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

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Key points

The contribution of the Compton scattered electrons to TGE flux is negligible.

The Aragats Solar Neutron Telescope (ASNT) 24/7 measures gamma ray and electron (if any) energy spectra for 15 years.

If the strong accelerating electric field is low above the earth's surface (150-200 m) TGE electrons reach ASNT and their energy spectrum is reliably recovered.

Comparison of the energy spectra of the electrons and gamma rays allows remote sensing of the vertical profile of the atmospheric electric field.

1. Introduction

E. Williams et al. (2022) questioned TGE electron energy spectra measured on Aragats; they conclude that "A more likely origin for any detected electrons at 3.2 km MSL is Compton scattering and pair production activated by longer-range bremsstrahlung gamma rays, themselves produced by runaway electron encounters with nuclei in breakeven field at higher altitude ".

In this comment, we show that the selection criteria of "electron" TGEs unambiguously reject the assumption on the origination of TGE electrons from the Compton process of the TGE gamma rays. Additionally, comparison of recovered gamma ray and electron energy spectra allows to estimate the height of the strong accelerating electric field above particle spectrometers and establish 24/7 monitoring of the horizontal profile of the atmospheric electric field during thunderstorms.

1. Electron and gamma ray propagation in the terrestrial atmosphere

When gamma rays and electrons multiplied in the relativistic runaway electron avalanche (RREA, Gurevich et al., 1992, Babich et al., 2001, Dwyer, 2003) exit the region of the strong electric field, both species are attenuated in the dense air, but in a very different way. Electrons lose almost a fixed portion of energy crossing each meter of air (0.2 MeV at altitudes 3-4 km), whereas the gamma rays lose at each meter only a small percent of their intensity; therefore, gamma rays of all "primary" energies can reach the ground. This difference in the attenuation rates of the main species of TGE allows one to approximately estimate the height above ground where the strong electric field terminates. From Table 1 we can see, that if the electric field terminates at 400 m above the ground, the TGE electrons with energies above 64 MeV only can be registered. At exceptional atmospheric conditions, only very few electrons can be accelerated to such high energies. In contrast, 50% of gamma rays can reach the ground and lead to a large enhancement of intensity measured by surface detectors; the energy spectrum of gamma rays can be reliably recovered by NaI and other scintillation spectrometers. Sure, the gamma ray “beam” traveling in the air undergoes various well-known interactions with air atoms. The most important are the photoelectric effect, pair production, and Compton scattering (in MeV region, the Compton scattering is the dominant process).

Table 1. Energy losses of electrons and attenuation of the gamma ray flux traveling different distances in the air above Aragats station (3200 m a.s.l.)

Distance above Aragats station (m)	Expected gamma ray flux absorption (%)	Electron losses on ionization (MeV)
		-
		-

However, the number of electrons produced by RREA gamma rays is rather small as compared to the “parent” gamma ray number, and their energies are also much smaller than gamma ray energies. As we can see in Fig. 1, the fraction of Compton scattered electrons in the TGE flux is less than 1% relative to the gamma ray flux. Obviously, for such a small fraction, it is not possible to reliably separate the electron flux from the overall TGE flux. Only gamma ray energy spectrum can be recovered from the energy release histograms in particle spectrometers operating on Aragats.

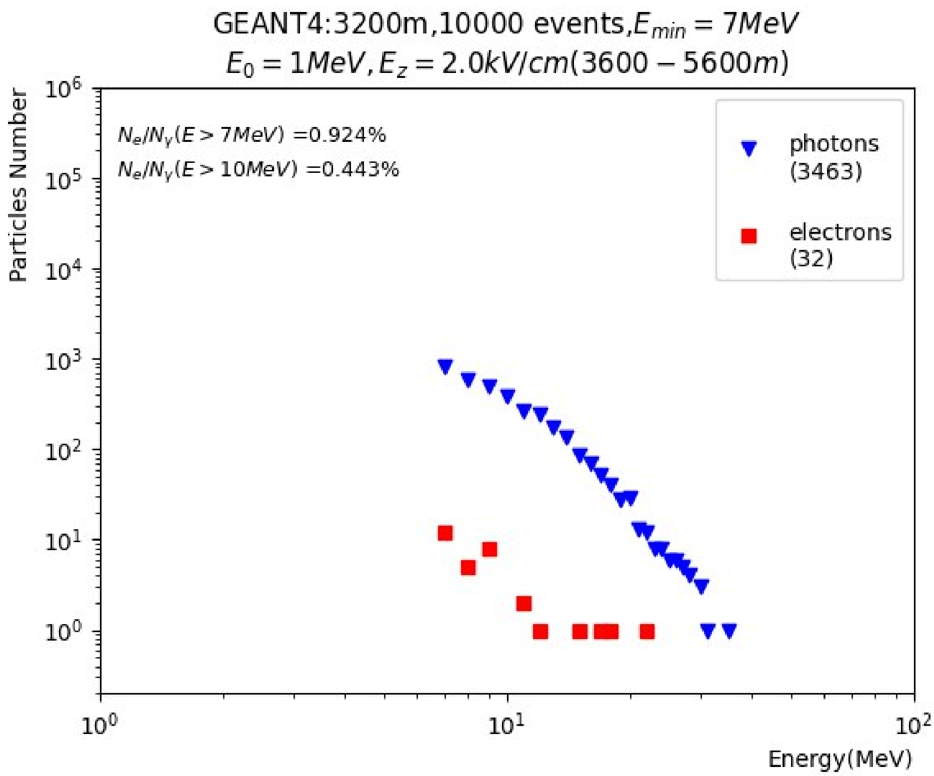

Figure 1. The comparison of the energy spectra of the gamma rays (parent particles) and Compton scattered electrons. The accelerating electric field terminates at the height of 400 m above detectors.

In Fig. 1 we show the electron and gamma ray energy spectra obtained with GEANT4 simulations of the RREA in the atmosphere. We examined the RREA process for various vertical profiles of the atmospheric electric field, and on the basis of this examination, we select plausible combinations of the field strength and extension, which support RREA emergence (Chilingarian et al., 2021a and 2021b). Using some of these values (electric field 1.9-2.1 kV/cm and field extension 2 km) we simulate the RREA propagation to the earth's surface using 1 MeV electrons as seeds. The height of the termination of the accelerating electric field was preset to 400 m, thus no RREA electron can reach the ground, see Table 1. Only electrons generated by the gamma rays nearby the earth's surface can be registered. The electron content is less than 1% for simulations of the gamma ray content for the electron energies above 7 MeV. Under these conditions, it is practically impossible to recover the electron energy spectrum with the ASNT spectrometer, it can be done only if the electron to gamma ray ratio is larger than 10%. A detailed description of the ASNT spectrometer and the method of energy spectra recovery can be found in (Chilingarian et al., 2022c). Thus, the necessary condition of recovering of the electron energy spectrum is the considerably large portion of electrons relative to gamma rays.

1. **Examples of the electron spectrum recovery**

In Fig. 2a we show the time series of count rates of two ASNT coincidences, namely "01" – signal only in the lower layer of the ASNT spectrometer (60 cm thick scintillator), and "11" – signals in both layers of the spectrometer (also in the upper layer – 5 cm thick scintillator). The detection efficiency of the 5-cm scintillator is 99% for electrons and 6-7% for gamma rays; for the 60-cm thick scintillator, the efficiency is 99% for electrons, and nearly 50% for gamma rays. Thus, particles registered by "01" coincidence are mostly gamma rays, and by "11" coincidence – electrons. As we can in Fig. 2a, during the minute 2:03-2:04 on October 6, 2021, we have a significant enhancement of the electron flux, that allows one to recover electron energy spectra. In Fig. 2b we show the recovered energy spectra of both species of TGE. The electro-to-gamma ray ratio reaches 13%, much larger than the "11"/"01" ratio due to the much larger attenuation of the electrons compared to gamma rays in the upper scintillator of the ASNT spectrometer. To reach the lower scintillator, electrons cross the 5 cm thick scintillators and metallic tilts of the detector housings.

The fraction of electrons can be quite large if the strong electric field extends almost to the ground. An example of a large fraction of electrons is demonstrated in Fig.2c which shows an exceptional TGE that occurred on 19 September 2009, just at the start of the TGE research on Aragats.

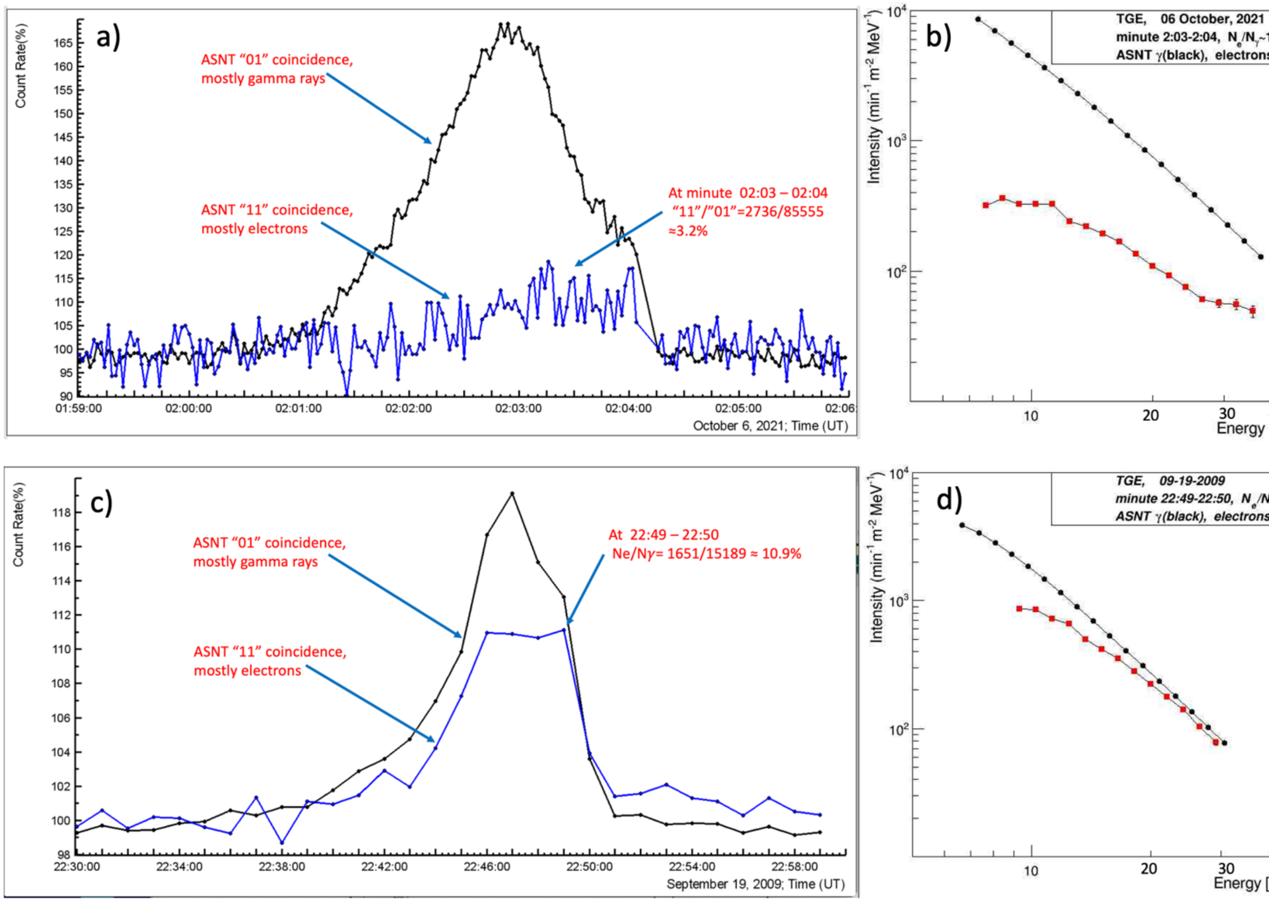

Figure 2. a) 2-s time series of count rates of coincidences registered by ASNT spectrometer, shown in percent of the count rates measured at fair weather before TGE; b) energy spectra of both TGE species recovered from energy release histograms; c) 1-min time series of count rates of coincidences registered by ASNT spectrometer; d) energy spectra of both TGE species recovered from energy release histograms.

In Fig. 2c we show the same ASNT spectrometer coincidences, as in Fig. 2a but for the 1-min time series of count rates (in 2009 the ASNT electronics sampling time was 1 minute.). As we can see in Fig. 2d, the intensities of electron and gamma ray spectra are almost equal at high energies, and the electron to gamma ray ratio reaches 66% at the minute 22:49-22:50. It can happen only if a strong accelerating electric field is very low above the ground (we estimate the height to be 25-50 m) and the electron avalanche covers a sizable area on the ground. Thus, the fraction of electrons in the TGEs selected for energy spectra recovering, are much larger than the fraction of Compton scattered electrons.

1. **Characteristics of selected TGE events with large electron content**

In Table 2 we show several parameters of TGEs for with we recover the electron energy spectrum and estimate the height of the termination of the accelerated electric field. A full set of TGE parameters is available from the Mendeley data set (Chilingarian et al., 2022b)

In the first column of the table, we put the date of the TGE that occurred during 3 last years (2019-2021). In the second column of the table, we show the power-law index of the electron differential energy spectra derived from the energy release histograms measured by the

ASNT spectrometer; in the third column - the same for the gamma ray spectra. In the fourth column - integral electron spectra from 7 MeV, in the fived - the same for gamma ray spectra. In the sixth and seventh columns, maximal energies of electrons and gamma rays; in the eighth column, we post the TGE significance - the percent of flux enhancement relative to fair weather value measured just before TGE, count rate of SEVAN detector upper scintillator (combination “100”) was used (energy threshold 7 MeV).
In the ninth column, we show the approximate estimate of the strong accelerating electric field termination height obtained by the equation: H(m) (1.2E (max)- Ee(max))/0.2, where E (max) and Ee(max)) are estimates of maximum energies of gamma rays and electrons as measured on the earth’s surface and 0.2 MeV in the denominator is an approximate value of electron energy losses in the 1 m of air (Chilingarian et al., 2021d). We assume that the maximum energy of electrons on the exit of the strong electric field can be approximated by the measured on the earth’s surface maximum energy of gamma rays multiplied by a coefficient of 1.2 (this approximate equation is valid for the electric field heights up to 200 m). Due to the fast attenuation of the electron flux, electron spectra cannot be measured reliably by the ASNT spectrometer if the accelerating electric field terminates above 200 m). In the tenth column, we post the TGE duration; in the eleventh column, we show the share of electron flux related to gamma ray flux (above 7 MeV).

Table 2. Parameters of electron and gamma ray energy and estimates of the electric field heigh. Significances of peak enhancement are larger than 5%, Ne/Ng – larger than 0.06

Date, (month.day. year)	Power law. Index el.	Power law index gamma rays	Int. Spectra el.	Int. Spectra gamma rays	Max energy el. (MeV)	Max energy gamma (MeV)	TGE significance (%)	El. Field height (m)	TGE duration (min)	Ne/N
.19										
.19										
.19										

.20			
.20			
.20			
.20			
.21			
.21			
.21			
Mean	,92	,53	,8

Averaged over 10 TGEs, the number of electrons is 2398, and number of gamma rays is 19730. The Total number of Compton scattered electrons according to Figure 1 will be 1% of a total number of gamma rays, i.e., 197. It will be 8.2% of the total number of electrons only. From Fig. 1 we can see those energies of scattered gamma electrons are much lower than the energies of parent gamma rays, and consequently, much lower than the energies of TGE electrons. Thus, the contamination of the Compton scattered electron can slightly influence only lower energies of the recovered electron energy spectrum.

1. **Conclusions**

   If the accelerating electric field is terminated high above the ground TGE electrons are attenuated, the contribution of the Compton scattered electrons is negligible (less than 1% relative to gamma ray flux) and such TGEs never allow recovery of the electron energy spectrum.

   The electron energy spectrum recovered only for TGEs with large electron content (mean 20%, see last row of Table 2 and Figure 2).

   The corresponding height of the electric field termination is less than 150 m (mean 100 m). Only from these heights electrons from RREA above Aragats can be reliably recovered by the energy releases histograms measured by the ASNT spectrometer.

   Continuous monitoring of gamma ray and electron energy spectra allows remote sensing of the atmospheric electric field horizontal profile during thunderstorms.

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