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COMMENT

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Key Points:

- The contribution of the Compton scattered and pair-production electrons to TGE flux is negligible and cannot "mimic" the TGE electron flux
- The criteria used in the energy spectrum recovery from Aragats Solar Neutron Telescope (ASNT) reliably select "electron" TGE events and reject TGE events with small electron content
- If the strong accelerating electric field terminates low above the earth's surface (25–100 m), electrons from the large RREAs reach ASNT, and their energy spectrum can be reliably recovered

Correspondence to:

A. Chilingarian,
chili@aragats.am

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Author Contributions:

Conceptualization: A. Chilingarian
Data curation: B. Sargsyan
Formal analysis: A. Chilingarian, D. Aslanyan, B. Sargsyan, M. Zazyan
Methodology: A. Chilingarian, G. Hovsepyan
Project Administration: A. Chilingarian, T. Karapetyan
Resources: T. Karapetyan
Software: G. Hovsepyan, D. Aslanyan, B. Sargsyan, M. Zazyan
Supervision: A. Chilingarian
Validation: G. Hovsepyan, D. Aslanyan
Visualization: G. Hovsepyan, M. Zazyan
Writing – original draft: A. Chilingarian

TGE Electron Energy Spectra: Comment on "Radar Diagnosis of the Thundercloud Electron Accelerator" by E. Williams et al. (2022)

A. Chilingarian[1], G. Hovsepyan[1], D. Aslanyan[1], T. Karapetyan[1], B. Sargsyan[1], and M. Zazyan[1]

[1]Alikhanyan National Lab, Yerevan Physics Institute, Yerevan, Armenia

Abstract E. Williams et al. (2022, commented paper) questioned electron energy spectra derived from thunderstorm ground enhancements (TGEs) measured on Aragats; they concluded that "A more likely origin for any detected electrons at 3.2 km above sea level is Compton scattering and pair production activated by longer-range bremsstrahlung gamma rays, themselves produced by runaway electron encounters with nuclei in the breakeven field at higher altitude." In this comment, we show that the selection criteria of "electron" TGEs unambiguously reject the assumption of the origination of TGE electrons measured on Aragats from the Compton and pair production processes. Thus, the strong accelerating electric field above the earth's surface can be significantly lower (25–150 m) than derived in the commented paper 500 m altitude.

Plain Language Summary Electron accelerators operate in the thunderous atmosphere, sending copious particles to the Earth's surface. To get inside the models of electron acceleration and multiplication by strong atmospheric fields, the critical problem is the measurement of electrons and their energies as they arrive at the earth's surface. It is rather tricky because electrons are fast attenuated in the air, and the flux of accompanied gamma rays is attenuated much less and reaches the ground in overwhelming amounts. We developed special hardware and software methods to prove electrons' existence in the vast particle fluxes reaching the ground and to measure their energies. Simulations and careful examination of the registered particle fluxes check these methods.

1. Introduction

In the commented paper, proceeding from thunderstorm ground enhancements (TGEs) observed on Mt Aragats (3.2 km above sea level), the altitude-resolved S-band radar observations of graupel are used to demonstrate distinct differences in storm structure relative to the near-surface electric field (NSEF) polarity. The authors conclude that the altitude of downward electron acceleration and avalanching may be sufficiently distant (>500 m) from the surface detector, and electrons observed by Aragats detectors are not likely avalanche/runaway electrons. Instead, they are Compton-scattered and pair-produced electrons from bremsstrahlung gamma radiation emanating from the high-field avalanche region aloft.

We demonstrate that simulations of the particle transport in the atmosphere and parameters of measured TGEs contradict this statement; they show that Compton scattering and pair production do not produce enough energetic electrons to mimic the electron energy spectra measured on Aragats. When gamma rays and electrons exit the region of the strong electric field, in which the relativistic runaway electron avalanche (RREA, Babich et al., 2001; Dwyer, 2003; Gurevich et al., 1992) was developed, electrons of MeV energies lose almost a fixed portion of energy per meter of air (≈200 KeV at altitudes 3–4 km). In contrast, the gamma rays lose only a small percent of their intensity at each meter. In Figure 1, we show the histograms of the energies of electrons and gamma rays reaching the earth's surface after exiting the strong electric field. The insets show the number of electrons (Ne) and gamma rays (Nγ) reaching the earth's surface for different energy ranges. We used the CORSIKA code (Heck et al., 1998) version 7.7400, which considers the electric field's effect on the transport of particles (Buitink et al., 2010). We examined the RREA process for various vertical profiles of the atmospheric electric field. We selected plausible combinations of the field strength and extension, which support RREA emergence and TGE observation (Chilingarian, Karapetyan, et al., 2021; Chilingarian, Hovsepyan, & Zazyan, 2021; Chilingarian, Hovsepyan, et al., 2021). Using several particular electric field parameters (for instance, field strength Ez = 2.0 kV/cm, field extension 2 km), we simulate the RREA propagation using seed electrons with a fixed energy of $E_0 = 1$ MeV. The accelerating electric field termination height was preset to 200 m (Figure 1a)

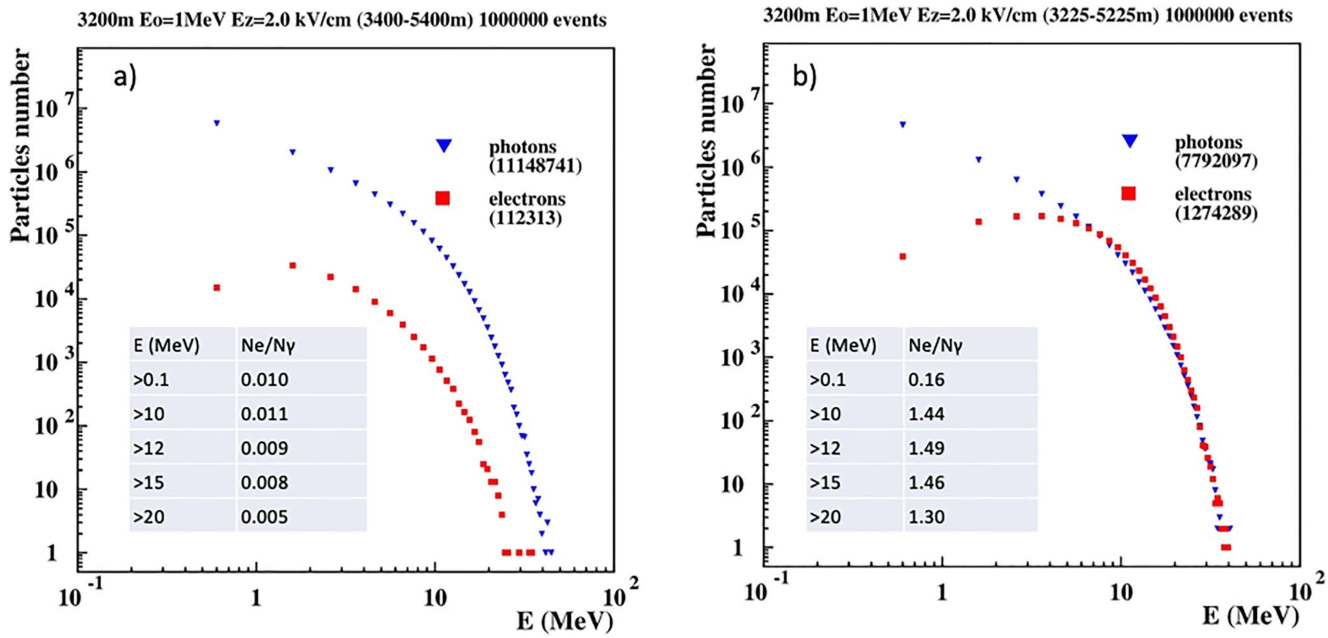


Figure 1. The comparison of the energy spectra of the gamma rays and electrons developing in the electric fields, which terminates at heights of 200 m (a) and 25 m (b) above the spectrometer (CORSIKA simulations with 1 MeV seed electrons and uniform electric field).

and 25 m (Figure 1b). Sure, the simulation of the RREA process is somewhat simplified; we cannot introduce swift changes in the atmospheric electric field that accelerated electrons in the direction of the earth's surface.

The gamma ray "beam" traveling in the air undergoes well-known interactions with air atoms. The most important are the photoelectric effect, pair production, and Compton scattering (in a MeV region, Compton scattering is the dominant process). Almost all electrons coming from 200 m will lose their energy in interactions with air atoms; only electrons generated by gamma rays by pair production and by Compton scattering will reach the ground. However, as we can see in the inset to Figure 1a, the electron content of RREA reaching the ground is ≈1% or less relative to the gamma ray content for all electron energies of interest. Due to their tiny fraction, it is impossible to separate the electron flux from the dominant gamma ray flux in the energy-release histograms. However, if the accelerating electric field continues until 25 m above ground, the electron content exceeds the gamma ray content (see the inset to Figure 1b). Thus, only if a strong accelerating electric field is well below 200 m can RREA electrons be registered by particle detectors, and their energy spectrum can be recovered. A detailed description of the Aragats solar neutron telescope (ASNT) and the method of energy spectra recovery can be found in (Chilingarian, Hovsepyan, Karapetyan, Sargsyan, & Chilingaryan, 2022) and in the next section, where we formulate the necessary condition for the revealing TGE electrons.

The second section will describe the ASNT spectrometer and explain the electron flux validating procedures. In the third section, we will present TGE events registered on Aragats in 2019–2021 and discuss their characteristics necessary for electron spectrum recovery. In the fourth section, we will formulate the criteria for the "electron TGEs" on the example of TGE registered on 27 June 2020.

2. Revealing TGE Electrons by the Aragats Solar Neutron Telescope (ASNT) Measurements

The electron energy spectra were recovered from energy release histograms measured by the ASNT spectrometer shown in Figure 2a. The name of the spectrometer is a historical one; the primary goal of its operation started 20 years ago was the registration of the direct neutrons originated in the violent solar flares. The spectrometer consists of four modules, each of two stacked scintillators of 5 cm (veto layer, scintillators 5–8) and 60 cm thickness (spectrometric layer, scintillators 1–4). The electron registration efficiency in both layers is larger than 95%, and gamma ray registration efficiency is 5%–6% for the thin scintillator and 40%–70% for the thick one.

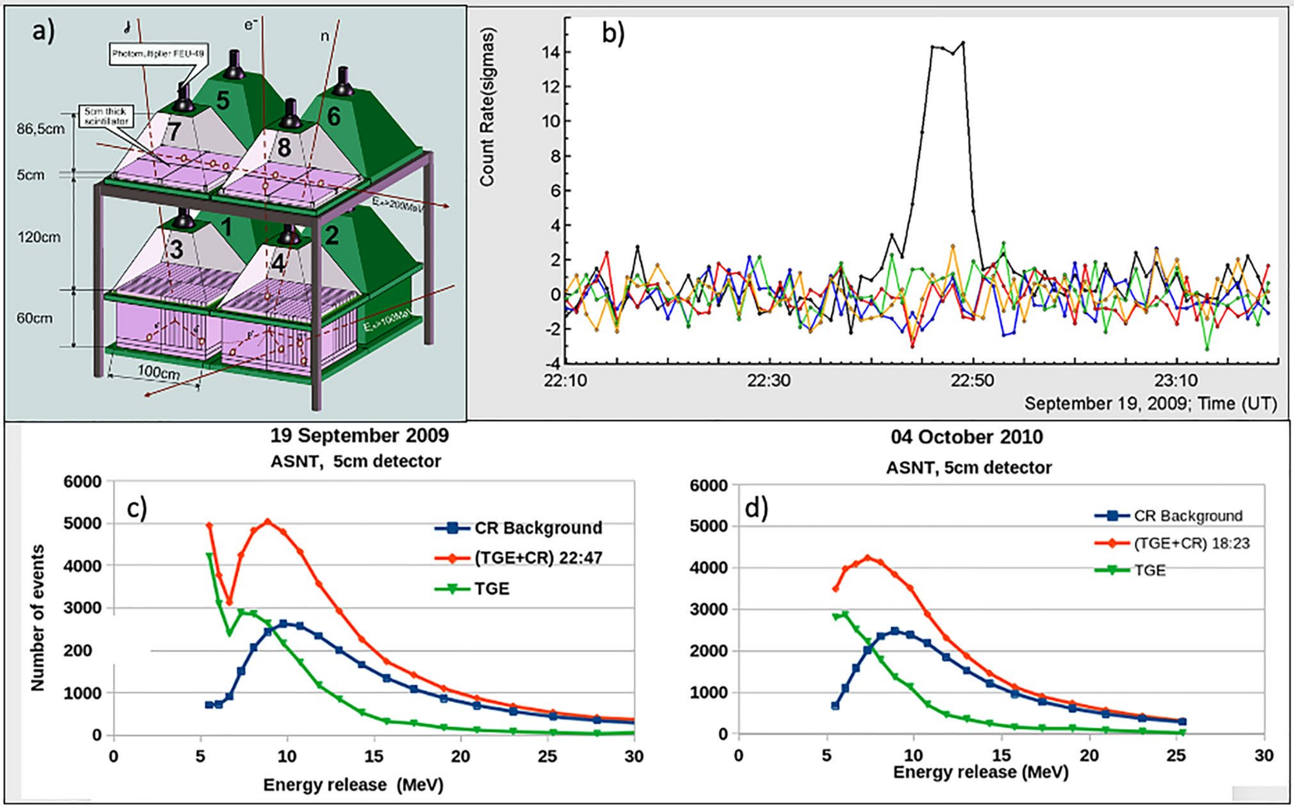
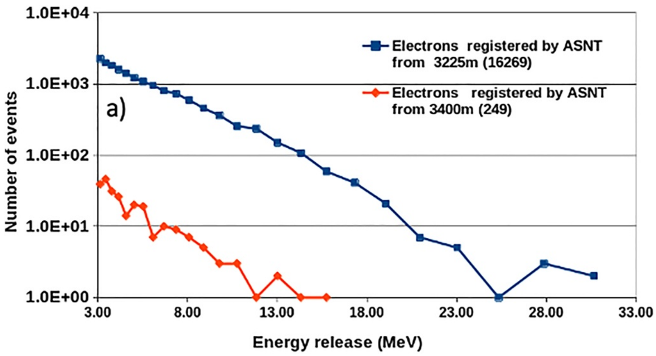


Figure 2. (a) The layout of the ASNT spectrometer; (b) 1-min count rate of ASNT "11" coincidence for five angles of incidence; (c) the energy release histograms in the upper 5 cm thick plastic scintillator for the TGE observed in September 2009: red, measured during TGE; blue, background measured before TGE; green, a difference of both, the TGE particle energy release; (d) the same for the TGE, which was observed in October 2010 (no electrons).

The count rates corresponding to all possible coincidences between two layers (within one microsecond) are separately counted and stored every minute (after 2012—every 2 s). We also store time series of count rates corresponding to the "01" coincidence—if the signal is in the lower layer only (mainly gamma rays), and corresponding to the "11" coincidence—signals in both layers of the spectrometer (primarily electrons). Additionally, the energy release histograms in both layers of the ASNT spectrometer and energy releases corresponding to the "01" coincidence (with a veto on charged particles) are stored each minute.

Figure 2b shows the count rates of "11" coincidence. Coming within the near-vertical direction in the cone of 0°–22° (black curve, coincidences 1:5, 2:6, 3:7, and 4:8) and within the zenith angle of 22°–58° (colored curves). Only the vertical direction of the TGE particle arrival demonstrates a 4-min-long large peak (≈14 standard deviations) because a vertical intracloud electric field accelerates electrons. Inclined trajectories do not demonstrate any count rate enhancement. Electron scattering in the ASNT detector can widen the electron zenith angle distribution and enhance the share of the inclined trajectories; however, our simulations show that the frequency of such cases is not more than 10%; not for even one TGE, we did not register any peak in the inclined trajectories.

In Figure 2c, we demonstrate the energy release histograms of all particles traversing the 5 cm thick scintillator (without any trigger) at minute 22:49–22:50 on 19 September 2009. From the histogram measured during TGE (red curve), we subtract the background histogram measured on fair weather before the TGE starts (blue curve). The residual green curve represents the energy releases of the TGE gamma rays and electrons in the 5 cm thick scintillator. As we can see in Figure 2c (green curve), the energy releases during TGE peaked at 7–9 MeV, as electron losses in the scintillator are ≈1.8 MeV per centimeter, and electrons with energies starting from 7 MeV can enter the sensitive volume of the scintillator and release energy. The energy releases of gamma rays in the 5 cm thick scintillator have an exponential shape and do not produce any peak, as we can see in Figure 2d (green curve), where we show another large TGE observed on 4 October 2010. This TGE does not contain electrons (the accelerating electric field stopped high above the earth's surface, and the electron flux attenuated before reaching



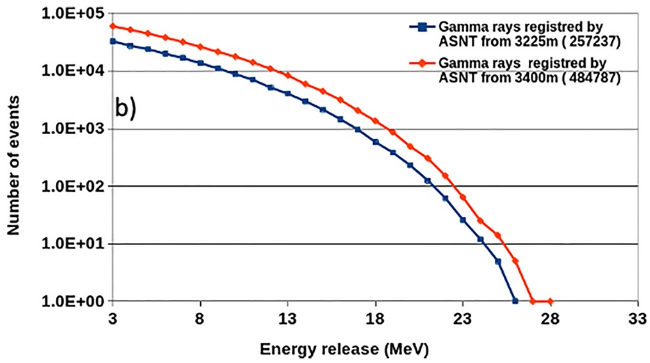


Figure 3. (a) Energy release histogram of TGE electrons in the lower thick scintillator of the ASNT spectrometer, the red curve corresponds to the case when the electric field terminates at 200 m above the detector, blue—25 m above the detector; (b) the same for the gamma ray flux. Both fluxes were simulated by CORSIKA code with parameters described in Figure 1.

the spectrometer). We detect no peak in the TGE energy release histogram. Thus, if we have a significant rise in the time series of “11” coincidence (vertical direction, Figure 2b) and a peak in the energy releases in the 5 cm thick scintillator (green curve in Figure 2c), we can be sure that TGE contains sizable electron fraction. A long tail in the energy release distribution can be explained by pair production by high-energy gamma rays in the scintillator or by multiple particles entering ASNT.

Experimentally, the electron energy spectrum is recovered from energy release histograms in the 60 cm thick scintillator by subtracting the histogram corresponding to the “01” selection from the overall energy release histogram (without veto option). The “01” energy release histogram derives the gamma ray energy spectrum. We solve the inverse problem of recovering energy spectra from energy release histograms using a detailed simulation of the detector response made with GEANT4 code (see details in Chilingarian, Hovsepyan, Karapetyan, Sargsyan, & Chilingaryan, 2022).

In Figure 3, we show the energy release histograms corresponding to simulated RREAs (Figure 1) obtained after tracking electron and gamma rays through the exact model of the ASNT detector, including all experimental procedures. In Figure 3a, we show the energy release distribution corresponding to the “11” coincidence for the electrons reaching ASNT from 200 m (red curve) and 25 m (blue curve). The equal distribution for simulated gamma rays is shown in Figure 3b.

Paradoxically, the number of gamma rays reaching the detector from 200 m is larger than 25 m. The intense bremsstrahlung process of the electrons in the dense lower atmosphere explains it.

The significant weakening of the electron flux can be explained by the ionization losses in the dense air and the detector matter. Only 1.28% of simulated electrons that reach 3,200 m were registered by the ASNT lower scintillator if the electric field terminated 25 m above the spectrometer (blue curve of Figure 3a, 16,269 from 1,274,689). Suppose the electric field ends 200 m above the spectrometer (TGE electrons will not reach the detector), and electrons are born in the air of the detector by the “gamma ray beam” (mostly Compton scattered electrons). This ratio is much smaller, only 0.2% (red curve of Figure 3a, 249 from 112,313). The matching numbers for the gamma ray flux are correspondingly 3.3% for the 25 m (blue curve in Figure 3b, 257,237 from 7,792,097) and 4.3% for 200 m (red curve in Figure 3b).

No pure gamma ray and electron “beams” exist, which were used in the simulation. Sure, the ASNT spectrometer cannot distinguish energy released by an electron from the energy released by a gamma ray. We can isolate electrons only statistically, subtracting the “pure gamma ray histogram” (coincidence “01”) from the total energy release histogram. To recover electron energy spectra, we need a sizable portion of electrons in the joint energy release histogram registered by ASNT (the ratio “11”/“01” to be well above the statistical fluctuations). Thus, the “11”/“01” ratio controls the possibility of recovering the energy spectrum. Using the "pure" beams obtained in simulations (Figure 1), after tracking them through the ASNT detector, we estimate the “11”/“01” ratio:

$$\text{“11”/“01” (25m)} = 16,269/257,237 \approx 6.3\%; \text{“11”/“01” (200m)} = 249/484,787 \approx 0.05\%$$

Table 1
Parameters of the TGEs With Significant Electron Content

Date	SEVAN significance (%/σ)	ASNT "11" significance max. flux minute (%/σ)	"11"/"01" max. flux minute	Ne/Nγ $E > 10$ MeV max. flux minute	NSEF (kV/m)	Flash time/dist. (UT/km)
06.18.19	13/16	4.6/6.1	0.029	0.18	+23/−26	22:13:53/2.6
06.14.20	20/24	5/7.8	0.025	0.15	+13/−16	19:43:32/7.1
06.27.20	9/17	6/7.6	0.047	0.26	+12/−22	No
09.25.20	26/32	3.8/4	0.007	0.19	+12/−22	18:52:00/5.5
05.24.21	9/11	5.1/5.5	0.061	0.21	+1/−20	No
10.06.21	46/55	10/11	0.034	0.11	+10/+26	2:04:06/4.4
Sim. 200m			0.0005			
Sim. 50m			0.063			

Thus, the electron content is more than 100 times more for the RREAs developing in the electric field prolonging to 25 m above the ground (TGE electrons) compared with RREAs going out of the electric field at the height of 200 m above the ground (Compton scattered electrons). Suppose the electric field terminates 200 m above the ground. In that case, only 249 electrons (0.05% relative to gamma rays) are expected to appear in the joint histogram of energy releases, and the electron energy spectrum recovery obviously could not be done. In contrast, if the electric field is prolonged down to 25 m above the ground, using ≈16,000 electrons (6.3% relative to gamma rays), it will be possible to recover the electron energy spectrum. Consequently, Compton scattered electrons and electrons from the pair production cannot mimic TGE electrons.

3. Characteristics of Selected TGE Events With Significant Electron Content

A complete set of TGE parameters is available from the Mendeley data set (Chilingarian & Hovsepyan, 2021). Table 1 shows the parameters of TGEs, with significant electron content observed in 2019–2021. In the last two rows, we put the data obtained from the simulation of RREA in the atmosphere for cases when the electric field terminated at 200 and 25 m.

In the first column of Table 1, we put the date of the TGE. In the second column, we post the TGE significance by the percent of the enhancement above the mean value measured on fair weather and by the number of standard deviations from the mean value (by the 1-min time series of the count rate of the SEVAN's detector upper scintillator). In the third column, we post the significance of the "electron" peak (the "11" coincidence at maximum flux minute).

In the fourth column, we post the ratio of the "11" to "01" coincidences (for the maximum flux minute, each with subtracted own fair-weather value). In the fifth column, we show the share of electron flux relative to gamma ray flux above the ASNT detector obtained by recovered electron and gamma ray spectra (for the maximum flux minute and energies above 10 MeV, see details of spectra recovery in Chilingarian, Hovsepyan, Karapetyan, Sargsyan, & Zazyan, 2022). We put the NSEF value measured at the TGE beginning and the maximum in the sixth column. In the last column, we show the time of occurrence and distance to the lightning flash (if any).

All six selected TGEs are highly significant; the mean TGE enhancement above the fair-weather value is 5.8%, corresponding to 7$\boldsymbol{\sigma}$ significance. The critical condition for the electron TGE selection, namely the presence of a large peak in the time series of "11" coincidence, is fulfilled for all six selected TGEs, see the third column of Table 1. The "11"/"01" ratio, measured by the ASNT detector, is much smaller than the obtained from the recovered particle flux ratio Ne/Nγ (above the ASNT detector) because electrons are much more attenuated in the material of the detector compared with gamma rays.

We can compare the "11"/"01" ratio from Table 1 with simulation results shown in Figures 3 and 2 last rows of Table 1. We can see in the Table that for the observed events measured "11"/"01" ratio is compatible with a 25 m field height and is much larger than the one obtained for the 200 m height (Compton scattered electrons).

If a strong electric field terminates at 25 m from the ground, this ratio is 6.3%; if on 200 m, more than 100 times less—0.05%. Thus, the hypothesis that we detect Compton scattered electrons originating from the gamma ray "beam" is not supported by the measured TGEs and simulations.

Sure, the "11"/"01" ratio depends on the height of the electric field termination and the TGE size, which depends on unknown electric field strength and extension. For instance, if TGE is huge, like on 25 September 2020, the "11"/"01" ratio is the smallest. In massive avalanches, which leave a strong electric field high above the ground, electron flux attenuates, giving birth to many gamma rays, making the denominator of the "11"/"01" ratio huge.

In the simulation, we choose plausible parameters of the intracloud electric field from comparisons with observed energy spectra (see details in Chilingarian, Hovsepyan, et al. (2021)); the recovered spectra, in turn, were checked with count rates measured by independent particle detectors operated on Aragats (Chilingarian, Hovsepyan, Karapetyan, Sargsyan, & Chilingaryan, 2022). For the observed TGE events in Table 1, we don't know the field strength and extension values. Thus, the direct comparison of simulated and measured electron numbers is impossible. However, the "11"/"01" ratio should be at least larger than 1% (for gamma scattered electrons, it is 0.05%) to allow reliable recovery of the electron energy spectrum.

Five TGEs from six began when NSEF was positive, and before TGE flux reached the maximum, NSEF turned to a deep negative value. Only one TGE started and finished when NSEF was largely positive. Thus, both scenarios of the lower dipole are realized (see for details Chilingarian, Hovsepyan, et al., 2021). Four of six TGE events were abruptly terminated by nearby lightning flashes, confirming our hypothesis that the large electron flux in the thundercloud can make enough ionization for the lightning flash initiation (Chilingarian et al., 2017).

4. "Electron TGE" Selection Criteria

For selecting TGE candidates, we apply to observed enhancement in the count rate standard requirements: peak significance should be above 3$\boldsymbol{\sigma}$ for at least three independent particle detectors, and the absolute value of the near-surface electric field (NSEF) should be at least five kV/m. Until now, all registered TGEs were accompanied by NSEF disturbances with an amplitude of at least five kV/m. We use this check to ensure enhanced particle flux is due to the intracloud electric field and not an artifact connected with possible misfunctioning of the detectors (for instance, surges in the electricity supply or high-voltage device failure).

Figure 4 shows that the TGE occurred on 27 June 2020 (the third row in Table 1). TGE started at a very small positive NSEF and continued at a negative NSEF exceeding −20 kV/m. The count rates of three plastic scintillators with the same area of 1 m^2 and thicknesses 1, 3, and 5 cm peaked with significances of ≈17, 16, and 11$\boldsymbol{\sigma}$. Lightning flashes observed at 10 km and more distances do not terminate TGE.

The next step in selecting "electron" TGE is to check peak significances in the ASNT spectrometer. In Figure 5a, we demonstrate peaks of TGE gamma rays ("01" coincidence, peak significance 40$\boldsymbol{\sigma}$) and electrons ("11" coincidence, peak significance 7.6$\boldsymbol{\sigma}$), 1-min time series.

Only electrons can produce a peak in the region of 6–9 MeV in the energy release histogram. After confirming the significance of both peaks (Figure 5), we check the "11"/"01" ratio. If it is too small, we cannot disentangle the histogram of energy releases in the lower "spectrometric" 60 cm thick scintillator and separate electron and gamma ray fluxes. For instance, if only Compton scatter electrons reach the lower scintillator, this ratio is only 0.05%, and we can never recover the electron energy spectrum. We recover the electron spectrum if this ratio is 10 times larger (usually ≈100 times, see the fourth column of Table 1). The final check will examine the energy release histogram in the upper 5 cm thick scintillator of the ASNT detector.

5. Conclusions

We demonstrate that applied criteria effectively select TGEs with significant electron content. Both simulations and experimentally measured TGE parameters show that if a strong electric field is prolonged very close to the earth's surface, the ASNT spectrometer can register electrons, and their energy spectrum can be recovered. In turn, if the accelerating electric field is terminated high above the ground, TGE electrons are attenuated, and

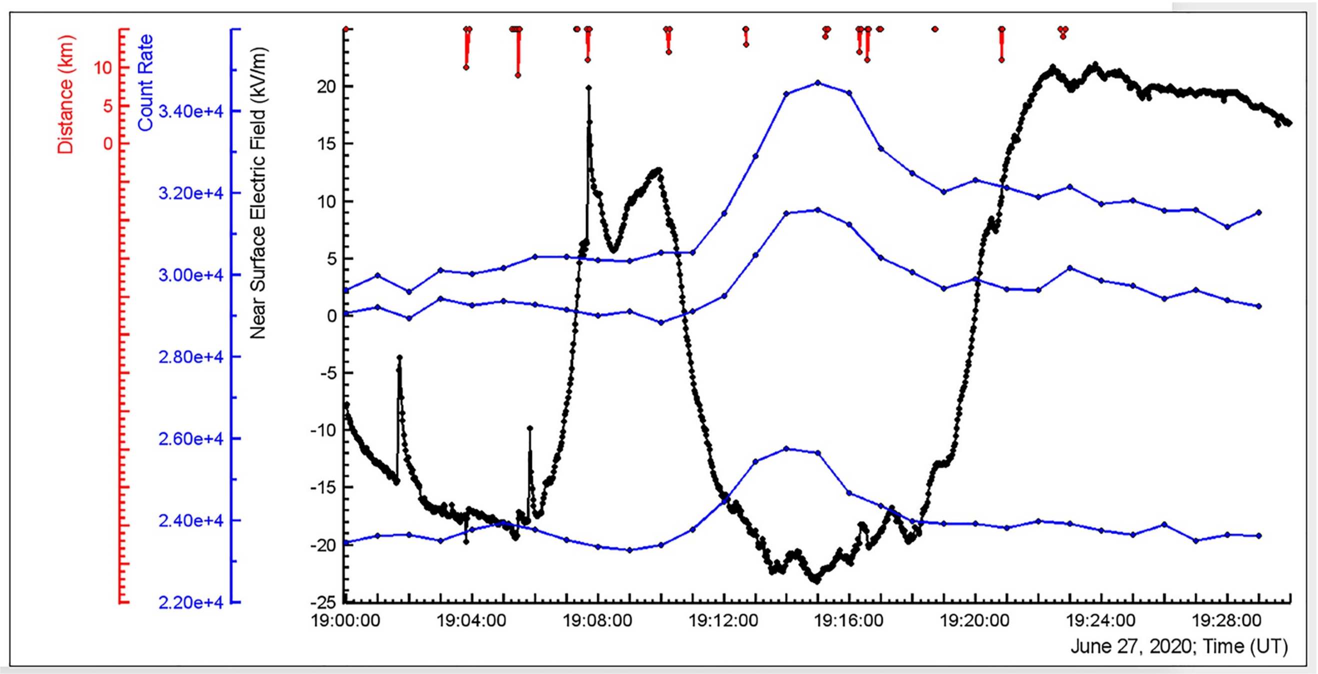


Figure 4. Black—disturbances of the NSEF, blue—-count rates of three independent particle detectors, red—distances to lightning flashes. TGE occurred on 27 June 2020.

recovery of electron energy spectra is not feasible. The contribution of the Compton scattered and pair production electrons is negligible, and such TGEs will never pass the selection criteria for the "electron TGE" candidates. The ultimate criteria for the "electron" TGEs are the presence of a sizable peak in the time series of the "11" coincidence (signals both in the upper 5 cm thick and in the lower, 60 cm thick ASNT scintillators) and the existence of a peak in the region 8–9 MeV in the distribution of energy releases in the upper 5 cm thick ASNT scintillator.

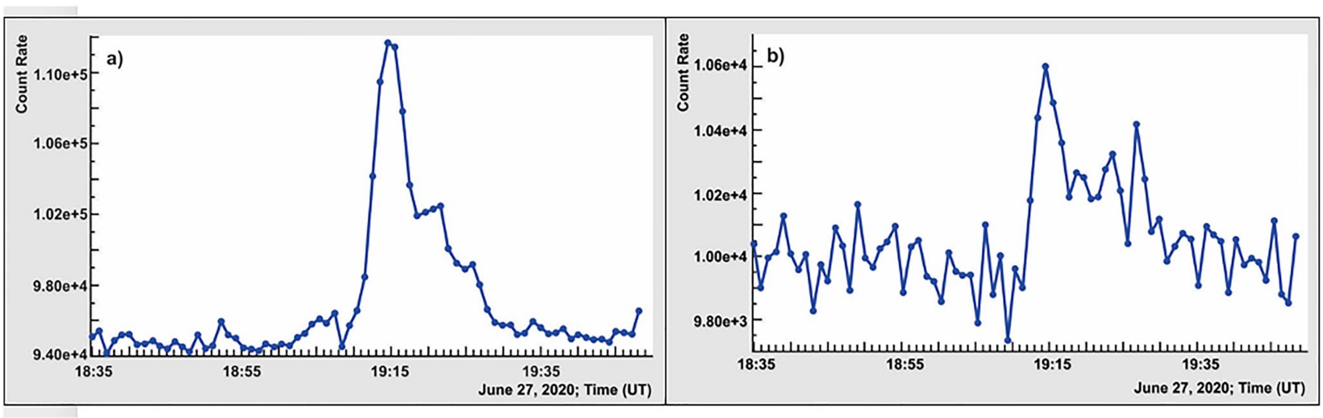


Figure 5. (a) 1-min time series of count rates of the "01" coincidence (mainly gamma rays); (b) 1-min time series of count rates of the "11" coincidence (with a large share of electrons).

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Data Availability Statement

The data that support the findings of this study are openly available at the following URL [database] http://adei.crd.yerphi.am/ URL [dataset] http://37.26.168.91/TGEsimul/.

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