Nuclear Inst. and Methods in Physics Research, A 874 (2017) 19–27

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

# In situ measurements of the Runaway Breakdown (RB) on Aragats mountain

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ARTICLE INFO

*Keywords:*
Atmospheric high-energy physics
Electron acceleration
Electron energy estimation
Scintillators

ABSTRACT

Acceleration and multiplication of the cosmic ray electrons by strong electric fields in the thundercloud are well-established phenomena comprising the core of the atmospheric high-energy physics. The majority of experimental data on particle acceleration in the thunderclouds comes from space-born experiments detecting Terrestrial Gamma flashes (TGFs) and from networks of particle detectors located on the earth's surface observing Thunderstorm Ground Enhancements (TGEs). Models for explaining both TGF and TGE are based on the concept of a Runaway Breakdown (RB) introduced by A. Gurevich. Prove of these models requires registration of the electromagnetic avalanches developing in the thundercloud and reaching the earth's surface. Unfortunately due to high location of cloud and fast attenuation of electrons in the atmosphere the registration of such an avalanches are very rare. On Aragats mountain in Armenia, where the cloud location is very low we observe several TGE events with sizable electron contribution. We present direct measurements of such an avalanches lasting less than a microsecond; hundreds of such avalanches comprise a TGE lasting few minutes. We recovered as well the differential energy spectra of electron and gamma ray content of avalanches. The abrupt termination of the particle flux by nearby lightning indicates that RB process precedes (initiates) the lightning flash.



## 1. Introduction

The high-energy physics in the atmosphere is a new emerging scientific field dealing with electromagnetic cascades originated in the thunderstorm atmospheres. The initial name of the cascade released by a runaway electron—the Runaway breakdown (RB, given by Gurevich et al., [1]), is recently often replaced by the term RREA (Relativistic Runaway Electron Avalanches, [2,3]). However, recent measurements on Aragats of the enhanced particle fluxes abruptly terminated by the lightning flashes show that the initial hypothesis of A. Gurevich that intense electron fluxes in atmosphere can initiate lightning flashes finally finds its prove.

Gurevich et al. (1992) [1] showed that when Møller scattering (electron–electron elastic scattering) is considered the runaway electrons would undergo avalanche multiplication, resulting in a large number of relativistic runaway electrons and gamma rays for each energetic seed electron injected into the strong electrical field region. Seed electrons belong to steady population (specific to the height in the atmosphere, latitude, and longitude of detection site) of the secondary cosmic rays, a product of numerous small and large cascades initiated in the atmosphere (Extensive Air Showers—EASs) by copious protons and fully stripped nuclei accelerated in the Galaxy and bombarded terrestrial atmosphere with a rather stable intensity.

Further development of the theoretic knowledge on the runaway process continued with intensive implementations of the Monte Carlo simulation. Sophisticated codes were used to model the propagation of energetic electrons in electric fields [2,4–7]. The runaway process is naturally embedded in simulations: when you switch on the appropriate electrical field and use incident cosmic ray electron flux as seeds; the electrons gain energy from the field, knock-off atomic electrons and cascade process develops in the atmosphere. Very popular, relativistic feedback discharge model (RFDM, [2]) was used for explaining Terrestrial Gamma flashes (TGFs, [8,9]). When the large-scale electric field in the cloud become relatively high the backward propagating positrons and backscattered X-rays generate new avalanches. Therefore, according to

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http://dx.doi.org/10.1016/j.nima.2017.08.022
Received 29 June 2017; Accepted 13 August 2017
Available online 24 August 2017
0168-9002/

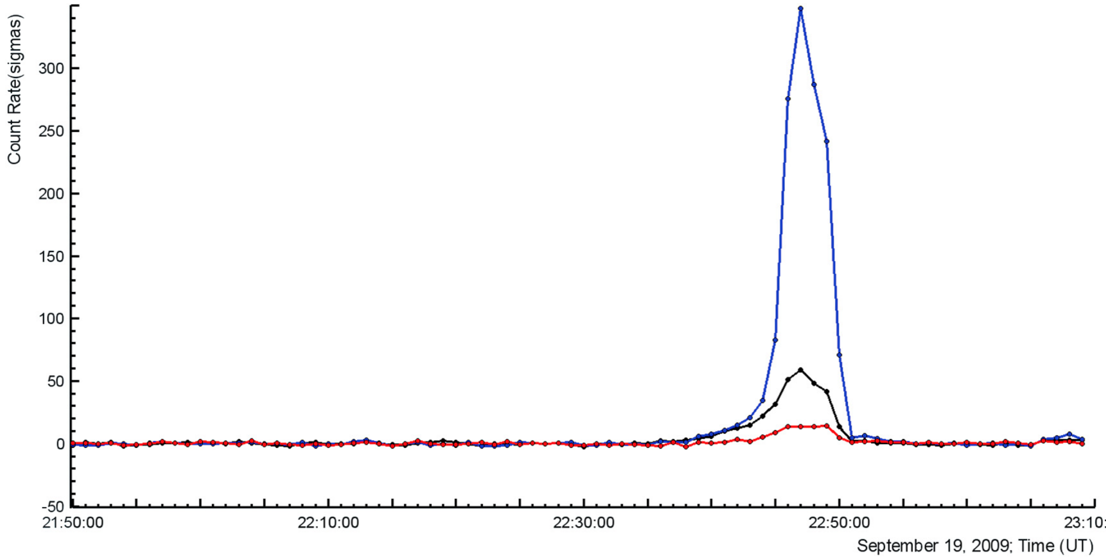


**Fig. 1.** "Significance" of TGE in the number of standard deviations from the mean value of 1-minute time series of count rate. Top curve corresponds to upper scintillators of the ASNT detector, middle—to lower and the bottom—to vertical particle transition through both scintillators.

this model, the avalanche becoming self-sufficient and can prolong until the conditions for the feedback are still effective.

The most difficult and most important part of the model validation is the comparison of competitive hypotheses with the measurements. The high-energy atmospheric physics (HEAP) includes 2 main sources of the experiential data: Terrestrial Gamma Flashes (TGFs)—brief burst of gamma radiation (sometimes also electrons and positrons) registered by the orbiting gamma ray observatories in the space and Thunderstorm ground enhancements (TGEs)—the prolonged particle fluxes registered on the ground level. The central engine initiated TGF and TGE is believed to be RB/RREA mechanism accelerated seed electrons in the terrestrial atmosphere up to 40–50 MeV. The *in situ* observation of numerous TGEs during strong thunderstorms on Aragats resulting in the first simultaneously measured energy spectra of TGE electrons and gamma rays [10]. Further measurements of the gamma ray energy spectra by the network of NaI spectrometers allow to reliably extending energy range of the "thunderstorm" gamma rays up to 100 MeV [11] due to another "thunderstorm" gamma ray production mechanism—MOdification of the electron energy Spectrum (MOS, [12]). The measurements performed on Aragats allow formulating a comprehensive model of TGE [13].

TGFs and TGEs share many common features, as they are results of RB. The drastic time difference (minutes for TGE and hundred of microseconds for TGF) is not essential because prolonged TGEs are nothing more than a superposition of the short microsecond scale avalanches, which Aragats group has named Extensive cloud shower (ECS), and Alex Gurevich et al., Micro runaway breakdown (MRB).

There exist numerous papers on simulations of particle cascades in the atmosphere, but very few of them contain comparisons with experimentally measured parameters. The goal of our paper is to present experimental data in the form that allows validation of the models. We analyze in details the largest TGE event from 19 September 2009 and 4 October 2014 and compare the time distribution of the ECSs with expected results from RDFM and TGE models.

## 2. *In situ* measurements of the RB process on Aragats

The first observation of the avalanches initiated by the runaway electrons was made at Aragats in 2009 [10]. MAKET and ASNT detectors (see supplement information for detector description) were used for the *in situ* detection of RB process (electron–photon avalanches originated in the thundercloud above detector site). In Fig. 1, we present the abrupt surge in the 1-minute particle count rate observed in the 1-minute time series of ASNT detector on 19 September. The flux started slow surge, then rockets for 4 min to the maximal value and then fast decays. This TGE is the largest ever-observed on Aragats. On 22:47 the upper scintillators of the ASNT detector registered 108% enhancement corresponding to 270 standard deviations from the mean value ($270\sigma$); the bottom scintillators registered 16% enhancement ($60.7\sigma$); the near-vertical flux (coincidences 3–7, 5–1, 6–2, 8–4) enhanced by 11.2% (16.8 $\sigma$).

In Fig. 2 we show particle flux enhancement registered by the 4 identical 5 cm thick plastic scintillators located above four 60 cm scintillators. Small differences in the count rates are explained by the individual variation of the photomultipliers (PMT). Registered TGE particles flux was rather large $\sim 30,000$ per min per m$^2$.

Thus, we observe particle flux continuing several minutes. This flux cannot be associated with an active solar event (there was no such an event registered by the gamma ray and X-ray sensors on board of Space Weather monitoring satellites) and with Extensive Air Showers (only one additional count will be registered on traversal of thousands of EAS particles in a few tens of nanosecond).

Consequently, we decide that it was a particle flux of the atmospheric origin. First of all, we check the direction of incoming particles. As one can see in Fig. 3 particles come from near-vertical direction (solid black curve with pronounced 4-minute duration peak) coinciding with the direction of the vertical electric field in the thundercloud. Other directions (selected by coincidences 5–4, 8–3, etc.) do not demonstrate any peak relative to the cosmic ray background. The background is due to EASs from galactic protons and nuclei that are not connected with thunderstorm. Another evidence of "thunderstorm" origin of particle flux comes from MAKET array's (see supplement information for detector description) 16 and 8-fold coincidences within trigger window of 1 μs (Fig. 4a and b). The electronics of the MAKET surface array counts number of events per minute, in which particles hit 8 scintillators within a window of 1 μs. Then, by off-line analysis we select events, in which all 16 scintillators were "fired". The abrupt enhancement of the coincidences occurred the same minutes when the flux of particles surges (128 and 67 counts for 8- and 16-fold coincidences, see Fig. 4b and a).

At fair weather (background counts), the surface array registered ~26.8 +/- 4.9 counts per minute (8-fold coincidences) and ~8.4 +/- 2.8 counts per minute (16 fold coincidences). Thus at 22:47 MAKET array observed ~730% enhancement of the 16-fold coincidences, corresponding to ~$22\sigma$ and 380% enhancement of the 8-fold coincidences,

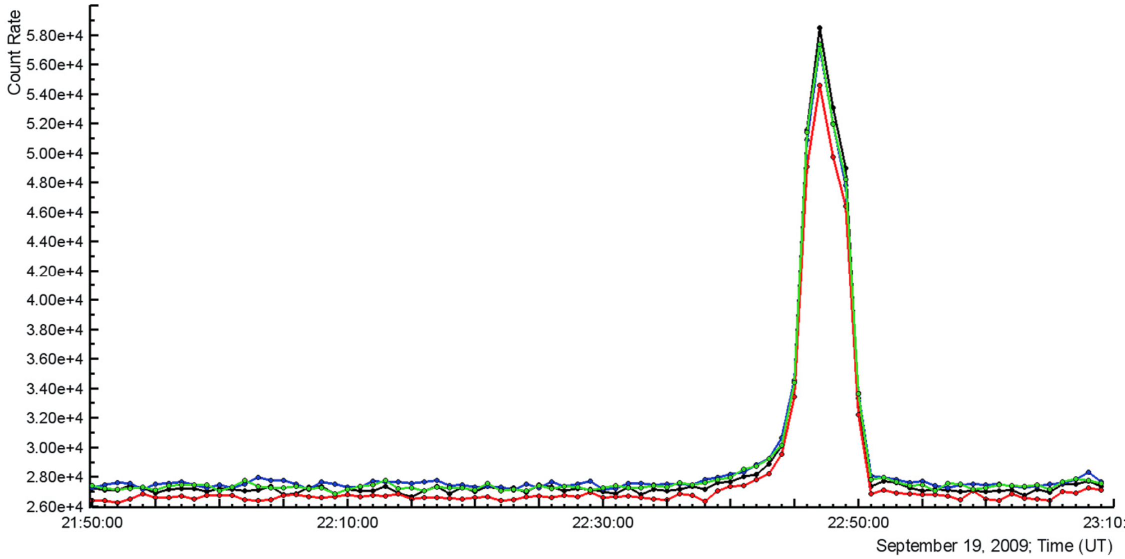


**Fig. 2.** Particle flux enhancement as measured on 19 September 2009 by four 5 cm thick 1 $m^2$ area plastic scintillators on top of ASNT detector; energy threshold ~ 7 MeV.

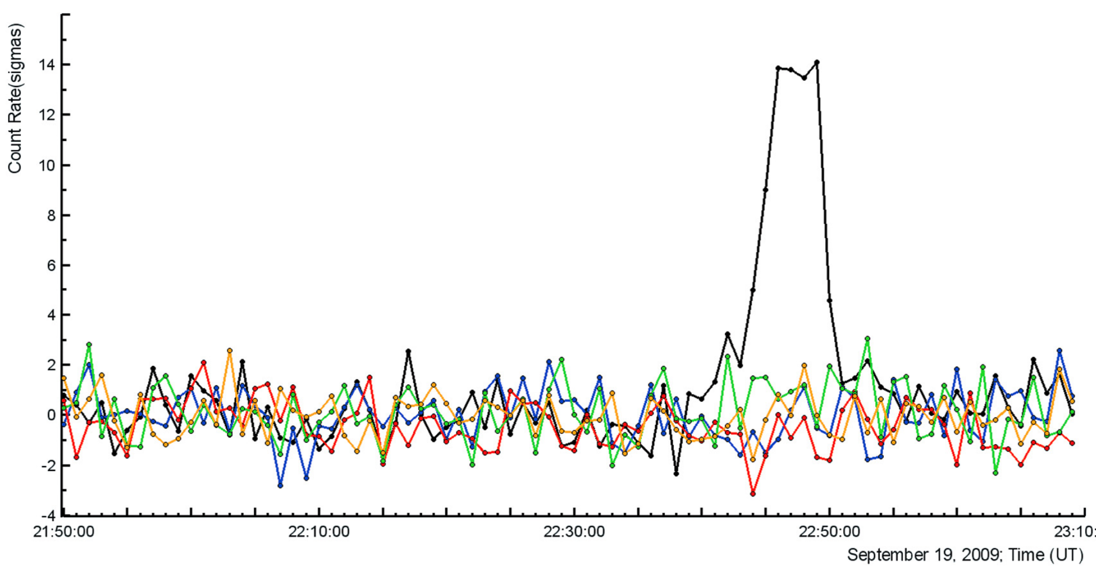


**Fig. 3.** The count rate of particles coming from different directions. The peak lasting 4 min is formed by particles coming from a near-vertical direction only (0–20°, black curve, coincidences of scintillators stacked vertically); the particles coming from the inclined directions (coincidences of scintillators that are shifted from each other, see Fig. 1 of supplement) do not show any enhancement. We present the count rates in numbers of deviations from the mean value to present data in the comparable scale. The count rates from inclined directions are less comparing with near-vertical one.

corresponding to ~20$\sigma$. Numerous "Extensive cloud showers" (ECSs, or Micro Runway Breakdowns—MRB, [14]) enhance the stable count rate of EASs generated by galactic cosmic rays. Both processes EAS and ECS independently contribute to the MAKET array count rate. The minutes long enhanced particle flux comprises from multiple ECSs initiated by a runaway electrons randomly injected into the strong electrical field region. In Fig. 5a and b we demonstrate the distribution of the registered by MAKET array showers during fair weather and during the minute when maximal flux was detected correspondingly.

The significant excess in shower number observed this minute (~100, Fig. 7b) comparing with showers observed during fair weather (Fig. 7a) is due to randomly distributed within this minute ECSs, several times occurred in triplets and quadruplets per second, but never more. If the RB process will be self-consistent i.e. the RREA will not stop and continuously generate showers via feed back positrons and scattered gamma rays (RDFM model, [2]) we should observe much more counts of ECSs. The maximal dead time of the MAKET array is 100 μs; thus after each 100 μs another shower can be registered by the surface particle array. Therefore, we can expect up to 10,000 showers per second (if the RDFM process prolongs 1 s), however, we register not more than 4.

## 3. Energy release spectra

ASNT data acquisition system registers energy release histograms both for events with and without veto i.e., if we have a signal in 5 cm thick scintillator the measured energy release is "vetoed" and do not participate in the histogram. In this way, we obtained the energy spectra of the neutral particles i.e. TGE gamma rays, originated from bremsstrahlung of accelerated in the RB process electrons (Fig. 6). In addition, extracting histogram obtained with veto from the histogram obtained without veto we readily come to the histogram of electron energy releases (Fig. 6).

The intensity of electron flux is ~ 20 times less comparing with gamma ray intensity. Because of very fast attenuation of electrons in

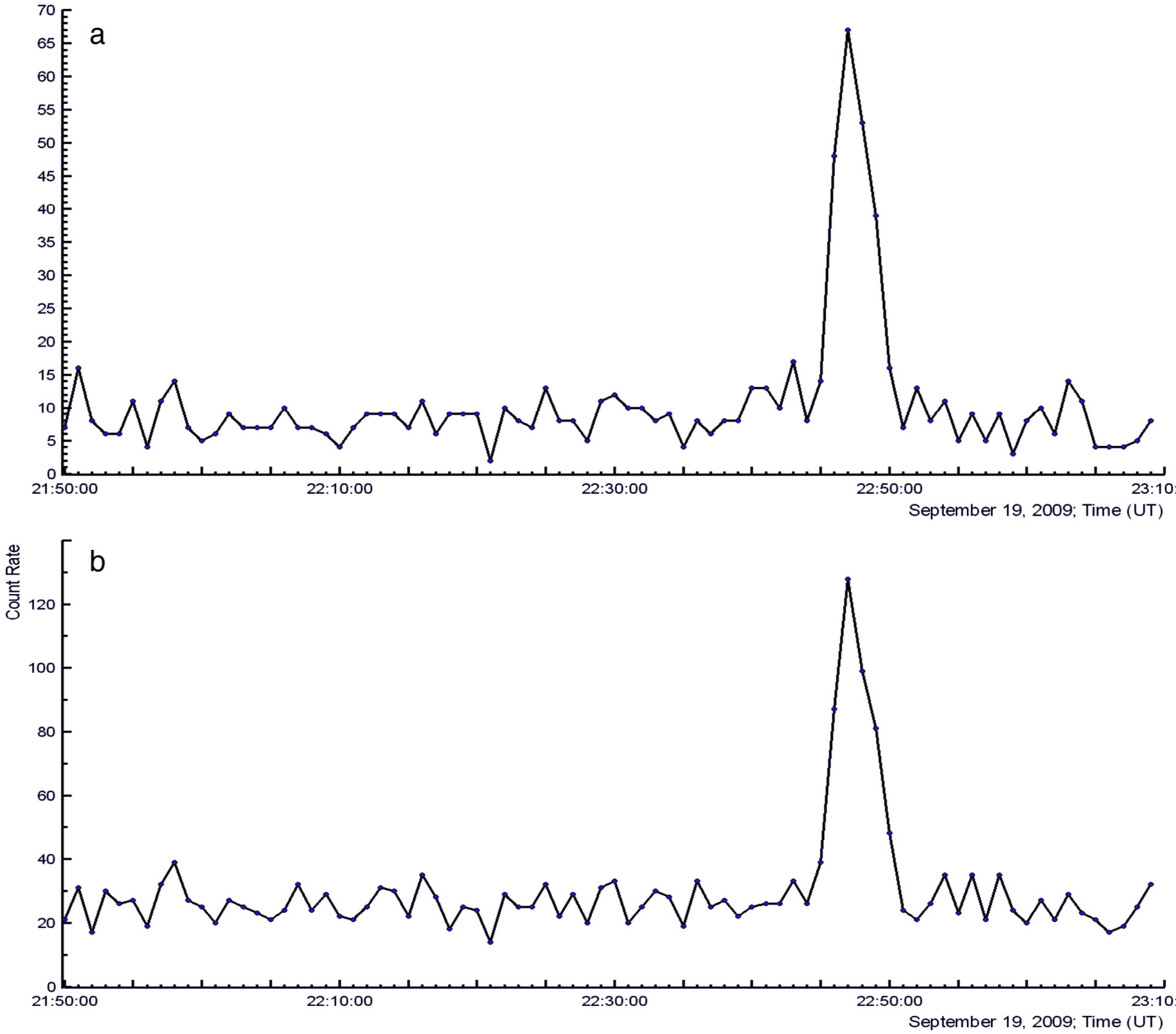


**Fig. 4.** 8 and 16-fold coincidences in the channels of MAKET surface array.

the atmosphere, TGE gamma ray flux significantly exceeds the electron flux; only for very low thunderclouds it is possible to detect electron flux (see Fig. 2, from [15]). The measured maximal energy release of TGE electrons in the 60 cm thick scintillator was ~25 MeV, for gamma rays maximal energy release ~35 MeV. Not the whole energy of particles is released in the scintillator; highest energy particles can escape from the scintillator sides. Thus, energy release is less or (in the best case) equal to the energy of particle. TGE particles in order to be registered in the 60 cm thick scintillator have to traverse significant amount of matter above the detector, see Fig. 8. The electron energy losses in the matter above the scintillator (~10 g/cm$^2$) are ~20 MeV. Thus, we come to maximal electron energy above the roof ~45 MeV in a good agreement with the model of the TGE initiation [12,13].

The gamma rays produce neutrons in the photonuclear interactions with atoms of the air. As well, the gamma rays and atmospheric hadrons produce secondary neutrons in nuclear reactions in the lead [16–18]. Aragats Neutron Monitor (ArNM, see supplement information for detector description) registered significant enhancement (>6$\sigma$ ) at 22:47 on 19 September 2009; the same time as the gamma ray and electron enhancement. The count rates corresponding to dead times of 0.4, 250, and 1250 μs are approximately identical. In contrast, EAS can enhance count rates observed with the minimal dead time of 0.4 μs only. Neutrons born in the photonuclear reactions of the TGE gamma rays with air atoms (or—in the lead absorber of ArNM) are randomly distributed within 4 min of the high-energy gamma ray flux alike the TGE particles, shown in Fig. 5b. In both cases, the origins of neutrons are the photonuclear reactions of TGE gamma rays (see Fig. 9).

## 4. The super TGE event occurred on October 4

After observing the first large TGE in 2009 on Aragats were established new facilities for particle detection, for monitoring of near surface electric field, for location of lightning flashes and for measuring of meteorological parameters [19]. The multi-parameter, multi-detector approach for TGE research allows establishing causal relations between meteorological parameters, particle fluxes and atmospheric discharges and formulation of the model of lightning initiation [20]. Particularly, we estimate the height of electric field in the thundercloud above earth's surface by measuring outside temperature and dew point. In Fig. 10 we show large TGE occurred on 4 October 2014, first described in [21]. The particle count rate of 3 cm thick outdoors plastic scintillator of the STAND1 detector (see supplement information for detector description) reaches a maximum of 1808 counts per second at 14:12:14 (mean value with fine weather is 525 counts per second, MSD ~23). The

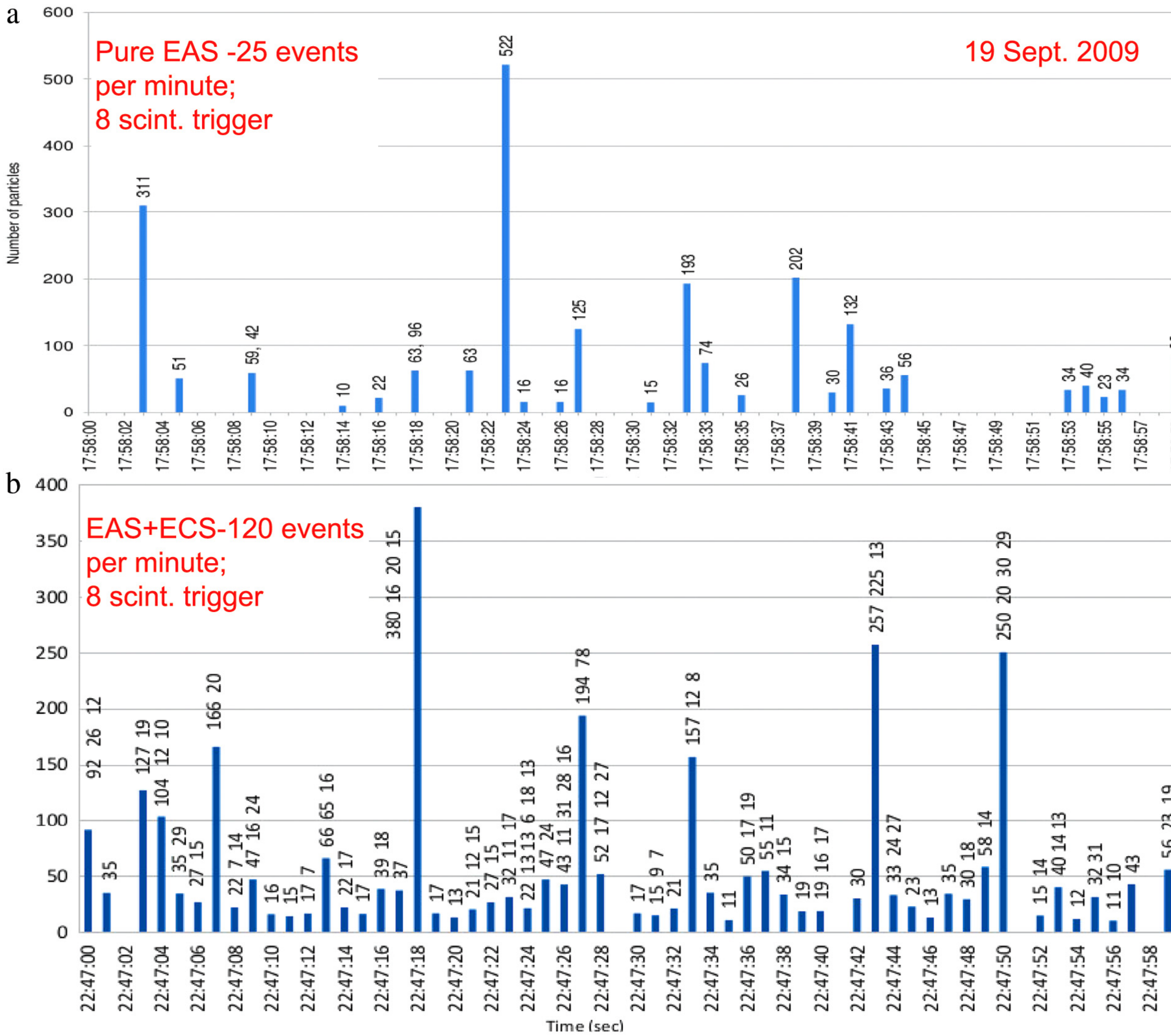


**Fig. 5.** Particle showers (EASs) detected during 60 s of the fair weather (a) and during a thunderstorm at maximal particle flux (EASs + ECSs) (b). Vertical bars show the number of particles in showers. If there were more than one shower in a second the height of a bar is equal to the size (number of particles) of the largest shower, next number after an interval is the number of particles in the next ECS, and so on. Note that maximal number of ECSs in a second is 4.

TGE particle flux enhancement was enormous; reaching 340% at the maximum flux second which is equivalent to the *p*-value of 53$\sigma$. The height of the cloud is calculated by the measured "spread" parameter—the difference between the surface temperature and the dew point. The calculation of the height of cloud base is based on the assumption that the air temperature drops 9.84 degrees C per 1000 m of altitude and the dew point drops 1.82 degrees C per 1000 m altitude. In WEB there are several calculators designed to approximate the altitude of a cloud (see, for instance http://www.csgnetwork.com/cloudaltcalc.html). The simplified estimate consists in simple multiplication of spread measured in C degrees by 122 m. With this approach we readily obtain ~25 m for the cloud base (see Fig. 10). The approximate energy losses of high energy electron in the 50 m of air on altitude 3250 m are ~5 MeV.

The maximal energy release of the electrons in the 60 cm thick scintillator was 20 MeV (Fig. 11), in the construction above detector electron losses estimated to be ~20 MeV. Thus we come to the maximal energy of electrons leaving the cloud 25 m above detector to be 45 MeV in good agreement with estimates obtained in [12] and with the larger TGE occurred on 19 September 2009 (the meteorological parameter measurement were not available at that time). The maximal energy of gamma rays equal to 35 MeV also agreed with "parent" electrons energy. Thus, this event is another evidence of the runaway avalanche process in the thunderclouds.

## 5. Discussion and conclusions

By measuring the electrons from electromagnetic avalanches unleashed by the runaway electrons in the thunderstorm atmosphere we prove the existence of the Runaway Breakdown process. The energy release histograms of TGE electrons reaching and registering in the 60 cm thick scintillators of the ASNT detector prolonged up to 25 MeV. The energy losses in the matter below the roof of the building are ~20 MeV. Taking into account the amount of matter above the 60 cm thick scintillator we estimate the maximal energy of the electrons above the roof to be 40–50 MeV. Thus, the energy spectra of the super-events occurred on 19 September 2009 and 4 October 2014 are in good agreement with the model of TGE initiation [12,13].

Measured TGE temporal distribution (Fig. 7b) proves that the large fluxes of electrons and gamma rays detected during thunderstorms comprise from the numerous very short RB cascades registered by the particle detectors located on the mountain altitudes. During TGE, a large number of very short bursts (individual runaway avalanches, Extensive cloud showers, or Micro runaway breakdowns, [14]) were developed in the thundercloud. An only very low location of the thunderclouds on Aragats allows measuring electrons. Estimates of the height of cloud made with meteorological information as well as estimates performed

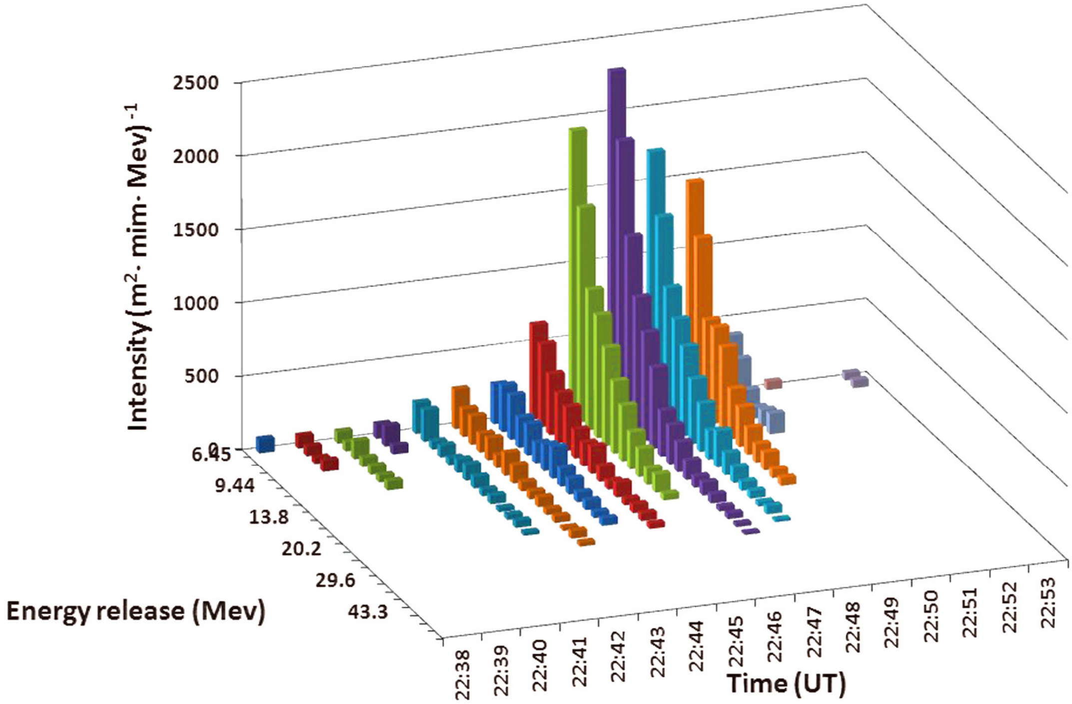


**Fig. 6.** Differential energy release histogram of the TGE gamma rays obtained in 60 cm. Thick scintillators of the ASNT array.

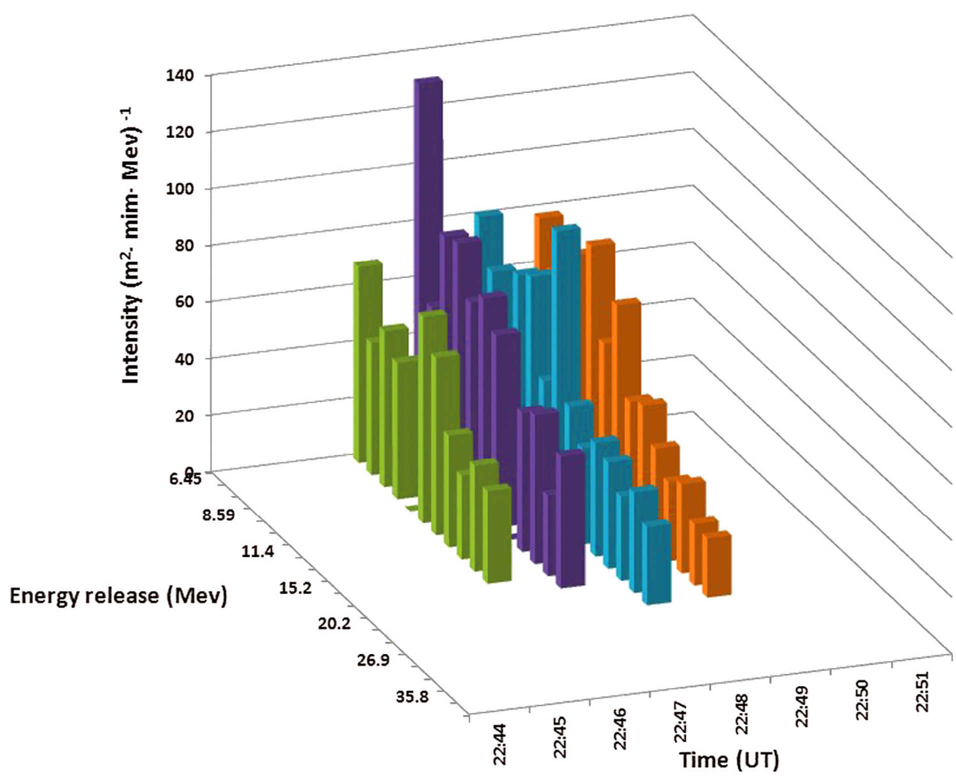


**Fig. 7.** Differential energy release histogram of the TGE electrons obtained in 60 cm. Thick scintillators of the ASNT detector.

with measured maximal energy of the TGE electrons well coincide with TGE model predictions.

The validity of the RDFM model is very difficult to prove with TGF data only; TGF measurements are performed with orbiting gamma ray observatories at the distances hundreds of km from thunderclouds, from which the particle is assumed to reach fast moving satellite. With such an experiment arrangement self-sustained acceleration of electrons is very difficult to prove. The detected TGFs are very short, maybe parented by very few seed electrons injected into the strong electrical field region. The TGEs, in contrast, can prolong minutes, 6 orders of magnitude longer than TGFs. The RB continued down to several tens of meters above firmly fixed particle detectors. Thus, various RB models

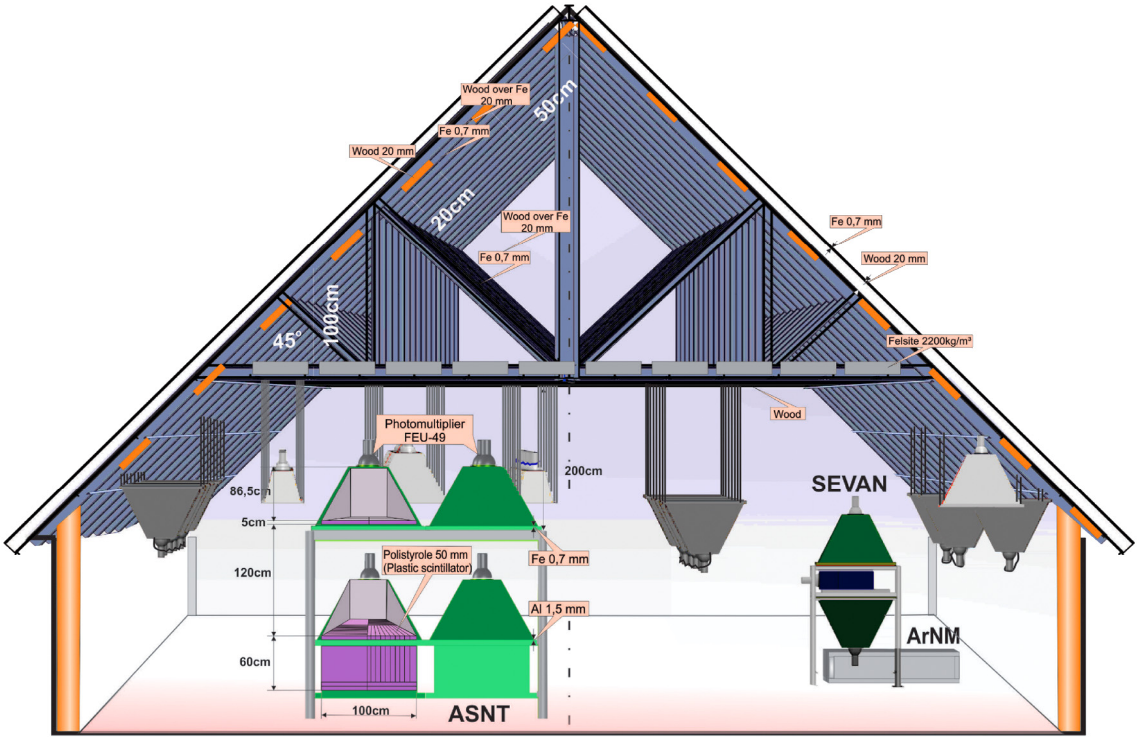


**Fig. 8.** Setup of ASNT detector in the MAKET experimental hall.

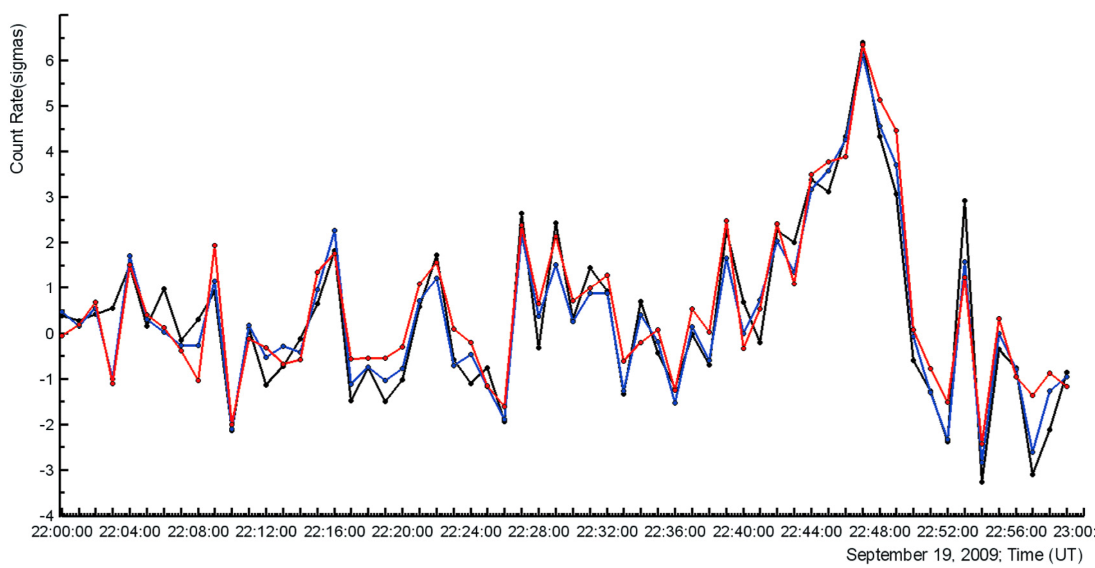


**Fig. 9.** Time series of ArNM 1-minute count rate displayed in the number of standard deviations. Time series corresponding to 3 dead times are approximately identical.

can be validated by *in situ* measurements on Aragats, the natural electron accelerator provided many tens of TGEs each year [19,22].

If the RB process due to feedback prolonged continuously we can expect much more detections per second (up to $10^4$, as a maximal dead time of MAKET array of ~100 μs); however the experimentally measured number of ECSs per second is 4, see Fig. 5b). Thus, the temporal distribution of ECSs rejects the hypothesis of continuous acceleration of electrons in the cloud, i.e. the RFDM hypothesis, at least on the timescale of a millisecond. Sure TGFs and TGEs are not fully symmetrical processes the first one is propagated in the thin atmosphere becoming thinner as avalanches propagate upward; TGEs are propagating in the dense atmosphere becoming denser as TGE approach Earth's surface. However, the runaway process is in the heart of both and experimental evidence acquired from TGE observations can be used to validate TGF models.

## Acknowledgments

The authors thank the staff of the Aragats Space Environmental Center for the uninterruptible operation of Aragats research station facilities. The data for this paper are available via the multivariate visualization software ADEI on the WEB page of the Cosmic Ray Division (CRD) of the Yerevan Physics Institute, http://adei.crd.yerphi.am/adei. A.C. appreciates the support by Russian Science Foundation grant (project No. 17-12-01439).

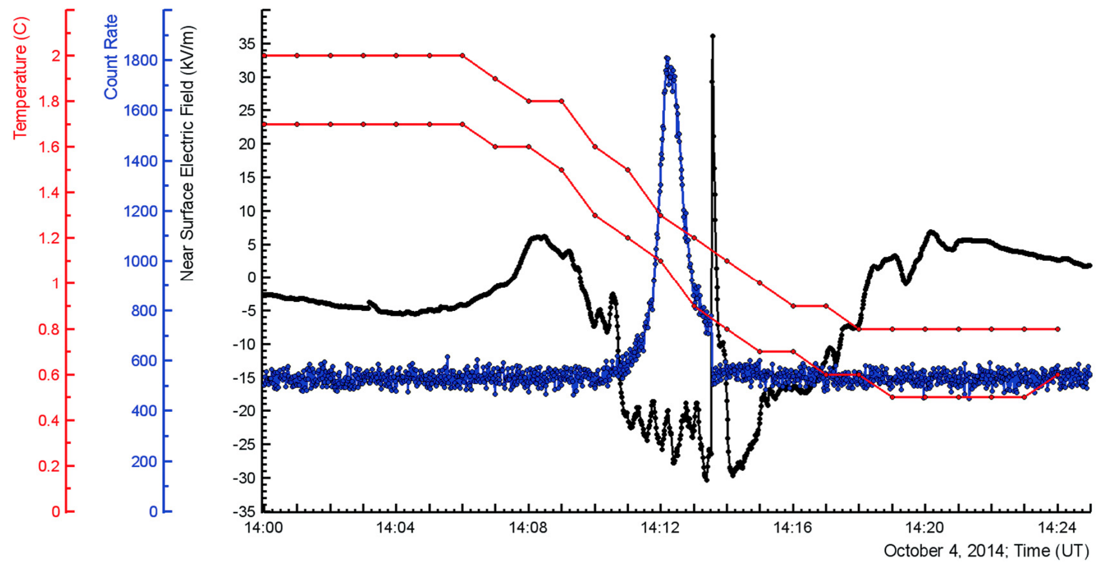


**Fig. 10.** 1 sec time series of count rate of 3 cm thick plastic scintillator (blue), near surface electric field (black); temperature (~1.3 °C) and dew point (~1.1 °C) used for the spread calculation (red). Strong lightning flash abruptly terminates TGE on 14:13:38. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

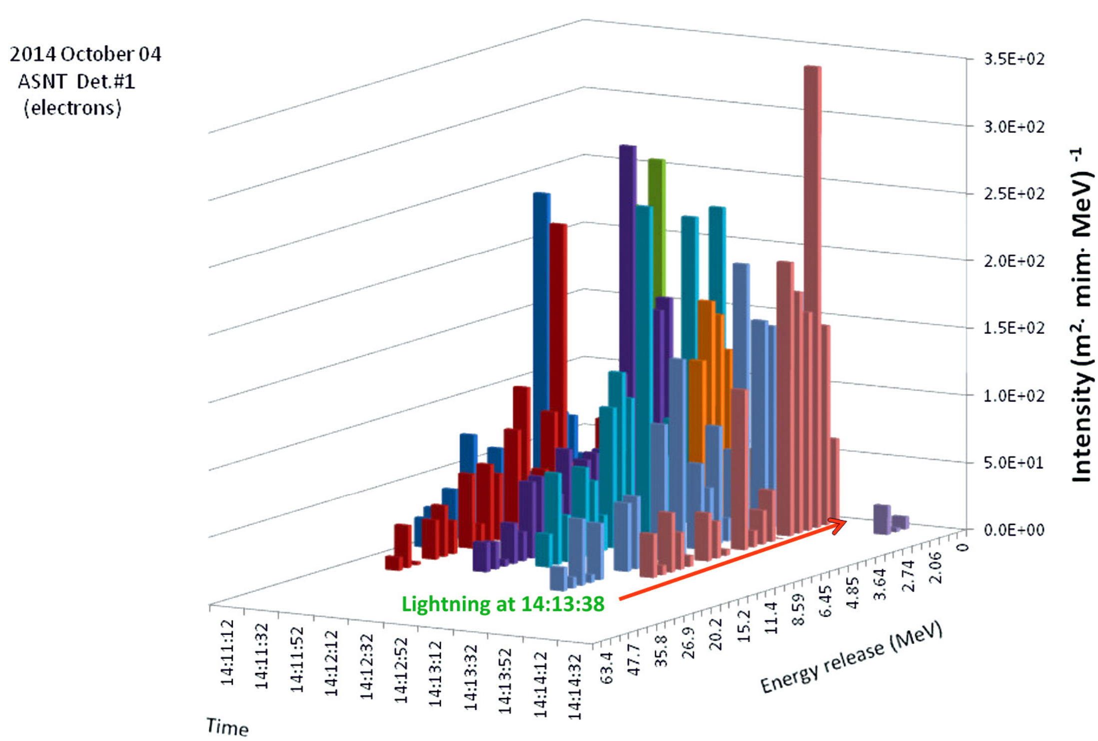


**Fig. 11.** Differential Energy spectra of RB electrons; maximal energy equals 20 MeV. After lightning flash flux of electrons abruptly terminates.

## Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.nima.2017.08.022.

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