Charge distribution in the thundercloud, electron acceleration, and lightning initiation

A.Chilingarian[1,2], G. Hovsepyan[1]

[1]A. Alikhanyan National Lab (Yerevan Physics Institute), Yerevan 0036, Armenia

[2]National Research Nuclear University MEPhI, Moscow 115409, Russia

Abstract

The comparative analysis of three thunderstorms on Aragats in May 2021 demonstrates that relativistic runaway electron avalanches (RREAs) are developing in large areas of the thunderous atmosphere. In the active storm zone, RREAs last tens of seconds to a few minutes, until lightning flashes terminate electron acceleration. Thus, RREAs development is paired with lightning activity, creating huge electron fluxes preceding the development of lightning leaders. If the lightning activity is far from the detector site, measured particle fluxes (thunderstorm ground enhancements - TGEs) are smoothly enhanced and decayed when the atmospheric conditions cannot anymore sustain the electron runaway process. In this case, the TGE has a more or less symmetrical shape and can last up to 10 minutes and more. Thus, the total surface area exposed to ionizing radiation can reach 100 km^2 and total number of gamma rays directed to the earth's surface – 2*10^{18}. The differential energy spectra of electrons and gamma rays recovered by particle spectrometers are used to estimate the heigh of a strong accelerating electric field region, which can extend down to tens meters above the earth's surface.

Plain language summary

Many species of elementary particles are born in the terrestrial atmosphere by high-energy protons and fully-stripped nuclei accelerated at exotic galactic sources. During thunderstorms, to this more-or-less constant flux are added electrons and gamma rays from the most powerful natural electron accelerator operated in the electrifying atmosphere. Huge fluxes of electrons and gamma rays can exceed the background up to 100 times and pose yet not estimated influence on the climate. More than 2,000 thunderstorms are active throughout the world at a given moment, producing on the order of 100 flashes per second. The overall surface of the thunderous atmosphere each moment can be estimated as 200,000 km^2, and according to our estimates 2*10^{18} gamma rays are hitting the earth's surface each second. The long-term effects of this radiation on humans should be carefully estimated

Key points

The most powerful electron accelerators operated in thunderclouds send billions and billions of MeV particles in direction of the earth's surface per second;

These electrons are precursors of the lightning flashes by opening ionized channels to the lightning leaders;

The strong accelerating electric field extends very low to the earth's surface

1. **Introduction**

It is widely accepted, that the cloud charge structure for a typical thunderstorm contains an upper positive charge region consisting of ice crystals, a main negative charge region consisting of both graupel and ice crystals, and a lower positive charge region consisting of graupel. The electric charge of graupel is positive at temperatures warmer than -10° C, and negative at temperatures cooler than -10° C (Takahashi, 1978, Wada et al., 2021). In review (Williams, 1989) was stated that the tripolar structure of thunderstorms is supported by a wide variety of observations and that temperature appears to be the most important single parameter in controlling the polarity of charge acquired by the precipitation particles. When graupel falls into the region warmer than -10° C, a charge reversal will occur in the central part of the storm, and the graupel population will change the charge from negative to positive. Large and dense graupel population either suspended in the middle of the thunderstorm cloud or falling toward the earth's surface constitutes a "moving" lower positive charge region (LPCR). The dipole formed by the LPCR and relatively stable main negative (MN) charge region significantly intensify the electric field of the dipole formed by the MN and its mirror image in the ground (MN-MIRR, first scenario of RREA initiation, see Fig.1 in Chilingarian et al., 2021a). A free electron entering the strong and extended electric field accelerates and unleashes the relativistic runaway electron avalanches (RREA, Gurevich et al., 1992). The RREA is a threshold process, which occurred only if the electric field exceeds the critical value in a region of the vertical extent of about 1–2 km. When the second scenario of the RREA origination (MN-MIRR and MN-LPCR) is realized the electric field in the cloud frequently surpasses the critical value and an intense RREA ends up in an extreme thunderstorm ground enhancement (TGE, Chilingarian et al., 2010, 2011) exceeding the background level of gamma rays and electrons up to hundred times (Chum et al., 2021). After the graupel fall, or after the lightning flash consuming positive charge of the LPCR, the surface electric field again is controlled by the main negative charge region only (see the detail of the RREA initiation model in (Chilingarian et al, 2020 and 2021a).

At Aragats research station we develop a new approach for understanding thunderclouds charge structure based on the new kind of messengers, namely, the secondary cosmic rays modulated by the intracloud electric field (Chilingarian et al., 2021b). The 24/7 monitoring of almost all species of secondary cosmic rays is going on near 12 years. We simultaneously observe graupel fall, the outside temperature (a proxy of the intracloud temperature), the near-surface electric field (a proxy of the intracloud electric field), and fast-changing during thunderstorms neutral and charged particles count rates. Such a multisensory approach allows us to get insight into the charge structure of the thundercloud using particle physics methods.

1. Comparative analysis of 23 - 25 May 2021 thunderstorms

According to the adopted approach of the multivariate correlation analysis, we use as many as possible measurements for characterizing high-energy processes in the atmosphere. The count rate of electron and gamma ray fluxes, as well, as the energy release histograms, are registered by the large spectrometer allowing to recover differential energy spectra of both charged and neutral fluxes (Aragats solar neutron telescope, ASNT, Chilinarian et al., 2017a). The lightning identification and distance to lightning flash estimation are done by monitoring of disturbances of the near-surface (NS) electric field with the network of EFF-100 electric mils of BOLTEC company. Meteorological measurements are made with DAVIS weather station. The moon-glow panoramic cameras are used for the monitoring of skies above Aragats.

On May 23, 2021 a large storm was unleashed in direct vicinity of the Aragats research station. Storm duration was 6 hours with more than hundred nearby lightning flashes. NS electric field shows many episodes of deep negative and deep positive (-20 - +20 kV/m) electric field excursions. The electric field direction reversals after lightning strikes were very fast (a few seconds). In the first part of storm numerous attempts to start TGE were registered by the ASNT spectrometer. In Fig 1, we present a 20-minute period of the thunderstorm with 2 TGEs terminated by the lightning flash on the initial stage of development. The duration of TGEs was 20 sec, the NS electric field was in the negative domain, the amplitude of the NS field surge caused by the terminating lightning flash was 50 kV/m (see Table 1). In the frame a) we show the descending distance to the cloud base, estimated by one of atmospheric thermodynamics' calculators available on the internet which uses measurements of the outside temperature and dew point (Omni, 2019). In frames b) we show the shots of the panoramic camera monitoring skies above Aragats. The characteristic patterns on the camera glass are due to graupel fall (see Chilingarian et al., 2021c). Not very intense graupel fall continues before and during observed two TGEs. It is interesting to note that a new TGE started just after lightning kills the previous one during the electric field recovering stage. This is evidence of the largely electrified atmosphere, when a new started TGE opens path to the lightning leader (Chilingarian et al., 2017b).

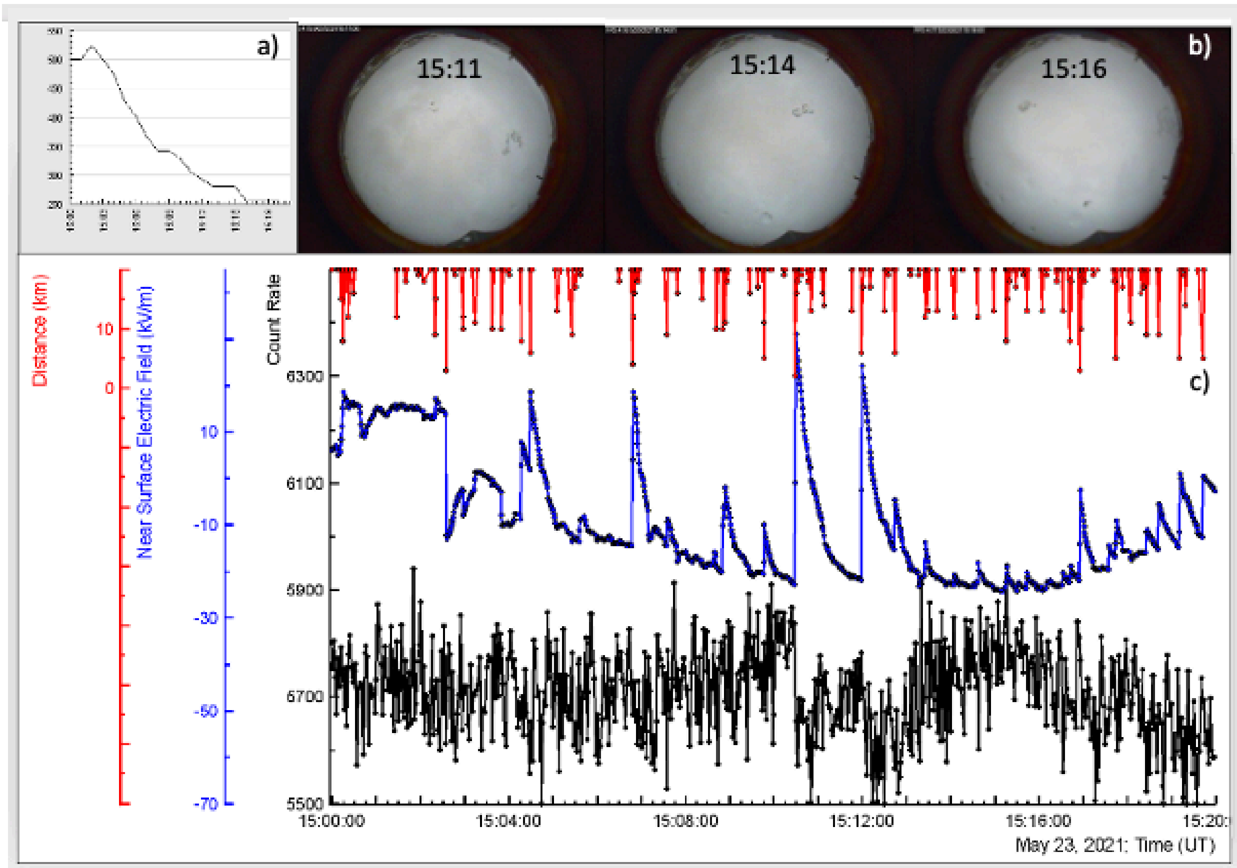


Fig. 1. A pattern of the progress of the storm on Aragats on 23 May. a) The distance to the cloud base. b) Images of the graupel fall. c) Disturbances of the NS electric field (blue), count rate of ASNT spectrometer (black), and distance to lightning (red).

During the second storm that occurred the next day on May 24 and lasted for 3 hours, the electrification of the atmosphere above the station was much smaller. The nearby lightning flashes occurred only during the first hour of the storm terminating a small TGE at the end of its development. During the large TGE followed 6 minutes later, the nearest lightning flash was at a distance of more than 15 km, consequently, it did not disturb smooth evolution of long duration (12 minutes) intense TGE (see Table 1 for more detail). The cloud base height was smaller than on 22 May, the graupel fall was moderate.

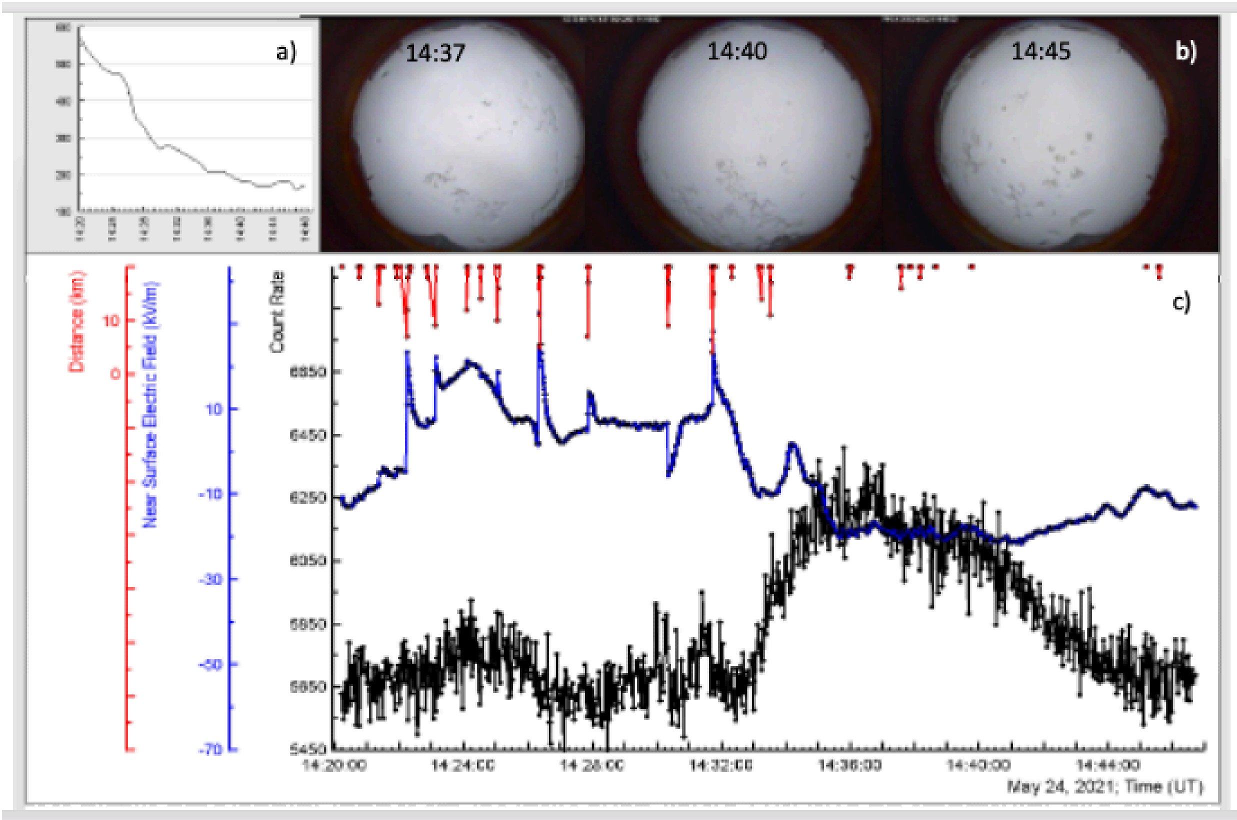
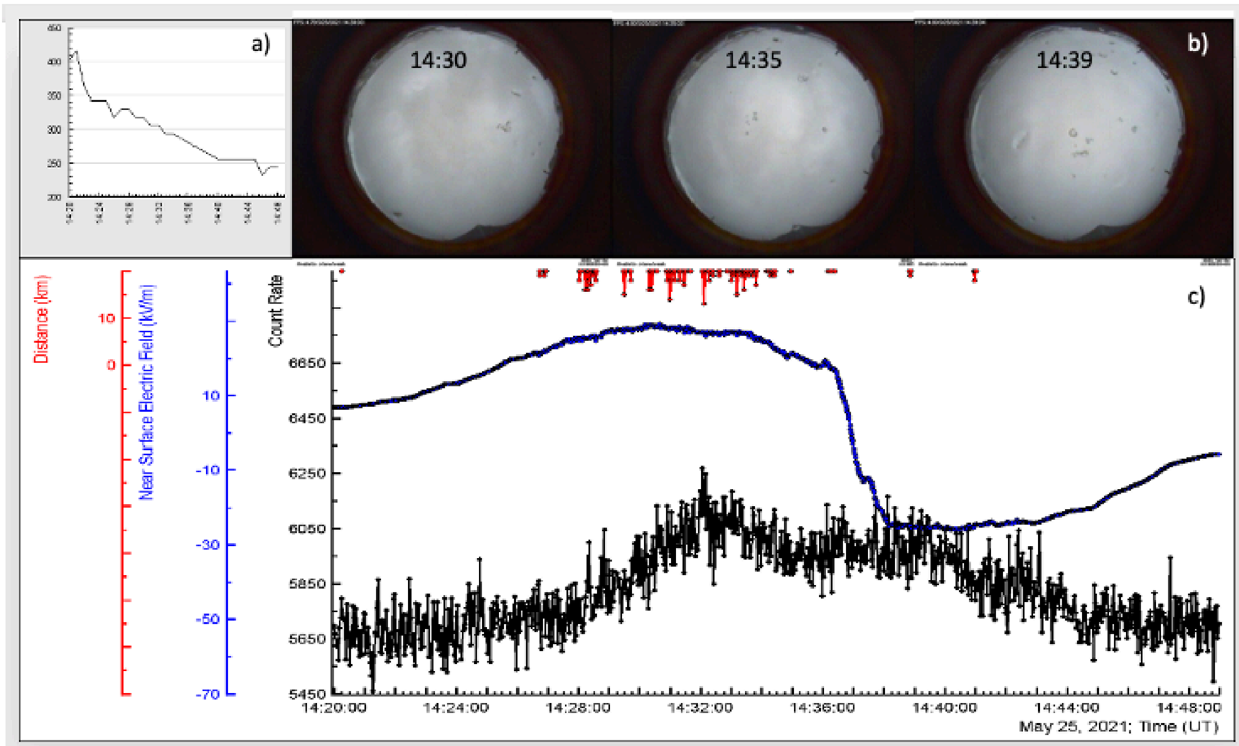


Figure 2. A pattern of the progress of the storm on Aragats on 24 May.) The distance to the cloud base. b) Images of the graupel fall. c) Disturbances of the NS electric field (blue), count rate of ASNT spectrometer (black), and distance to lightning (red).

On 25 May during a 1-hour long storm, no nearby lightning flashes were registered at all. TGE was lengthy, its duration was 18 minutes and particle flux continued both during positive and negative NS electric field, demonstrating that both main scenarios of TGE initiation (with and without emerging LPCR) can be rather smoothly continued during field reversal in the lower part of the cloud. Cloud base was higher than that on 24 May and graupel fall was intense.



Fi

3. A pattern of the progress of the storm on Aragats on 25 May. a) The distance to the cloud base. b) Images of the graupel fall. c) Disturbances of the near NS electric field (blue), count rate of ASNT spectrometer (black), and distance to lightning (red).

In Table 1 we summarize characteristics of TGEs registered on Aragats during storms in May 2021.

In the first 2 columns we post the TGE start and finish times; in the third the percent of flux enhancement relative to pre-TGE value; in the fourth – mean NS electric field during TGE (on May 25 there were 2 distinct values of NS field – both are posted, separated by slash); in the fifth column – the mean temperature and distance to cloud base separated by a slash; it the sixth – the time of a terminated flash (if any); in the seventh – distance to lightning flash; in the last column - flash initial and final NS electric field, again separated by a slash.

Table 1. Parameters of the TGE events and terminating lightning flashes during May storms on Aragats

	TGEs on 23 May,15:00-15:20, totally 30 lightning flashes on < 10 km distance						
TGE start	**TGE Finish**	**TGE%**	**Mean Field kV/m**	**T ©, Dist. Cloud(m)**	**Time of Flash**	**Dist. to flash (km)**	**El. Field change kV/m**
15:10	**15:19:30**	**2.**	**-20**	**4.2/300**	**15:19:30**	**1.6**	**-21/+31**
15:10:50	**15:12**	**1.1**	**-3**	**4/300**	**15:12**	**5.4**	**-21/24**
TGE on 24 May,14:20-14:48, totally 15 lightning flashes on < 10 km distance							
14:23:01	**14:26:20**	**4.5**	**17**	**4.5/470**	**14:26:20**	**4.4**	**2/32**
14:32:50	**14:45:10**	**12.7**	**-19**	**1.6/200**			

TGE on 25 May,14:20-14:48, totally no lightning flashes on $<$ 10 km distance				
14:26:45	**14:44:45**	**10/8**	**+28/-25**	**3.0/240**

In Fig. 4 we present differential energy spectra measured by a 4 m^2 area and 60 cm thick scintillation spectrometer ASNT (detail see in Chilingarian et al., 2017a). Spectra were approximated by the power-law dependence; the power low indices were roughly constant during 4 minutes and equal to 2.0 for electron spectra and 2.4 – for gamma ray spectra. As it is expected due to large ionization losses of electrons the intensities and maximal energies of the electron flux are smaller than the same parameters of the gamma ray flux. However, the proximity of maximal energies of both TGE species demonstrates that the strong accelerating electric field in the atmosphere is extended almost until the earth's surface, lower than the estimate of the cloud base height.

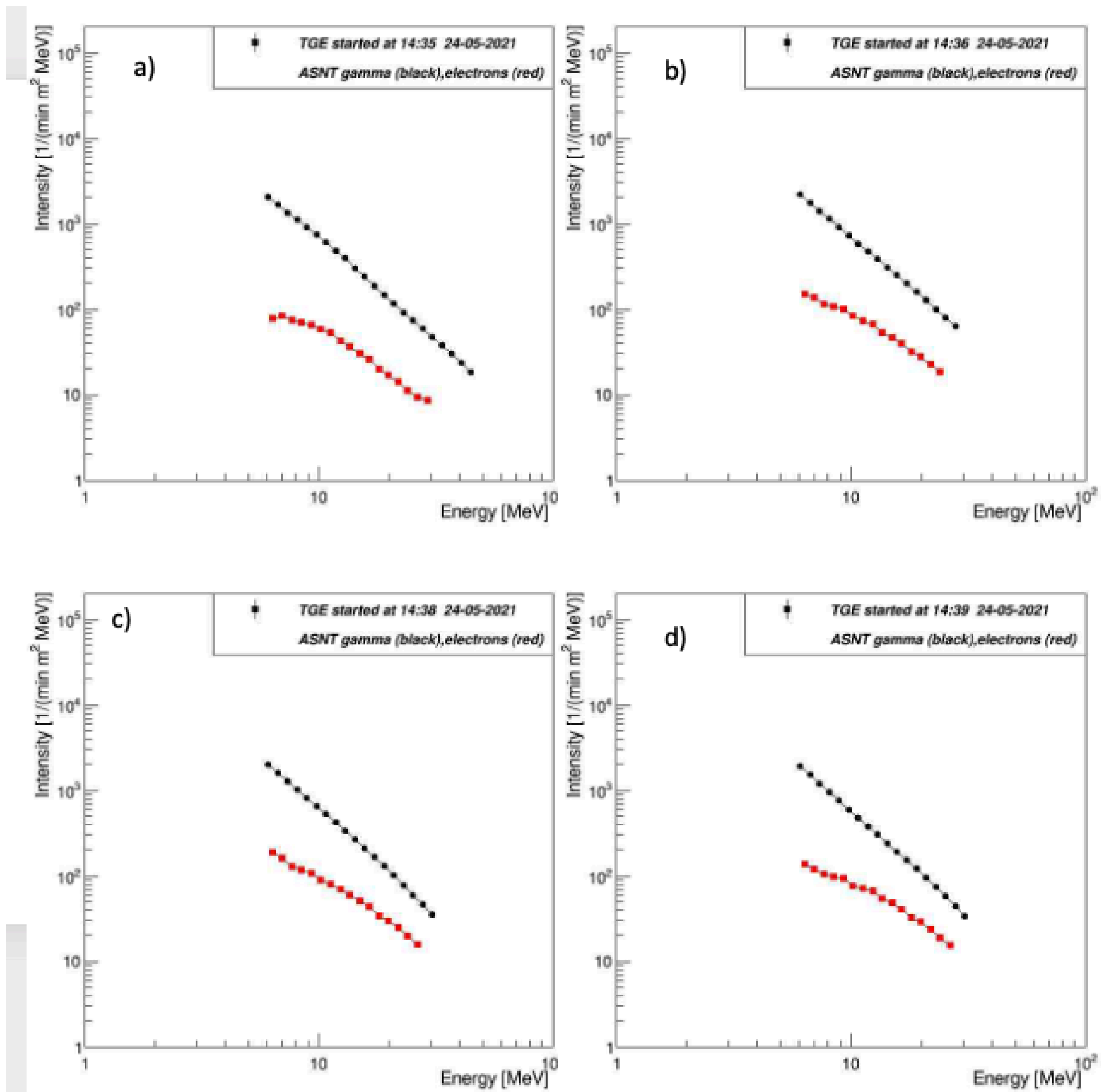


Figure 4. Differential energy spectra of electrons (red) and gamma rays (black) were registered on May 24, 2021

In Table 2 we post the parameters of the energy spectra of both species for 4 minutes of the maximum TGE flux. In second and third columns – the integral energy spectrum of both fluxes (started from 7 MeV); in fourth – the electron-to-gamma ray ratio; in the fifth and sixth – maximal energies of differential energy spectra for both species; and in the last – an approximate estimate of termination height of the strong accelerating electric field (according to the algorithm from Chilingarian et al., 2021d).

Table 2. Parameters of gamma ray and electron energy spectra measured on 24 May 2021

Date	Integral Spectrum E>7MeV					
24 May 2021	Electron	Gamma Ray	N_e/N	$E^e{}_{max}$ (MeV)	E_{max} (MeV)	Est. E.
14:35:00	974	8090	0.12	29	45	75
14:36:00	1530	8580	0.18	24	28	50
14:38:00	1640	7240	0.23	26	31	60
14:39:00	1550	6660	0.23	26	31	60

Discussion and conclusions

Strong electric fields in thunderclouds give rise to RREAs, which in turn precede lightning flashes and discloses the structure and strength of atmospheric electric fields. 3 episodes of electron acceleration observed at the end of May 2021 on Aragats demonstrate a rich variability of the electron accelerator operation depending on the proximity of the detection site to the active storm region. On 23 May when the storm was above particle detectors, the highly electrified atmosphere terminates the runaway process and a nearby (at distances 1.6 – 5.4 km) lightning flashes terminate RREA after a few tens of seconds. If the storm active zone is far away from particle detectors (>10 km) the TGE extends 12 and 18 minutes and smoothly terminates when conditions of the atmospheric electric field fail to support RREA. Thus, the RREA can be unleashed in a very large spatial domain around the storm, reaching 6-10 km in radii. Adopting the energy spectra of a large TGE registered on May 30, 2018 (Chilingarian et al., 2018) we estimate the total number of electrons and gamma rays (with energies above 100 keV) hitting the earth's surface to be $7*10^7/m^2$min. Assuming that 2000 thunderstorms are active on the globe and that the overall surface of the thunderous atmosphere each moment can be estimated as 2.000 * 100 km^2 = 200,000 km^2 (0.04% of the globe surface), we come to an estimate of $2*10^{18}$ gamma rays are hitting the earth's surface each second!

Proceeding from discussed TGE events and from the vast majority of TGEs registered on Aragats during the last 12 years (more than half-thousand) we confirm the statement formulated in (Chilingarian et al., 2017b) that TGEs are precursors of lightning flashes (see Fig. 1).

In previous papers we consider two scenarios of TGE initiation:

a) The electric field originated between the main negative and its mirror in the ground (MN-MIRR) forms a lower dipole that accelerates electrons downward;

b) Additional second dipole (MN-LPCR) emerges, which is parallel to the first at least in the most part of the cloud.

LPCR is sitting mainly on precipitation (graupel) that becomes positively charged above -10. Thus, the falling LPCR elongates the accelerating field until very low heights above the ground and the electric field of the lower dipole accelerates electrons to high energies due to large potential differences. In the Spring season, almost every thunderstorm and TGE on Aragats was accompanied by a graupel fall which was monitored on a minute time scale. The TGEs occurred on 24-25 May are a good verification of the described above model.

We confirm the emergence of the graupel dipole, apparently seen on May 25 (first part of TGE, Fig 3c). It is interesting to note a minute-long polarity reversal of the NS field (Fig 3c). Several remote lightning flashes during the positive NS field period led to a field reversal in few minutes and the NS field fall in the deep negative domain, sustaining the second phase of TGE (no lightning flashes occurred during this phase).

The measured energy spectra and estimates of strong electric field termination heights (Fig.4 and Table 2) also confirmed the low location of the strong electric field in good agreement with the TGE initiation model, and - with simulation results (Chilingarian et.al., 2020 and 2021a).

Data Availability Statement

The data for this study are available on the WEB page of the Cosmic Ray Division (CRD) of the Yerevan Physics Institute, http://adei.crd.yerphi.am/adei.

Acknowledgment

We thank the staff of the Aragats Space Environmental Center for the operation of the uninterruptable operation of all particle detectors and field meters. Special thanks to T.Karapetyan and B.Sargsyan for tuning and maintaining the ASNT spectrometer. The authors thank S. Soghomonyan for useful discussion and help in preparing the manuscript. *The authors acknowledge the support of the Science Committee of the Republic of Armenia, in the frames of the research project № 21AG-1C012.*

References

A. Chilingarian, A. Daryan, K. Arakelyan, et al., Ground-based observations of thunderstorm-correlated fluxes of high- energy electrons, gamma rays, and neutrons, Phys. Rev. D 82 (2010) 043009.

A.Chilingarian, G. Hovsepyan, A. Hovhannisyan, Particle bursts from thunderclouds: natural particle accelerators above our heads, Phys. Rev. D 83 (2011) 062001.

Chilingarian A., Hovsepyan G., Mailyan B., 2017a, In situ measurements of the Runaway Breakdown (RB) on Aragats mountain, Nuclear Inst. and Methods in Physics Research, A 874,19–27.

Chilingarian A., Chilingaryan S., Karapetyan T., et al., 2017b, On the initiation of lightning in thunderclouds, Scientific Reports **7**, Article number: 1371, DOI:10.1038/s41598-017-01288-0.

A.Chilingarian, G. Hovsepyan, S. Soghomonyan, M. Zazyan, and M. Zelenyy, Structures of the intracloud electric field supporting origin of long-lasting thunderstorm ground enhancements, Physical review 98, 082001(2018).

A. Chilingarian, G. Hovsepyan, T. Karapetyan, G. Karapetyan, L. Kozliner, H. Mkrtchyan, D. Aslanyan, and B. Sargsyan, Structure of thunderstorm ground enhancements, Phys. Rev. D 101, 122004 (2020).

A. Chilingarian, G. Hovsepyan, E. Svechnikova, and M. Zazyan, Electrical structure of the thundercloud and operation of the electron accelerator inside it, Astroparticle Physics 132 (2021a) 102615 https://doi.org/10.1016/j.astropartphys.2021.102615.

Chilingarian, A., Hovsepyan, G., & Zazyan, M. (2021b). Muon tomography of charged structures in the atmospheric electric field. *Geophysical Research Letters*, *48*, e2021GL094594. https://doi.org/10.1029/2021GL094594

A. Chilingarian, G. Hovsepyan, G. Karapetyan, and M. Zazyan, Stopping muon effect and estimation of intracloud electric field, Astropart. Phys. 124, 102505 (2021d).

A.Chilingarian, G. Hovsepyan, and M. Zazyan, Measurement of TGE particle energy spectra: An insight in the cloud charge structure, Europhysics letters (2021d), 134, 6901, https://doi.org/10.1209/0295- 5075/ac0dfa

J. Chum, R. Langer, J. Baše, M. Kollárik, I. Strhárský, G. Diendorfer, and J. Rusz, Significant enhancements of secondary cosmic rays and electric field at high mountain peak during thunderstorms, Earth, Planets Space 72, 72 (2020).

Gurevich, A., Milikh, G., & Roussel-Dupre, R. (1992). Runaway electron mechanism of air breakdown and preconditioning during a thun- derstorm. Physics Letters A, 165(5–6), 463–468. https://doi.org/10.1016/0375-9601(92)90348-P.

Omni atmospheric thermodynamics calculator, https://www.omnicalculator.com/physics/cloud-base

Takahashi, T. (1978), Riming electrification as a charge generation mechanism in thunderstorms, J. Atmos. Sci., 35, 1536–1548.

Wada, Y., Enoto, T., Kubo, M., Nakazawa, K., Shinoda, T., Yonetoku, D., et al. (2021). Meteorological aspects of gamma-ray glows in winter thunderstorms. Geophysical Research Letters, 48, e2020GL091910. https://doi.org/10.1029/2020GL091910

E.R. Williams, The tripole structure of thunderstorms, JGR 94 (1989) 151-13,167.