rate enhancement. The TGE reached its maximum at 0:34-0:35 before ending with a flash at 00:35:08 (2.7 km distance) that grounded the potential difference between charged layers in the cloud. The NSEF was mainly in the negative domain and was deepest at ≈-30 kV/m. Sometimes, it touched the positive domain before lightning flashes.

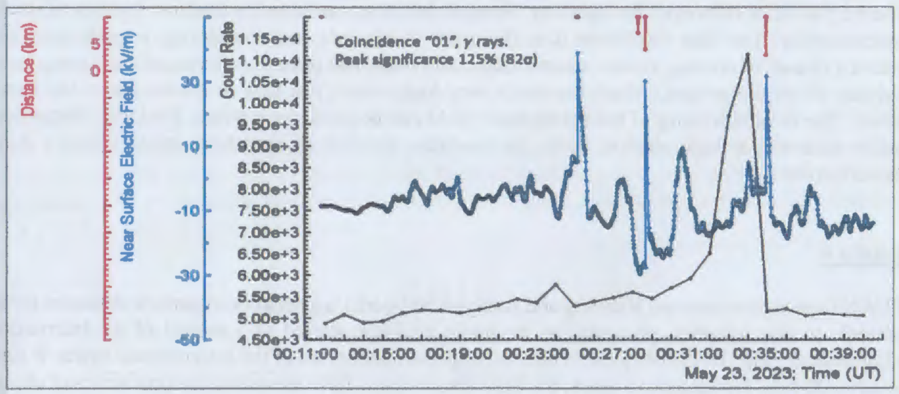


Figure 14. One minute time series of the "01" coincidence measured by CUBE detector on Aragats, black; One second time series of NSEF, blue, and distances to lightning flash, red.

In Figure 15a, we show the measured histogram of energy releases of particles selected by "01" coincidence. This coincidence picks gamma rays because the probability of a signal in the upper 1-cm thick scintillator is very low for gamma rays and very high for electrons. The lower 20-cm thick scintillator is much more efficient in registering gamma rays. Although atmospheric neutrons can also be detected, the flux of neutrons resulting from the photonuclear reactions of TGE gamma-rays is only 1-2% of the gamma-ray flux. In the energy release histogram, the maximum energy exceeds 40 MeV. Thus, the TGE on 23 May 2023 was enormously intense, surpassing all TGEs observed on Aragats last 15 years. Figure 15b shows the recovered differential energy spectrum of TGE gamma rays. The spectrum is soft for small energies below 10 MeV, reflecting the low efficiency of gamma-ray registration (much more pronounced in energy release histogram).

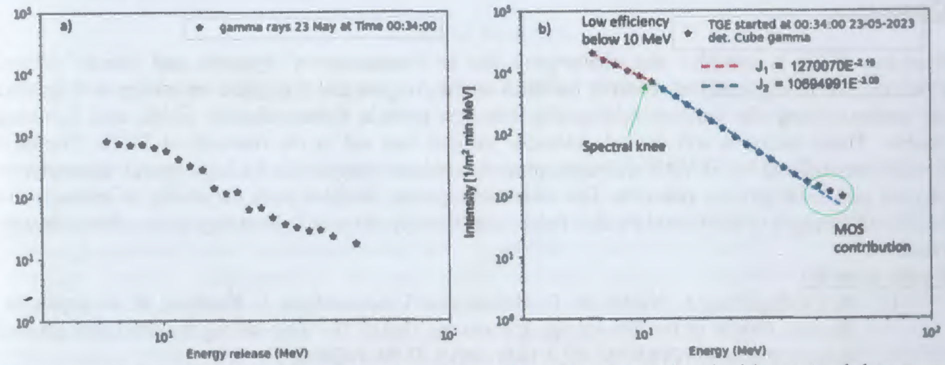


Figure 15. a) Energy release histogram of particles selected by the "01" coincidence (mainly gamma rays) in the 20-cm thick scintillator of CUBE detector; b) differential energy spectrum of TGE gamma rays recovered from energy release histogram using detector response function.

In 2024, we introduce new logic in the CUBE detector's data acquisition, calculating directly "11" coincidences of 1 cm thick (veto) and 20 cm thick (spectrometric) scintillators. As the 1 m^2 area veto scintillator fully covers the 0.25 m^2 scintillator, the "11" coincidence selects the TGE charged flux (electrons and positrons) with very high efficiency. During autumn thunderstorms on October 2, 2024, a TGE occurred with large electron content, similar to the autumn storms of 2023 covered in [12]. In Fig. 16, we show this TGE's electron and gamma-ray energy spectra. The electric field height calculated according to equation 4 gives a value of 65 m, perfectly coinciding with the cloud base height estimated by spread (difference between outside temperature and dew point, which is ≈60 m.) shown in the inset to Fig. 16a. Thus, numerous electrons escaping from the strong accelerating field at the height of 60 m from the surface survive in the dense air and reach spectrometers.

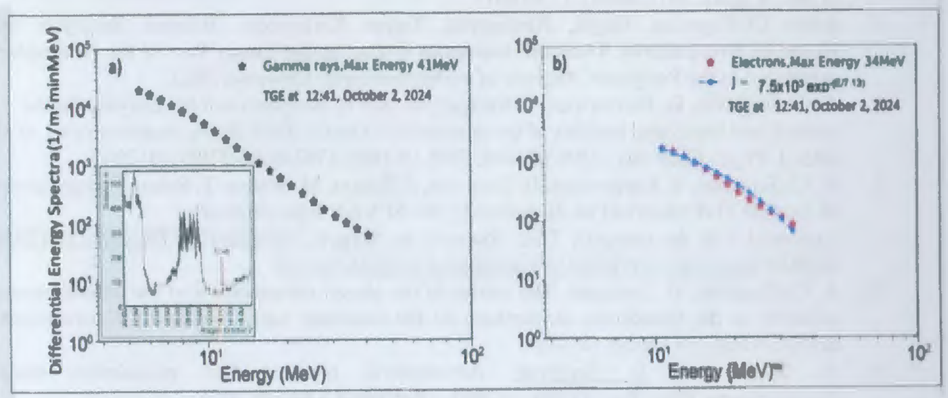


Figure 16. Recovered gamma ray and electron differential energy spectra of TGE occurred on 2 October 2024. In the inset distance to the cloud base, red arrow shows the TGE time.

Conclusion

Studying TGEs is complex and challenging due to thunderstorms' dynamic and chaotic nature. However, the newly installed research facilities on the Aragats and Zugspitze mountains will be vital for understanding the intricate relationship between particle fluxes, electric fields, and lightning flashes. These facilities will provide valuable insights and aid in the research of TGEs. The new possibilities offered by SEVAN detectors present 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.

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Саргсян Балабек

Энергетические спектры электронов и гамма-лучей в диапазоне энергий 0,3-100 МэВ во время связанных с усилением грозового наземного возрастания.

Измерения энергетических спектров электронов и гамма-лучей на самых высоких вершинах Восточной Европы, Армении и Германии позволили получить доказательства нового физического явления, известного как грозовое наземное усиление (TGE). Эти события TGE характеризуются значительным увеличением потока частиц во время грозы.

Открыт эффект циркуляции радона, объясняющий явление подъема аэрозолей с прикрепленными к ним изотопами радона в атмосферу и их последующего возвращения на землю с осадками.

Обнаружено 5 кратное усиление потока позитронов во время грозы, которое объясняется формированием четвертого диполя между нижней положительно заряженной областью и землей.

Установлено значительное усиление естественного гамма-излучения во время возмущений атмосферного электрического поля, что проливает свет на связь между динамикой атмосферы и радиационными явлениями.

Обнаружены световые свечения нового типа в нижних слоях атмосферы во время грозовых наземных усилений.

Показано возникновение крупномасштабного атмосферного электрического поля, во время гроз на склонах горы Арагац.

Разработаны методы изучения гамма-излучения изотопов радона и оценки потока позитронов во время гроз.

Модернизирован детектор частиц SEVAN, позволяющий проводить точные измерения энергетических спектров.

Սարգսյան Բալաբեկ

Ամպրոպային վերգետնյա ավելացումների ժամանակ էլեկտրոնների և գամմա ճառագայթների էներգետիկ սպեկտրերը 0.3 -100ՄէՎ էներգիաների տիրույթում

Արևելյան Եվրոպայի, Հայաստանի և Գերմանիայի ամենաբարձր լեռնագագաթների վրա էլեկտրոնների և գամմա ճառագայթների էներգետիկ սպեկտրների չափումները թույլ են տալիս ապացուցելու ֆիզիկական նոր երևույթը, որը հայտնի է որպես ամպրոպային վերգետնյա ավելացումներ (ԱՎԱ)։ Այդ ԱՎԱ դեպքերը բնութագրվում են ամպրոպների ժամանակ մասնիկների հոսքերի զգալի ավելացումներով։

Հայտնաբերվել է ռադոնի շրջանառության էֆեկտը, որը բացատրում է աերոզոլների՝ դրանց կպչող ռադոնի դուստր իզոտոպների մթնոլորտ բարձրանալու և տեղումների հետ դեպի երկրի մակերևույթ վերջիններիս հետ վերադարձի ֆենոմենը։

Հայտնաբերվել է ամպրոպների ժամանակ պոզիտրոնների հոսքի հնգապատիկ ավելացումը, ինչը բացատրվում է չորրորդ դիպոլի ձևավորմամբ՝ ստորին դրական լիցքավորված շրջանի և գետնի միջև։

Հաստատվել է մթնոլորտային էլեկտրական դաշտի խաթարումների ժամանակ բնական գամմա ճառագայթման զգալի աճերի երևույթը, ինչը լույս է սփռում մթնոլորտի դինամիկայի և ճառագայթային երևույթների միջև կապի վրա։

Ամպրոպային վերգետնյա ավելացումների ժամանակ մթնոլորտի ստորին շերտերում հայտնաբերվել է լուսային առկայծումների նոր տեսակ։

Ցուցադրվել է լայնածավալ մթնոլորտային էլեկտրական դաշտի առաջացումը Արագած լեռան լանջերին ամպրոպների ժամանակ։

Մշակվել են մեթոդներ ռադոնի իզոտոպների գամմա ճառագայթումն ուսումնասիրելու և ամպրոպների ժամանակ պոզիտրոնների հոսքերի գնահատման համար։

Արդիականացվել է SEVAN մասնիկների դետեկտորը, ինչը թույլ է տալիս կատարել էներգետիկ սպեկտրների ճշգրիտ չափումներ։