In Situ Measurements of the Runaway Breakdown (Relativistic Runaway Electron Avalanche) on Aragats: Experimental Data and Models A.

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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. However, the origin and location of charged centers in the thundercloud (one of the most important aspects of the atmospheric physics) and conditions for unleashing the particle cascades in the atmosphere are not clear until now. 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" electrons introduced by A. Gurevich. Prove of these models includes registration of the avalanches from the cosmic ray "seed" electrons entering the region of the strong electric field in the thundercloud. We present direct measurements of such an avalanches lasting less than a microsecond; hundreds of such avalanches comprise a TGE lasting few minutes. Our measurements prove that for explaining the TGE it is not necessary to invoke the relativistic feedback discharge model (RFDM) used for the TGF modeling.

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 all, 1992), is recently often replaced by the term RREA (Relativistic Runaway Electron Avalanches, Dwyer, Smith, and Cummer, 2012; Dwyer and Uman, 2013). However, the origin and location of charge centers in the thundercloud (one of the most important aspects of the atmospheric physics) are not clear until now. In fair weather conditions, the atmosphere is positively charged and the Earth has an opposite-polarity negative charge. A thunderstorm drastically changed the pattern of the atmosphere electrification. The top layer of the thundercloud has a positive charge with a negative screening layer just above it; the middle layer has a negative charge and a small local region of positive charge usually emerges in the bottom of the cloud (a lower positive charge region – LPCR (Stolzenburg et al., 1998, Chilingarian and Mkrtchyan, 2012). If we use the so-called "physics" sign convention (see discussion of the used sign conventions in Krehbeil et al., 2014), then the near- surface electrostatic field is negative during fair weather (positive ions slowly migrate from the atmosphere to the Earth) and - positive during thunderstorms (electrons are transported by the lightning from the cloud to the Earth). According to the tripole model (quadruple, if we add a negative screening layer above the main positive layer), there are several dipoles of opposite orientation in the cloud, which accelerate electrons downward, in the direction of the Earth and - towards the open space.

Gurevich et al. (1992) 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 by copious protons and fully stripped nuclei accelerated in the Galaxy and bombarded terrestrial atmosphere with a rather stable intensity (Extensive Air Showers – EASs).

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 (Lehtinen et al., 1999; Babich et al., 2001; Dwyer, 2003, 2007, 2012). 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, Dwyer, 2003, 2012) was used for explaining Terrestrial Gamma flashes (TGFs, Fishman, 1994, Briggs et al., 2011). When the large-scale electric field in the cloud become relatively high (approaches the relativistic feedback threshold) the backward propagating positrons and backscattered X-rays generate new avalanches. Therefore, according to 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 differential energy spectra of TGE electrons and gamma rays (Chilingarian et al., 2010). 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 (Chilingarian et al., 2013) due to another "thunderstorm" gamma ray production mechanism - MOdification of the electron energy Spectrum (MOS, Chilingarian, Mailyan and Vanyan, 2012). The measurements performed on Aragats allow formulating a comprehensive model of TGE (Chilingarian, 2014).

TGFs and TGEs share many common features, as they are results of RREA. 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 nanosecond 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 compare the time distribution of the ECSs with expected results from RDFM and TGE models.

2. INSTRUMENTATION

The Aragats Solar Neutron Telescope (ASNT, previously intended to measure neutrons coming from violent solar flares) is formed from 4 separate identical modules, as shown in Figure 1. Each module consists of forty 50 x 50 x 5 cm^3 scintillator slabs stacked vertically on a 100 x 100 x 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 special belts. The total thickness of the assembly is 60 cm. Four scintillators of 100 x 100 x 5 cm^3 each are located above the 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 8 channels if at least one channel reports a signal above threshold. The frequency of triggers is ~ 4 KHz due to incident Secondary cosmic rays (SCR) – products of the interaction of galactic cosmic rays with atmosphere; on 3200 m height on Aragats, the intensity of SCR is ~ 500 /m^2/sec. The flux of particles from thundercloud (TGE) can be 5 times larger than SCR (background) intensity.

The list of available information from ASNT is as follows:

1. 2 second time series of count rates of all 8 channels of ASNT (the integration time of the scintillator counts is 2 seconds);
2. Count rates of particles arriving from the different incident directions: 16 possible coincidences of 4 upper and 4 bottom scintillators;
3. Count rates of the 8 special coincidences, for instance, 1 signal from the upper scintillators and 1 signal from the lower ones, or no signals in upper, and more than 1 signal in the lower, etc.;
4. Estimates of the variances of count rates of each ASNT channel, variances are calculated by 12 five-second counts, i.e. in a minute 12 times (each with 5 sec integration time) all channel counts are stored; then with stored values the means and variances are calculated;
5. 8 x 8 correlation matrix of ASNT channels calculated by five-second count rates in 1 minute; with same stored values of the 5-sec time series each minute the correlation matrix is calculated to monitor possible cross-talk of channels;
6. Each minute (after 07.2012, each 20 second) the histograms of the energy releases in all 8 channels of ASNT are stored;
7. The same as in the previous point, but only for particles that dos not registered in the upper layer (veto on charged particles to select samples enriched by neutral particles);

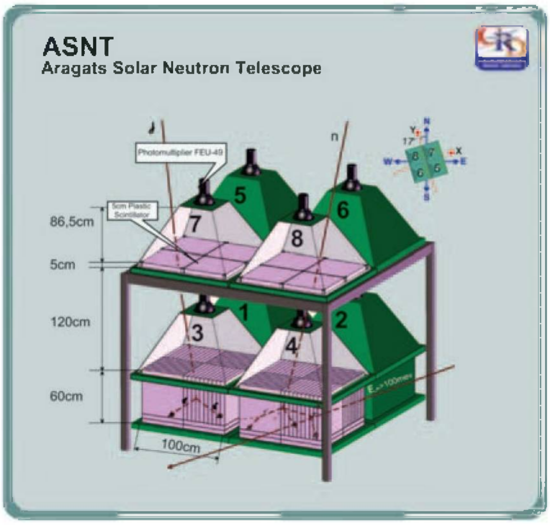

Figure 1. Assembly of ASNT with the enumeration of 8 scintillators and orientation of detector axes relative to the North direction.

A big advantage of ASNT is additional, so called, software triggers, exploiting the information on the energy releases in scintillators. The software triggers are not fixed in electronics and it is possible to add or change them very flexible.

For instance, one of the software triggers used along last 10 years is the selection of the muons traversing the 5 cm thick scintillators horizontally (0 – 0.5 degrees). The energy release of such an event should exceed 200 MeV due to a large path of muon in the scintillator. To avoid EAS contamination the condition of horizontal muon selection is the absence of signals in the thick scintillators below

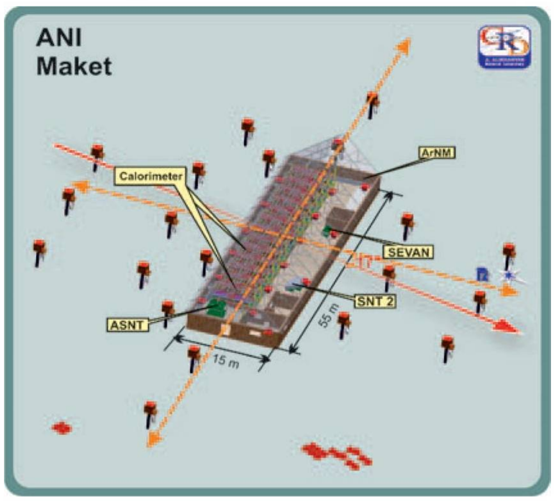

Figure 2. MAKET-ANI Extensive Air Shower (EAS) array

The MAKET-ANI surface array (Figure 2) consists of 92 five cm thick plastic scintillators covering 10,000 m2 to measure EAS particles. 24 of them have 0.09 m2 area and 68 have 1 m2 area. Logarithmic Analog to Digital Converters (ADC) and Constant Fraction Discriminators (CFD) are placed just above the PMT in the light-tight iron boxes. The dynamic range of the registered particle number is ~ 5 x 103. During multiyear measurements, the detecting channels were continuously monitored. Data on background cosmic ray spectra was collected for each detector. The slope of the spectra was used for detector calibration. The slope of the background spectra is a very stable parameter, which did not change even during very severe Forbush decreases (abrupt changes of cosmic ray flux intensity due to solar activity) when the mean count rates can decrease as much as 20%.

After publishing the final results of the MAKET-ANI experiment (Chilingarian et al., 2007) the research of high-energy galactic cosmic rays was stopped. Around the ASNT detector was arranged new array consisted of 16 scintillators, which registered EAS events that triggered 8 and all 16 scintillators within a time window of 1 microsecond.

3. *IN SITU* MEASUREMENTS OF THE RB/RREA PROCESS ON ARAGATS

The first observation of the avalanches initiated by the runaway electrons was made at Aragats in 2009 (Chilingarian et al., 2010). MAKET and ASNT detectors (Figs 1 and 2) were used for the *in situ* detection of RB/RREA process in the thundercloud above detector site. In Figure 3, we present the particle abrupt surge observed in the 1-minute time series of ASNT detector on 19 September. This TGE is the one of two largest ever observed on Aragats. On 22:47 the upper scintillators registered 108% enhancement corresponding to 270 standard deviations from the mean value (270σ); the bottom scintillators registered 16% enhancement (60.7σ); the near-vertical flux (coincidences 3 - 7, 5 – 1, 6 – 2, 8 – 4) enhanced by 11.2% (16.8σ). The flux started slow surge, then rockets in 3 minutes to the maximal value and decays in 4 minutes.

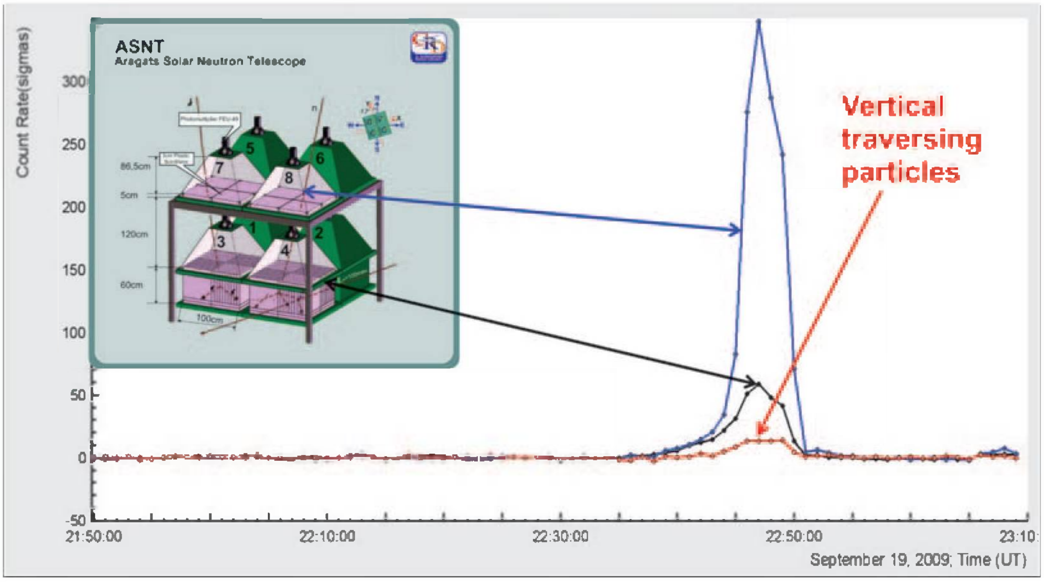

Figure 3. "Significance" of TGE in the number of standard deviations from the mean value of 1-minute time series of count rate. Top curve corresponds to upper scintillators, middle – to lower and the bottom – to vertical particle transition through both scintillators.

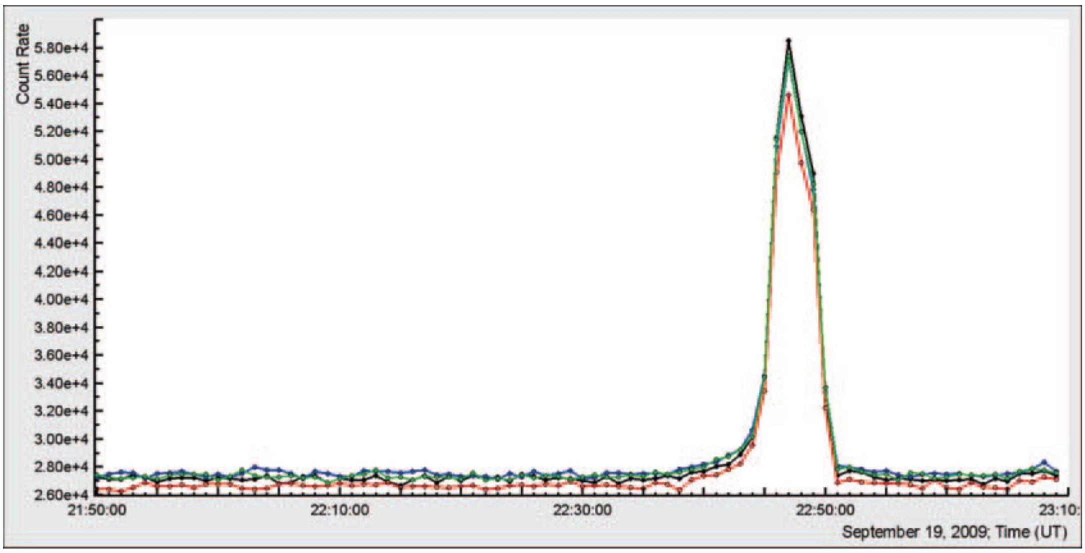

Figure 4. Particle flux enhancement as measured on 19 September 2009 by four 5 cm thick 1 m² area plastic scintillators on top of ASNT detector (Figure 1); energy threshold ~ 7 MeV.

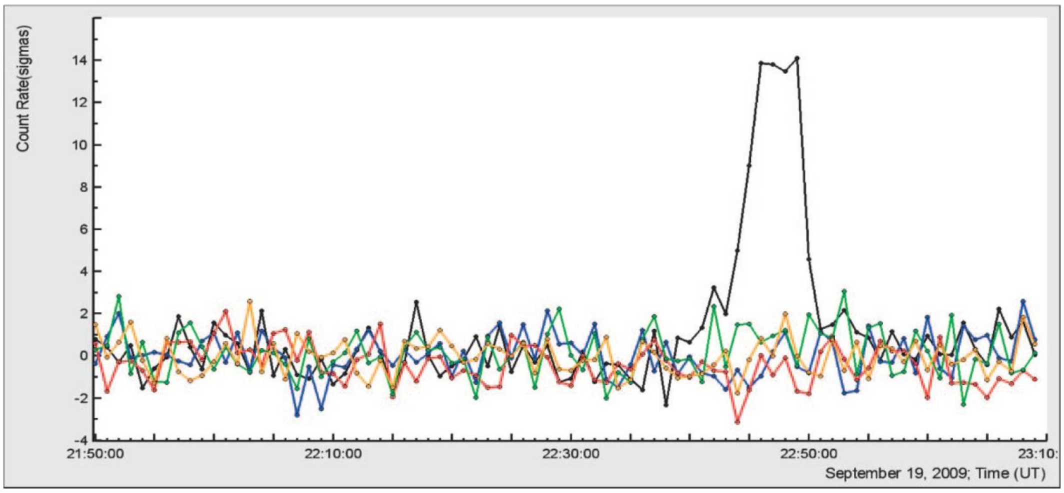

Figure 5. The additional count rate of particles coming from different directions. Tthe 4 minute peak is formed by particles coming from the vertical direction ((coincidences 3 - 7, 5 – 1, 6 – 2, 8 – 4); the particles coming from the inclined directions other combinations of coincidences of upper and lower scintillators, do not show any enhancement

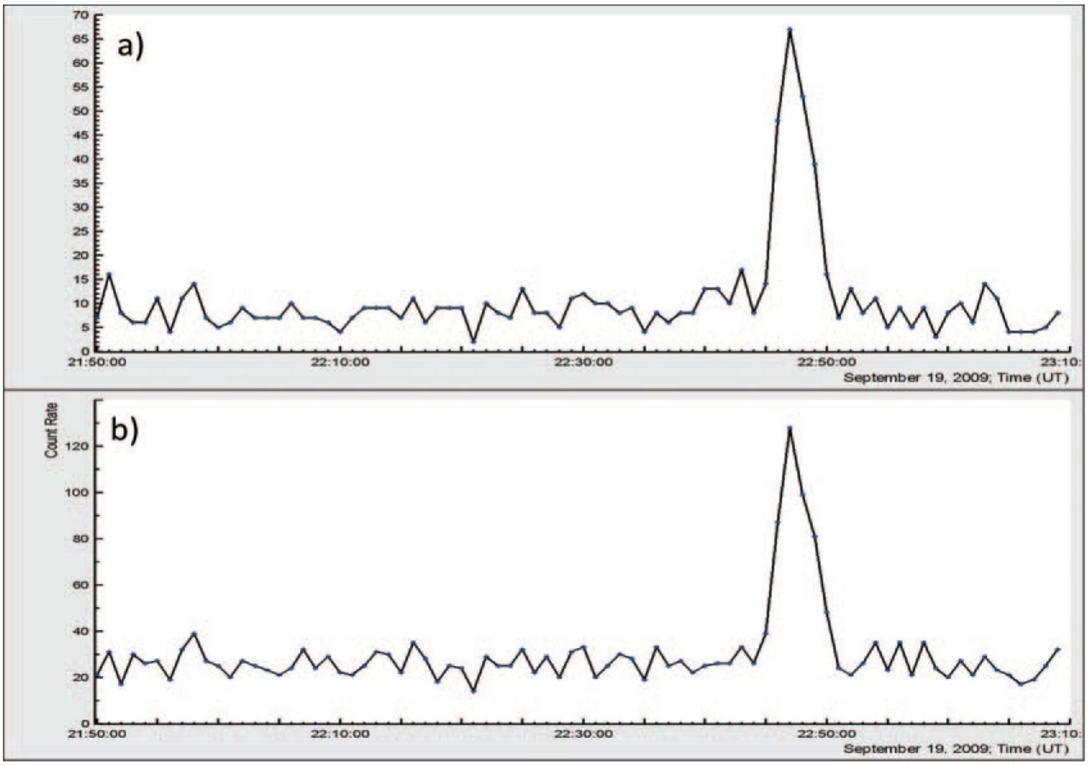

Figure 6. 8 and 16-fold coincidences in the channels of MAKET surface array

In Figure 4 we show rather uniform registration of the particle flux enhancement by the 4 identical 5 cm thick plastic scintillators. Small differences in the count rates are explained by the PMT individual variation. Registered TGE particles flux was rather large ~ 30,000 per min per m^2.

Thus, we observe continuous, several minutes long particle flux. 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 (EAS, 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 Figure 5 particles come from near-vertical direction coinciding with the direction of the vertical electric field in the thundercloud.

Another evidence of "thunderstorm" origin of particle flux comes from MAKET array's 16 and 8-fold coincidences within trigger window of 1 µsec (Figure 6 a and b). The abrupt enhancement the coincidences occurred the same minutes when the flux of particles surges. We observe ~730% enhancement of the 16-fold coincidences, corresponding to ~22σ (Fig 6a).

The significant excess in shower number observed this minute (~100) 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/RREA 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) we should observe much more counts of ECSs. The maximal dead time of the MAKET array is 100 µsec; thus after each 100 µsec another shower can be registered by the surface particle array. Therefore, we can expect up to 10,000 showers per second, however, we register not more than 4.

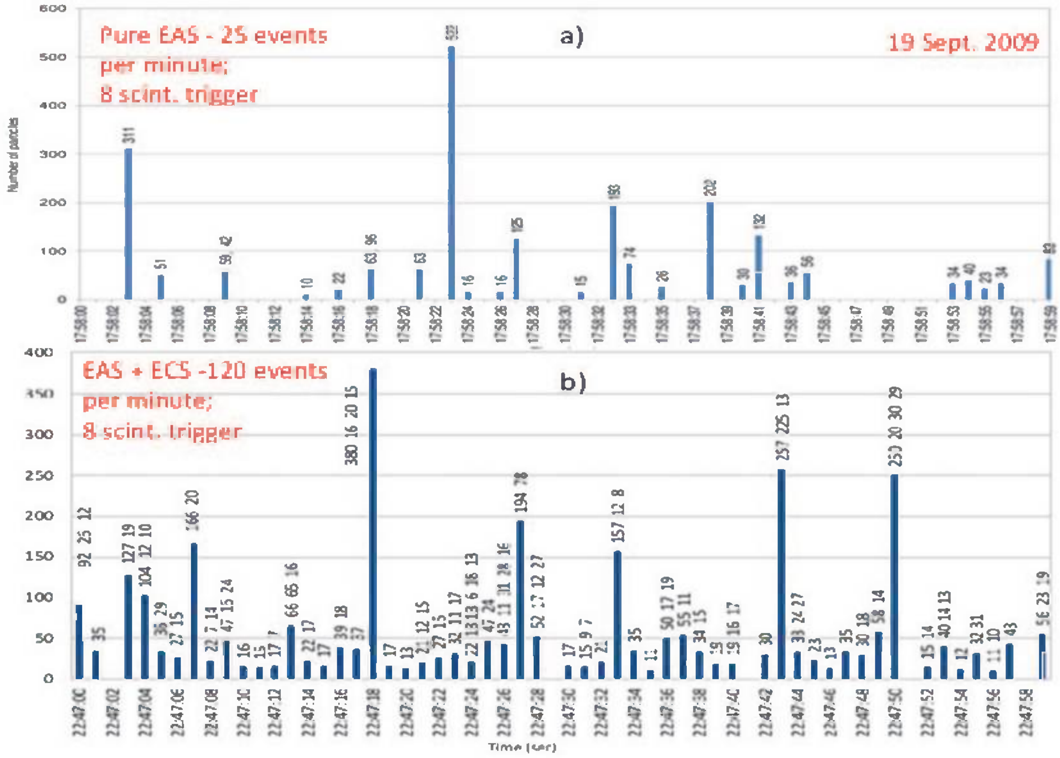

Figure 7. Particle showers detected during 60 seconds of the fair weather a) and during a thunderstorm at maximal particle flux b). Vertical bars show the number of particles in showers. If there were more than one shower in a second the height of a bar is equal to the size (number of particles) of the 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.

4. 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 this 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/RREA process electrons. In addition, extracting histogram obtained with veto from the histogram obtained without veto we readily come to the histogram of electron energy releases (Figure 8).

The spectrum of electrons is very shallow, has non-stability below 7 MeV and terminates at 20 MeV; the spectrum of gamma rays is prolonged until 30 MeV. However, TGE particles in order to be registered in the 60-cm thick scintillator have to traverse significant amount of matter above, see Figure 9.

The intensity of electron flux is ~ 20 times less comparing with gamma ray intensity. The maximal energy of electron reaches ~25 MeV and, gamma ray - 35 MeV. TGE particles in order to be registered in the 60-cm thick scintillator have to traverse significant amount of matter above, see Figure 10. To estimate maximal electron energy above the roof we calculate energy losses in the matter above the scintillator (~ 10.8 g/cm^2) and, considering the minimal required energy release in scintillator ~ 7 MeV, we come to maximal electron energy 40-50 MeV in a good agreement with simulation of TGE (Chilingarian, Mailyan, and Vanyan, 2012). The 4-minute flux of high-energy electrons detected by 60 cm thick scintillator proves a very low location of the thundercloud, possibly just above the roof of the MAKET building.

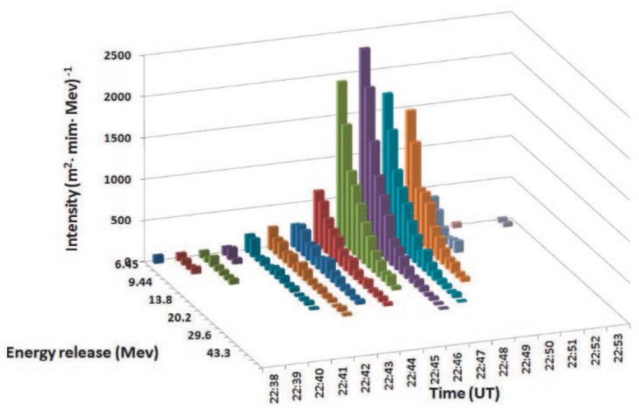

Figure 8. Differential energy release histogram of the TGE gamma rays obtained in 60 cm. thick scintillators of the ASNT array.

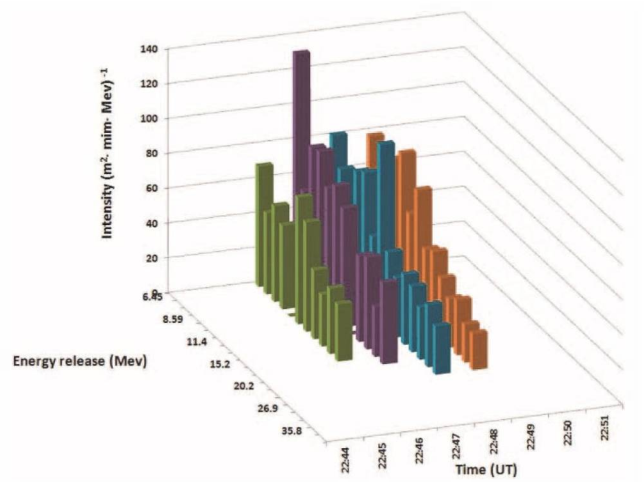

Figure 9. Differential energy release histogram of the TGE electrons obtained in 60 cm. thick scintillators of the ASNT array.

Aragats Neutron Monitor (ArNM, see details in Chilingarian, Hovsepyan and Kozliner, 2016) consists of 18 cylindrical proportional counters of CHM-15 type (length 200 cm, diameter 15cm) filled with BF3 gas enriched with B^{10} isotope and grouped into three sections containing six tubes each. The proportional chambers are surrounded by 5 cm of lead (producer) and 2 cm of polyethylene (moderator). The cross section of lead producer above each section has a surface area of $6m^2$, and the total surface area of three sections is 18 m^2 . The TGE gamma rays produce neutrons in the photonuclear interactions with air atoms. The gamma rays, as well as atmospheric hadrons, produce secondary neutrons in nuclear reactions in lead (Chilingarian et al., 2012a, 2012b, Tsuchiya et al., 2012). Then, the neutrons slow down to thermal energies in the moderator, enter the sensitive volume of the counter, and yield Li7 and α particle via interactions with boron gas. The α particle accelerates in the high electrical field inside the chamber and produces a pulse registered by the data acquisition electronics.

In Figure 11 we show significant enhancement (> 6σ at 22:47) of ArNM count rate lasting ~ 5 minutes on 19 September 2009; the same hour and minutes as the gamma ray and electron peaks. The count rates corresponding to dead times of 0.4 μs, 250 μs, and 1250 μs are approximately identical; EAS registration leads to enhancement only for the time series obtained with the minimal dead time of 0.4 μs.

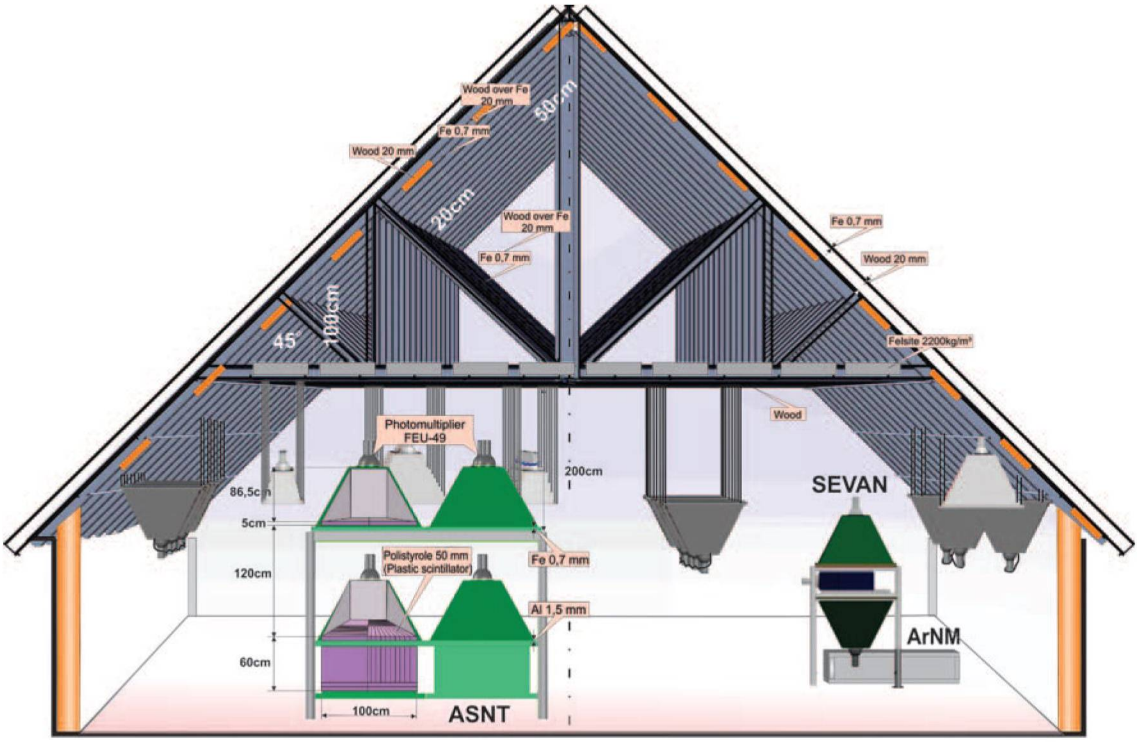

Figure 10 . Setup of ASNT detector in the MAKET experimental hall

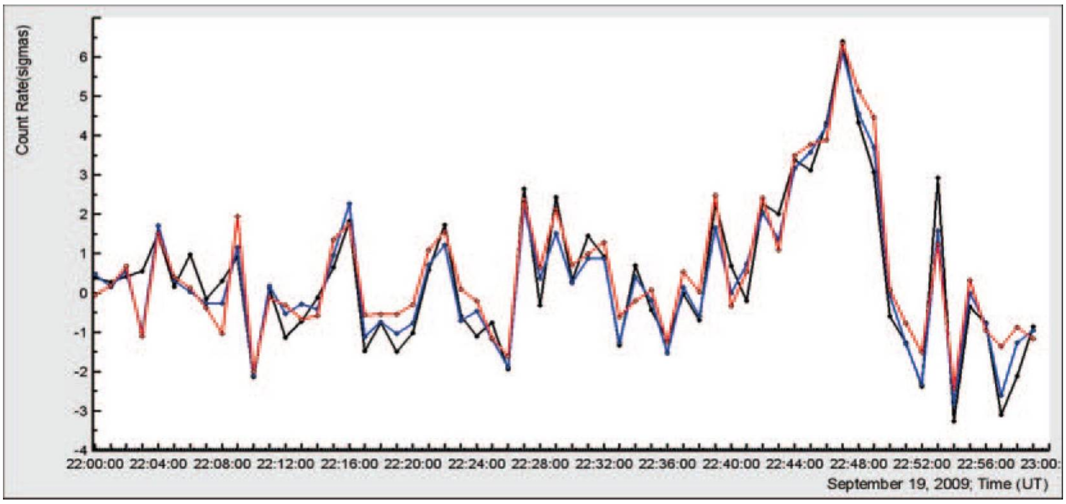

Figure 11. Time series of ArNM 1-minute count rate displayed in the number of standard deviations. Time series corresponding to 3 dead times are approximately identical.

5. DISCUSSION AND CONCLUSION

We measure the energy release histograms of TGE electrons reaching and registering in the 60 cm thick scintillators of the ASNT detector. The energy spectrum 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-event occurred on 19 September 2009 is in good agreement with the TGE model (Chilingarian, Mailyan, and Vanyan, 2012, Chilingarian, 2014).

Measured TGE temporal distribution demonstrates (Figure 7) proves that large fluxes of electrons and gamma rays detected during thunderstorms comprise from the numerous very short RB/RREA cascades registered by the particle detectors located on the mountain altitudes. During ~5 minutes of TGE, a large number of very short bursts (individual RRE avalanches, Extensive cloud showers, or Micro runaway breakdowns ECS/MRB, Gurevich et al., 1999) were developed in the thundercloud. For occurring of large TGE, clouds should be low above particle detectors; thus only on near-zero surface temperatures and high humidity, we detect largest TGEs (large negative near surface electric field is also a necessary condition).

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 does not appear obviously. 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 RREA continued down to several tens of meters above detector site. Thus, various RB/RREA models can be validated by *in situ* measurements on Aragats, the natural electron accelerator provided many tens of TGEs each year (Chilingarian et al., 2016).

If the RB/RREA 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 μsec); however the experimentally measured number of ECSs per second is 4, see Figure 7b). 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 and more. 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.

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REFERENCE

Babich, L.P., et al., 2001. Comparison of relativistic runaway electron avalanche rates obtained from Monte Carlo simulations and kinetic equation solution. IEEE Trans. Plasma Sci. 29 (3), 430–438, 2001.

Briggs, M. S., et al., 2011. Electron-positron beams from terrestrial lightning observed with Fermi GBM, Geophys. Res. Lett., 38, L02808.

Chilingarian, A., Gharagyozyan, G., Hovsepyan, G., Ghazaryan, S., Melkumyan, L., Vardanyan, A., 2004. Light and heavy cosmic-ray mass group energy spectra as measured by the MAKET-ANI detector. Astrophys. J. 603, L29–L32.

Chilingarian A., Gharagyozyan G., Hovsepyan G. et al., (2007). Study of extensive air showers and primary energy spectra by MAKET-ANI detector on Mount Aragats, Astroparticle Physics, 28, 58.

Chilingarian, A., Daryan, A., Arakelyan, K., Hovhannisyan, A., Mailyan, B., Melk- umyan, L., Hovsepyan, G., Chilingaryan, S., Reymers, A., Vanyan, L., 2010. Ground- based observations of thunderstorm-correlated fluxes of high-energy electrons, gamma rays, and neutrons. Phys. Rev. D: Part. Fields 82 (4), 043009.

Chilingarian, A., Hovsepyan, G., Hovhannisyan, A, 2011. Particle bursts from thunderclouds: natural particle accelerators above our heads. Phys. Rev. D: Part. Fields 83 (6), 062001.

Chilingarian, A., Mailyan, B., Vanyan, L., Recovering of the energy spectra of electrons and gamma rays coming from the thunderclouds. Atmos. Res. 114–115, 1 (2012).

Chilingarian A., Bostanjyan N., and Vanyan L., Neutron bursts associated with thunderstorms, Physical Review D 85, 085017 (2012a).

Chilingarian A., Bostanjyan N., Karapetyan T., Vanyan L., Remarks on recent results on neutron production during thunderstorms, Physical Review D 86, 093017 (2012a).

Chilingarian A., Hovsepyan G., and Kozliner L., Thunderstorm ground enhancements: Gamma ray differential energy spectra, Physical Review D 88, 073001 (2013).

Chilingarian A., Thunderstorm Ground Enhancements – model and relation to lightning flashes, J. Atmos. Solar-Terr. Phys. 107 (2014) 68–76.

Chilingarian A., G. Hovsepyan, G. Khanikyanc, A. Reymers and S. Soghomonyan, Lightning origination and thunderstorm ground enhancements terminated by the lightning flash, EPL, 110 (2015) 49001 Chilingarian A., Hovsepyan G., and Mantasakanyan E., 2016. Mount Aragats as a stable electron accelerator for atmospheric High-energy physics research, Phys. Rev. D: Part. Fields, 93, 052006.

Chilingarian A., Hovsepyan G., Kozliner L., Extensive Air Showers, Lightning, and Thunderstorm Ground Enhancements, Astroparticle Physics 82 (2016) 21–35.

J.R. Dwyer, D.M. Smith, S.A. Cummer, High-energy atmospheric physics: terrestrial gamma-ray flashes and related phenomena, Space Sci. Rev. 173 (2012) 133–196.

Dwyer, J. R. (2012), The relativistic feedback discharge model of terrestrial gamma ray flashes, J. Geophys. Res., 117, A02308.

J.R. Dwyer, M.A. Uman, The physics of lightning, Phys. Rep. 534 (4) (2013) 147–241.

Dwyer, J.R., 2007. Relativistic breakdown in planetary atmospheres. Phys. Plasmas 14 (4), 042901, http://dx.doi.org/10.1063/1.2709652.

Dwyer, J.R., 2003. A fundamental limit on electric fields in air. Geophys. Res. Lett. 30 (20), 2055, http://dx.doi.org/10.1029/2003GL017781.

G.J. Fishman, P.N. Bhat, R. Mallozzi, et all. Discovery of intense gamma ray flashes of atmospheric origin, 1994, Science V. 264 (5163), 1313.

Gurevich, A.V., Milikh, G.M., Roussel-Dupre, R., 1992. Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm. Phys. Lett. A 165 (5-6), 463–468.

Gurevich A.V., Zybin K.P., Roussel-Dupre R.A., Lightning initiation by simultaneous of runaway breakdown and cosmic ray showers, Phys. Lett. A 254 (1999) 79.

P. Krehbeil, V. Mazur, W. Rison, Standardizing the sign convention for atmo- spheric electric field measurements, Newslett. Atmos. Electr. 5 (2) (2014) 5.

Lehtinen, N.G., Bell, T.F., Inan, U.S., 1999. Monte Carlo simulation of runaway MeV electron breakdown with application to red sprites and terrestrial gamma ray flashes. J. Geophys. Res. 104, 24,699–24,712, http://dx.doi.org/10.1029/ 1999JA900335.

Stolzenburg M., Rust W., Marshall T., Electrical structure in thunderstorm convective regions 3. Synthesis, J. Geophys. Res. 103 (1998) 14097–14108.

Tsuchiya H., Hibino K., Kawata K. et al., Observation of thundercloud-related gamma rays and neutrons in Tibet, Phys. Rev. D 85, 092006 (2012).