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Energetic radiation from thunderclouds: extended particle fluxes directed to Earth's surface

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Abstract
After introducing spectrometers with the energy threshold of 0.3 MeV the pattern of the thunderstorm ground enhancements (TGEs) observed on Aragats dramatically changed demonstrating multi-hour radiation. In the paper, we analyze comprehensive observations made on different time scales and energy ranges. A new model of TGE is discussed explaining much larger time of particle fluxes from clouds.

Keywords Electron acceleration in atmosphere · Thunderstorm ground enhancements · High-energy physics in atmosphere

1 Introduction

In the electric fields in thunderclouds, seed electrons from an ambient population of cosmic rays are accelerated and form electron-gamma ray avalanches, directed either downwards to the Earth's surface or upwards into open space, depending on the direction of the electric field. Intense fluxes of gamma rays observed in space are called Terrestrial Gamma Flashes [TGFs, (Fishman et al. 1994; Briggs et al. 2011; Tavani et al. 2011)], in the atmosphere, they are called gamma glows (McCarthy and Parks 1985; Eack et al. 1996; Kelley et al. 2015; Kochkin et al. 2017), on the ground, they are called Thunderstorm Ground Enhancements [TGEs, (Alexeenko et al. 2002; Chilingarian et al. 2010, 2011; Torii et al. 2011; Tsuchiya et al. 2013; Kuroda et al. 2016; Kudela et al. 2017)]. In the latter, also neutron fluxes are observed (Gurevich et al. 2012; Tsuchiya et al. 2012; Chilingarian et al. 2012; Enoto et al. 2017). The duration of these fluxes ranges from milliseconds to a few minutes and consists of billions of particles (Mailyan et al. 2016; Chilingarian et al. 2017a). Runaway Breakdown [RB, (Gurevich et al. 1992)], also referred as Relativistic Runaway Electron Avalanche [RREA, (Babich et al. 2001, 2004; Dwyer 2003)], is the only theoretical model satisfactorily explaining "cloud electron accelerators". However, due to the scarcity of measurements and poor knowledge of the electric structures in the clouds, these phenomena are not well understood till now. On the basis of continuous monitoring of particle fluxes, electric fields, and meteorological conditions on Aragats mountain (Chilingarian et al. 2016) we discover that particle fluxes from the thunderclouds are much larger than expected from the previous observations. Using the measurements of differential energy spectra of electrons and gamma rays in the energy range from 0.3 to 50 MeV by the network of NaI spectrometers (Chilingarian et al. 2013a, b) we show that particle fluxes can last for several hours. We demonstrate also that very often particle avalanches precede lightning flashes (Chilingarian et al. 2017b).

2 Instrumentation

Neutral and charged particle fluxes are measured on Aragats with various elementary particle detectors. Count rates are measured with plastic scintillators, proportional chambers, and NaI and CsI crystals. The data are transformed to the time series of particles intensities on different time scales

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from tens of nanoseconds to minutes. Energy release histograms measured each minute with NaI crystals and each 20 s with 60 cm-thick plastic scintillators. We measure also the near-surface electrostatic field with a network of four electric field mills (Boltek's EFM-100) located on Aragats. The wideband fast electric field is measured by three circular flat-plate antennas attached to fast digital oscilloscopes which are triggered by the signal from active whip antennas. The oscilloscopes are used also to record the waveforms from the particle detectors to distinguish between the genuine particle signals and the electromagnetic interferences from nearby lightning flashes.

The detector network used to measure the particle energy spectra consists of seven NaI crystal scintillators packed in a sealed 3 mm-thick aluminum housing. The NaI crystal is coated by 0.5 cm of magnesium oxide (MgO) by all sides with a transparent window directed to the photocathode of an FEU-49 PMT, see Fig. 1. The large photocathode (15 cm in diameter) completely covers the window and provides a good light collection. The spectral sensitivity range of FEU-49 is 300–850 nm, which covers the spectrum of the light emitted by NaI(Tl). The sensitive area of each NaI crystal is ~ 0.0348 m^2. A significant amount of substance above the sensitive volume of NaI crystals (0.7 mm of roof tilt, 3 mm of aluminum, and 5 mm of MgO) eliminates electrons with energy lower than ~ 3 MeV.

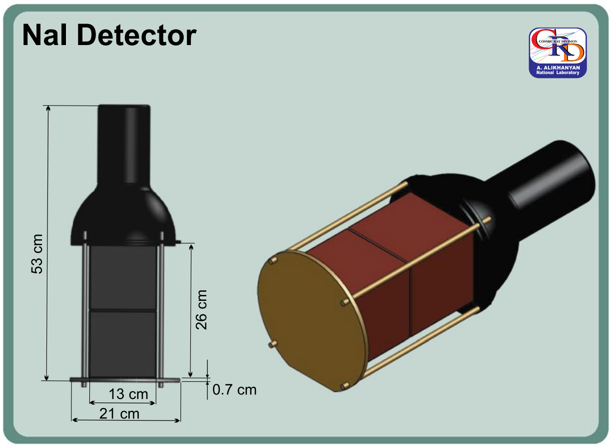


Fig. 1 NaI(Tl) crystal assembly

The NaI(Tl) spectrometers are located just below the tilted roof of the SKL experimental hall on Aragats station, at 3200 m above sea level (Fig. 2). The pulses from photomultiplier (PMT) optically connected to the crystal are fed through a preamplifier to an amplitude-to-digital converter (ADC).

The ADC dynamic range is > 200 and a scale factor **d** is used for the code-to-amplitude conversion.

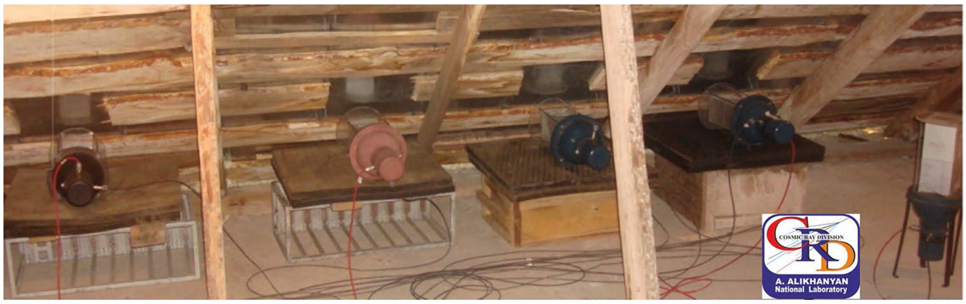
$$K = d * \ln\left(E/E_{\mathrm{o}}\right) + K_{\mathrm{o}}, \tag{1}$$

where K is the ADC code, E is energy deposited in the spectrometer, K_{o} is the code corresponding to the known energy deposit E_0. To determine parameter d, we need at least two calibration points with known ADC code values. The calibration was made with the gamma rays emitted by Caesium-137 (^{137}Cs) isotope and with the visible peak in the energy release histogram of the ambient population of secondary cosmic rays. The most probable value of energy deposit in 11.5 cm-thick NaI(Tl) crystal by the cosmic ray muons is ~ 60 MeV. Thus, the gamma ray energies used for calibration cover two decades in the energy range from 0.662 to 60 MeV. The energy resolution of spectrometers is ~ 30% at 662 keV. Parameters of the 12-channel ADC board were precisely estimated with a high-frequency signal generator in the pulse amplitude range (50–1500 mv), the maximum deviation from the linearity did not exceed 10%.

To obtain a pure TGE energy deposit histogram the cosmic rays background measured at fair weather just before TGE should be bin-by-bin subtracted from the histogram containing both background and additional counts from the particles coming from the thundercloud (see Fig. 3). For the recovery of the differential energy spectra measured by NaI network, the spectrometer response function was calculated with CERN GEANT package. To avoid uncertainty and additional errors connected with a selection of the energy spectra shape in response function estimation, three different spectral indices were tested.

The Aragats Solar Neutron Telescope (ASNT, previously intended to measure neutrons coming from violent solar flares) is formed from four separate identical

Fig. 2 NaI(Tl) spectrometers installed beneath the tilted roof of the SKL experimental hall at Aragats station



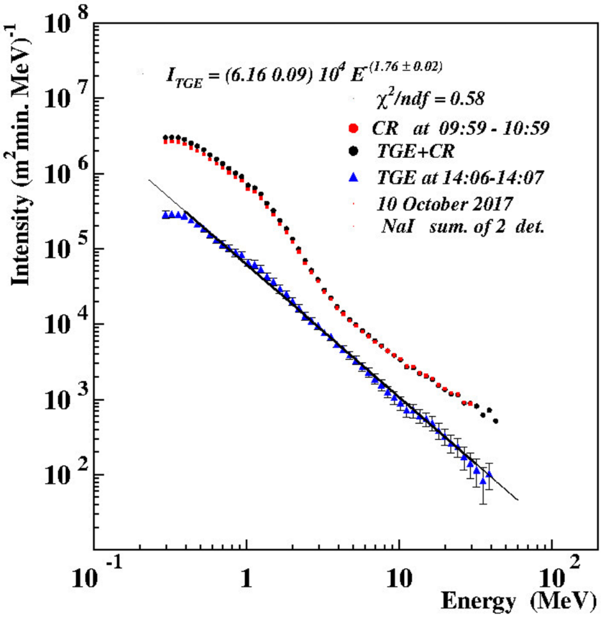


Fig. 3 Recovering the TGE signal (lower curve) by subtracting the pure background measured before TGE event at fair weather from the TGE histogram containing background and additional flux from cloud (two top curves)

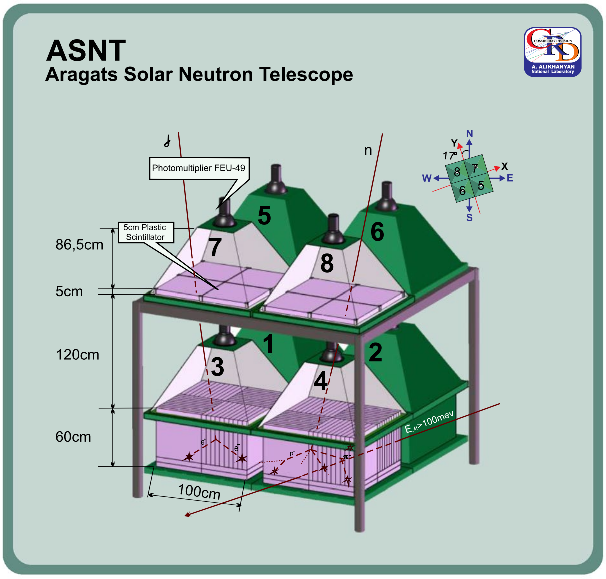


Fig. 4 Assembly of ASNT with the enumeration of eight scintillators and orientation of detector axes relative to the North direction

modules, as shown in Fig. 4. Each module consists of forty 50 × 50 × 5 cm^3 scintillator slabs stacked vertically on a 100 × 100 × 10 cm^3 plastic scintillator slab. Scintillators are finely polished to provide good optical contact of the assembly. The slab assembly is covered by the white paper from the sides and bottom and firmly kept together with belts. The total thickness of the assembly is 60 cm. Four scintillators of 100 × 100 × 5 cm^3 each are located above the 60 cm-thick scintillator assembly to indicate charged particle traversal and separate the neutral particles by "vetoing" charged particles (the probability for the neutral particle to give a signal in 5 cm-thick scintillator is much lower than in 60 cm-thick scintillator). A scintillator light capture cone and Photo Multiplier Tube (PMT) are located on the top of the scintillator housings.

The main ASNT trigger reads and stores the analog signals (PMT outputs) from all eight channels if at least one channel reports a signal above threshold. The frequency of triggers is ~ 10 kHz due to incident secondary cosmic rays. The flux of particles from thundercloud (TGE) can be five times larger.

The list of available information from ASNT is as follows:

1. 2 s time series of count rates of all eight channels of ASNT (the integration time of the scintillator counts is 2 s);
2. Count rates of particles arriving from the different incident directions: 16 possible coincidences of four upper and four bottom scintillators;
3. Count rates of the eight special coincidences, for instance, one signal from the upper scintillators and one signal from the lower ones, or no signals in upper, and more than one signal in the lower, etc.…;
4. Estimates of the variances of count rates of each ASNT channel;
5. 8 × 8 correlation matrix of ASNT channels to monitor possible cross-talk of channels;
6. Each 20 s the histograms of the energy releases in all eight channels of ASNT are stored;
7. The same as in the previous point, but only for particles that have not been registered in the upper layer (mostly neutral particles).

A 52 cm-diameter circular flat-plate antenna was used to record the wideband (50 Hz–12 MHz) electric field waveforms produced by lightning flashes. The antenna was followed by a passive integrator (decay time constant = 3 ms); the output of which was connected via a 60 cm double-shielded coaxial cable to a Picoscope 5244B digitizing oscilloscope. The oscilloscope was triggered by the signal from a commercial MFJ-1022 active whip antenna that covers a frequency range of 300 kHz–200 MHz. The record length was 1 s including 200 ms pre-trigger time and 800 ms post-trigger time. The sampling rate was 25 MS/s, corresponding to 40 ns sampling interval, and the amplitude resolution was 8 bit. The flat-plate and the whip antennas were installed at the same location, within 80 m of particle detectors and two electric field mills. The distance from the antennas to third field mill is 270 m. The near-surface electrostatic field disturbances are measured by a network of six field mills (Boltek EFM-100), four of which were placed at the Aragats station, one at the Nor Amberd station at a distance of 12.8 km from Aragats, and one at the Yerevan station, at a distance of 39.1 km from Aragats. The distances between the three field mills at Aragats were 80, 270, and 290 m. The electrostatic field changes are recorded at a sampling interval of 50 ms.

The lightning optical image is captured by a video camera at a frame rate of 30 frames/s. We also used data from the World Wide Lightning Location Network (WWLLN), which detects very low frequency (VLF, 3–30 kHz) emissions from lightning. Boltek's EFM-100 electric mill also provides an estimate of the distance to lightning.

3 Long-lasting TGES

Hundreds of TGEs were observed at the Aragats research station in Armenia during the last 10 years. The Aragats research station is located at an altitude of 3200 m on the plateau near a large lake, and as usual, the height of the cloud base above the ground is 25–100 m. In spring and autumn seasons numerous particle detectors and field meters are located in three experimental halls as well as outdoors; the facilities are operated all year round providing continuous registration of the time series of charged and neutral particle fluxes on different time scales and energy thresholds (see Chilingarian et al. 2017c, Supplementary material section for details).

In Fig. 5d we show typical shape of TGE (in 2017 we observed more than 10 TGE events with similar shape and characteristics); we present 1 min time series measured by two large NaI crystals, see Figs. 1 and 2, the electric

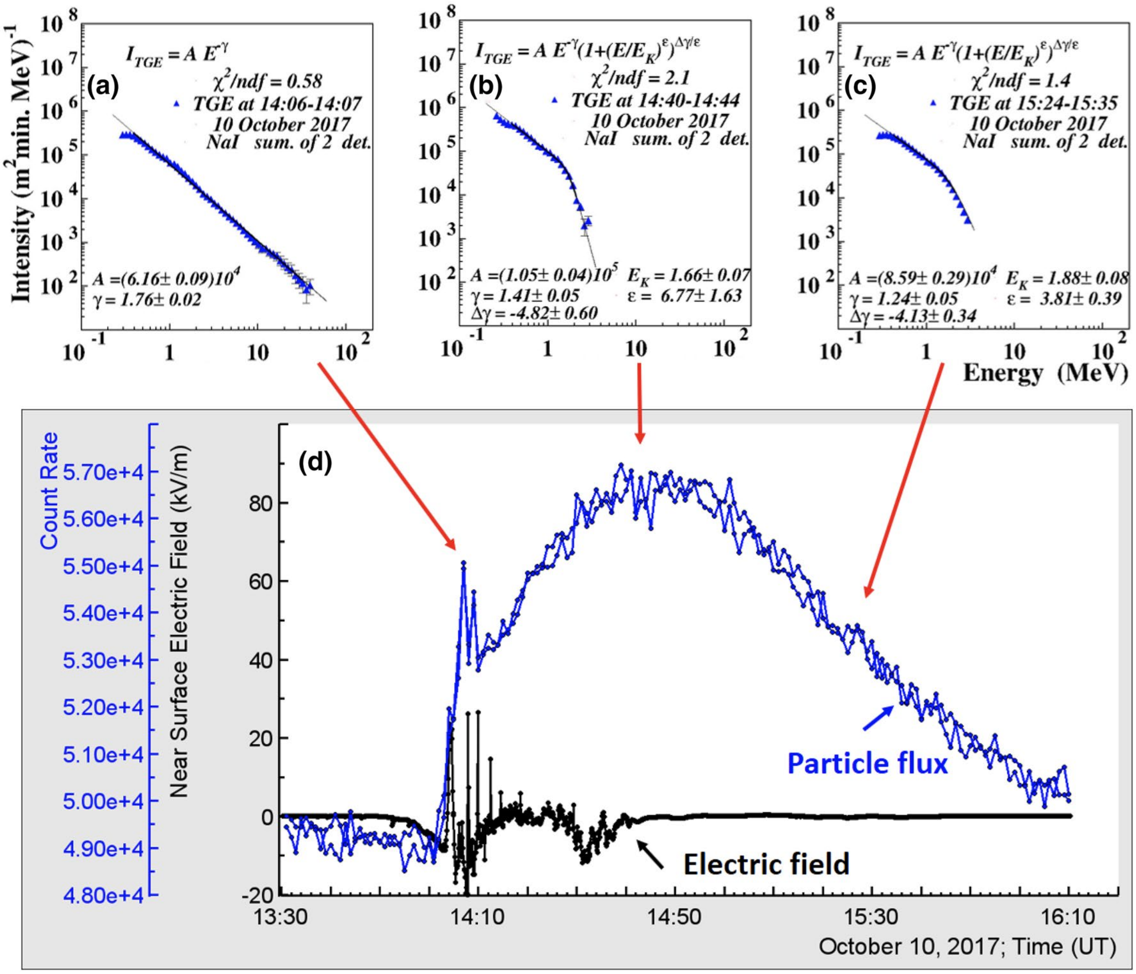


Fig. 5 Recovered energy spectra of the TGE event at different times (**a**–**c**.). One-minute time series measured by the first and second NaI detectors and disturbances of the near-surface electrostatic field (**d**)

field disturbances (slow field) are measured by electric mill EFM-100. In this paper, we use the atmospheric electricity sign convention, according to which the downward-directed electric field or field change vector is considered to be positive. Electrons are accelerated downward to the ground by the upward-directed electric field which is considered to be negative.

In Fig. 5a–c we show the recovered differential energy spectra obtained from the measured 1 min-energy release histograms (Chilingarian et al. 2017c). The arrows demonstrate the correspondent time of the particular energy spectrum. There were no precipitations during whole time of the event, therefore, the possible contamination to the TGE of the natural radioactive decays can be excluded.

From Fig. 5 we can see that in the beginning TGE spectrum contains high-energy particles [mostly gamma rays, see (Chilingarian et al. 2013a, b)] lasting few minutes. After declining of the high-energy flux, TGE continues 2 h and more with low-energy gamma rays (below 3 MeV). Although TGEs varied significantly in intensity and duration, nonetheless, based on numerous observed energy spectra (Chilingarian et al. 2010, 2016, 2017c) we can state that TGE can be considered as a two-stage process: short stage with high-energy particles when the region of a strong electric field in the cloud is just above the particle detectors. Intense RB/RREA process both multiplies particles and accelerates electrons up to 30–40 MeV. Electrons, in turn, emit high-energy gamma rays detected by the spectrometers on the Earth's surface. The much longer second stage comprised of low-energy gamma ray radiation from more distant RB/RREA cascades, or from much weaker electric fields above the particle detectors. The RB/RREA process continues at different locations in the thundercloud and, consequently, the flux of high-energy particles has spread over an area of few square kilometers beneath the cloud. TGE can start with low-energy phase, then exhibit intensifying when the particle emitting region of the cloud moves to detector site, and then again turn to low-energetic gamma ray flux when it moves away. TGE is not a short burst of relativistic particles, as was measured previously, but a major long-lasting energetic event in the terrestrial atmosphere.

4 TGE-lightning relation

For the understanding of TGE-lightning relation, we need to study both phenomena on more precise than minute time-scales. In Fig. 6 we show 1 s time series of the upper 1-cm thick and 1 m^2 area plastic scintillator (energy threshold ~ 0.8 MeV) located near MAKET experimental hall along with disturbances of the near-surface electrostatic field and distance to lightning flash (lines in upper part of figure).

The abrupt increase of the near-surface electric field followed by considerably slower recovery reveals a specific pattern of the negative lightning lowering the negative charge overhead (Chilingarian et al. 2017a). In Fig. 6 we can see that particle flux enhancements are not caused by atmospheric discharges; contrariwise, the atmospheric discharges stop particle fluxes (Chilingarian et al. 2017b). Thus, the RB/RREA process is rather short and usually is interrupted by the nearby lightning flash. To prove the decay of the avalanche process in the thunderclouds after a lightning flash, in Fig. 7 we show the 20 s energy release histograms collected by the 60 cm-thick plastic scintillators of the ASNT detector (Chilingarian et al. 2010, 2017c), see Fig. 4. ASNT detector is equipped with a veto system, eliminating the near-vertical charged flux, in Fig. 7 we demonstrate TGE gamma ray spectrum. Each time-slice of the three-dimensional histogram represents the energy release of particles in the 60 cm-thick plastic scintillator collected during 20 s. In Fig. 7 we can see that before first lightning flash that occurred at 14:07:53 the

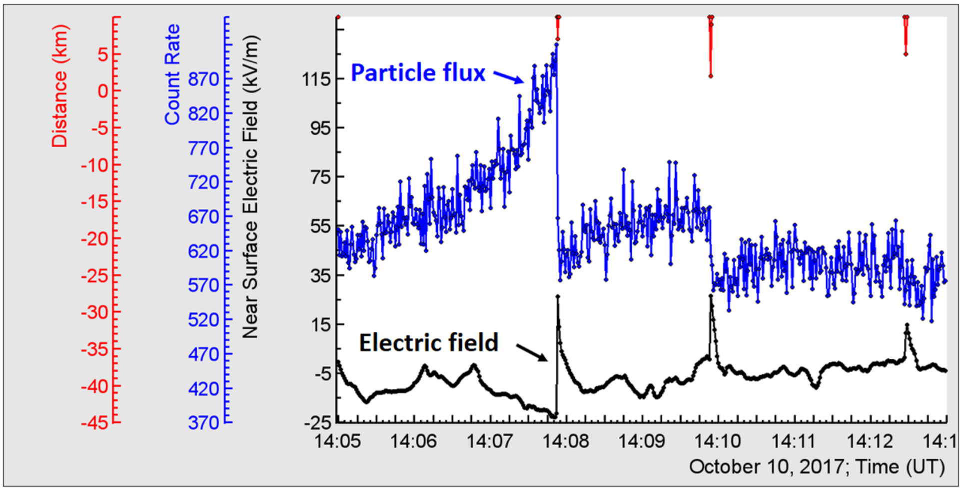


Fig. 6 1 s time series of the TGE flux abruptly terminated by the lightning flashes

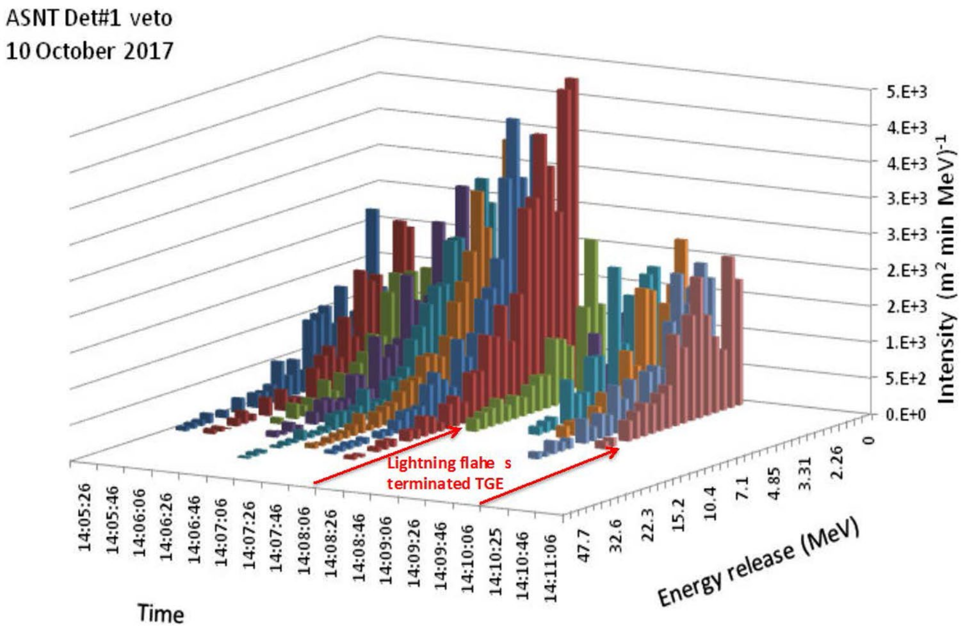


Fig. 7 The 20 s energy release histograms measured by the 60 cm thick plastic scintillator of the ASNT detector. The lightning flashes shown by arrows abruptly terminate the high-energy particle flux

energy release spectra extend up to 30 MeV. Afterward, the high-energy part of TGE completely vanishes and TGE starts again after a half-of-minute; however, next lightning flash completely kills it. Thus, lightning flash stops the electron-gamma ray avalanche in the atmosphere.

A more precise pattern of the lightning-particle flux relation is posted in Fig. 8, which shows the 50-ms time series of particle count rate and the disturbances of the near-surface electrostatic field, as well as triggers issued by three digital oscilloscopes used for detection of particle pulses and fast wideband electric field with 40 ns sampling (vertically ordered three large dots).

In the Fig. 8 we can see that the decay of particle flux (~ 60% in 200 ms) started before the trigger (start of detectable electromagnetic emission from lightning discharge that triggers digital oscilloscope) and rearrangement of the electric field in the thundercloud. Comparing Figs. 7 and 8 we can state that abrupt change in the particle flux is associated with the decrease of the high-energy particles flux, i.e., with the decline of the RB/RREA process. Thus, in the first stages of the lightning initiation, the TGE is abruptly declining. If we reverse this statement we can assume that the particle fluxes precede lightning and, furthermore, that TGEs can initiate lightning flashes (Chilingarian et al. 2017b).

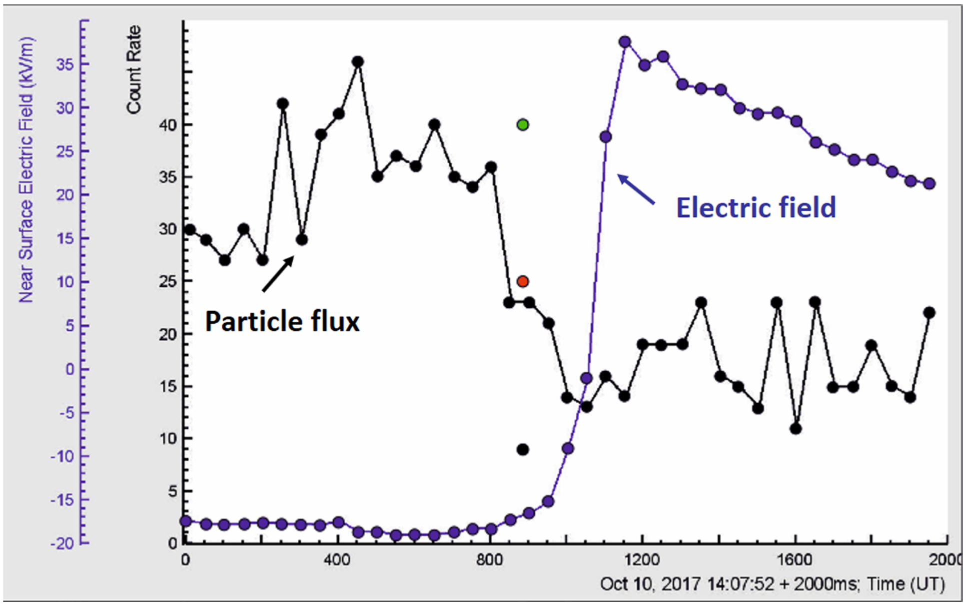


Fig. 8 The 50 ms time series of particle fluxes and electrostatic field disturbances produced by negative lightning flash (the first of the two flashes shown in Fig. 7)

RB/RREA avalanches (measured in space, on earth's surface, and in the atmosphere as TGF, TGE and gamma glow) are eternal during thunderstorm filling the atmosphere with gamma rays for many hours and initiating lightning flashes.

Our observations that TGE is lasting hours and not minutes may change common expectations in many areas, for instance for calculating possible bias in the carbon dating (Babich 2017a, b). Numerous TGEs observed on Aragats provide researchers with numerous energy spectra to validate the models and theories of atmospheric electricity and get a clearer understanding of atmospheric physics in general.

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Compliance with Ethical Standards

Conflict of interest The author declares that he has no competing financial and non-financial interests.

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