On the Maximum Strength of the Atmospheric Electric Field

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Abstract

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On the Maximum Strength of the Atmospheric Electric Field

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Keywords: Atmospheric electric field, thunderstorm ground enhancement, muon stopping effect

Abstract:
Particle detectors of the European SEVAN network located on mountain heights in Aragats (Armenia), Lomnicky Stit (Slovakia) and Musala (Bulgaria) are well suited for the detection of thunderstorm ground enhancements (TGEs, enhanced fluxes of electrons, gamma rays, neutrons). The modulation of charged particles flux by the electric field of the thundercloud results in a sizable change in the count rate of detectors, which measure fluxes of electrons, gamma rays, and high energy muons in the near-vertical and near-horizontal directions. The relation between electric field strength and changes of particle flux count rates is nonlinear and depends on many unknown parameters of atmospheric electric field and meteorological conditions. Nonetheless, employing extreme TGEs as a manifestation of the strong electric field in the thundercloud and by measuring fluxes of three species of secondary cosmic rays (electrons, gamma rays, and muons) by SEVAN detectors located at altitudes of ≈ 3 km we study the extreme strength of the atmospheric electric field. With the simulation of particle traversal through the electric field with CORSIKA code, we derive a maximum potential difference in the thunderous atmosphere to be ≈ 500 MV.

1. Introduction

Understanding the maximum potential difference (voltage) inside thunderstorms is one of the fundamental problems of atmospheric physics directly connected with enigma of the lightning initiation. In 1925 C.T.R. Wilson estimated the maximum potential difference in the atmosphere to be one gigavolt: "A particle may thus acquire energy corresponding to the greater part of the whole potential difference between the poles of the thundercloud, which may be of the order of 10^9 V"[1]. In the speech to Franklin Institute in 1929 [2] he presents detailed calculations: "The value found for the maximum potential difference in the cloud depends on the vertical thickness, i.e. the distance through which the maximum field extends. We can hardly be wrong as to the order of magnitude if we take this height as one kilometer. If a field of 10,000 volts per centimeter extends through one kilometer the whole potential difference is 10^9 volts, i.e. one million kilovolts ". Based on such a huge potential difference Wilson estimates the maximum energy that electron can gain in the electric field to be 1 GeV: "The general effect of an accelerating field is that a beta-particle, instead of dying as it were a natural death by gradual loss of energy, is continually acquiring more and more energy and increasing its chance of surviving all accidents other than direct encounters with the nuclei of atoms" [1]. Of course, in 1925 the particle cascade theory was not yet developed, and the measurements of the electric field in thunderclouds were not done, and C.T.R. Wilson overestimated the scale of electron acceleration. He thought that electrons could gain unlimited energy from the electric field, however, that is not possible, due to abundant radiation losses of electrons with energies greater than 50 MeV. The runaway electron [3] differential energy spectrum first measured in 2009 faded around 50-60 MeV [4]. The Intracloud electric field measured with the balloon experiments does not exceed 3,000 volts per centimeter. Thus, a potential difference as large as 1000 MV seems to be not feasible according to direct measurements: "Inside thunderstorm clouds the voltages ranged between -102 and +94 MV [5]. However, the estimate of maximum voltage based on the balloon soundings can be biased, because, first of all, balloon flights are rare, and second the balloon path within the thundercloud is a random walk depending on the updraft and wind speeds and hardly corresponds to the maximum possible voltage.

From the empirical relation between the first return stroke peak current and charge brought to ground, an empirical equation connecting the stroke current and voltage was derived (eq.3 of [6]). If we assume the extremal stroke current to be 200 kA, the maximum voltage will be approximately 200 MV. Another possibility to estimate maximum voltage is connected with the estimation of the mean electric field and its spatial extent in the cloud (like Wilson estimate). It was found that the electric field strength measured just before a lightning flash in the balloon flights, can exceed the runaway breakdown threshold by factors of 1.1 – 3.3 ([7], Figs 3 and 4). The height of the main negative layer above Aragats according to the satellite and radar measurements, also confirmed by the simulations of relativistic runaway electron avalanches (RREA), can reach 2 - 3 km. The height of the lower positive charged region for the largest thunderstorm ground enhancement events is 25-100 m [8,9]. Consequently, assuming maximum strength of the electric field 2.4 kV/cm (32% above RREA threshold) and field extension 2 we obtain the maximum potential difference 480 MV by multiplying the assumed 2.4 kV/cm electric field strength to 2 km. Of course, this estimate is an upper limit of maximum voltage: we hardly can expect a 2.4 kV/cm field for the whole 2 km length. Therefore, we come to large uncertainty in the estimation of maximum voltage in the thundercloud from 100 to 480 MV. Direct monitoring of the intracloud electric field with any of spaceborne or ground-based technologies is not feasible yet, hence, we suggest to use the monitoring of particle fluxes modulated by the electric field to estimate the attainable value of the potential drop. Measurements of the modulation of cosmic ray flux traversing the electrified cloud provide a new type of evidence on cloud electrification and, possibly, allows to obtain more tight limits on the maximum potential difference in thunderclouds. The big advantage of the "particle" approach is multiyear 7/24 monitoring of different species of cosmic rays available from the measurements of high-mountain research stations. In contrast, balloon flights cannot provide continuous observations of a thunderous atmosphere and can miss extremely large voltages. TGEs observed on mountain peaks during strong thunderstorms comprise millions of particles (electrons, gamma rays, and neutrons), enhancing the intensity of ambient flux of cosmic rays up to a hundred times [10]. The same field that accelerates electrons downward in the direction of the earth will reduce the flux of muons, due to enhanced positive over negative muon flux. Simultaneous monitoring of these species of secondary cosmic rays with SEVAN East-European network of particle detectors [11] gives a possibility to select from the multiyear observations on Aragats in Armenia, Musala in Bulgaria, and Lomnicky Stit in Slovakia most violent TGEs corresponding to extreme values of the electric field. Recently we published the analysis of the 10-year largest TGE observed on Aragats on 4 October 2010 and estimate the upper boundary of maximum potential difference to be 350 MV [12]. We will demonstrate in the present paper, the world largest TGEs registered in Slovakia and Bulgaria on the keen mountain tops not only confirm this result but prove that the voltage can reach 500 MV.

2. Registration of TGEs with SEVAN particle detectors on Musala and Lomnicky Stit mountains

A network of particle detectors known as SEVAN (Space Environment Viewing and Analysis Network [11], was developed in the framework of the International Heliophysical Year (IHY-2007) and now operates and continues to expand within the International Space Weather Initiative (ISWI). The SEVAN network is designed to measure fluxes of neutrons and gamma rays, of low energy charged particles and high-energy muons. The rich information obtained from the SEVAN network will allow estimating the solar modulation effects posed on different species of Galactic cosmic rays and fluxes of charged and neutral particles from the Solar energetic proton events (SEP). SEVAN modules located on mountain tops are actively participating in the research in the newly emerging field of high-energy physics in the atmosphere. Thus, with the same detector, we can investigate both the solar-terrestrial relations and atmospheric high-energy physics. Cheap and reliable SEVAN detectors can be installed at different locations to participate in the global network of monitoring Solar-terrestrial relations and atmospheric electricity. Observational data from SEVAN particle detectors located on mountain tops Musala (Altitude – 2925 m, Latitude - 42º11', Longitude - 23º35' in Bulgaria, and Lomnicky Stit (Altitude – 2634 m, Latitude - 49º12', Longitude - 20º12') in Slovakia reveal extreme TGE events. They comprise enormous enhancement of the electron and gamma ray fluxes and simultaneous decrease of muon flux. In Fig.1 we show the chart of the SEVAN detector. The detector is assembled from standard slabs of plastic scintillators of 50x50x5cm^3 size. Thick 50 x 50 x 20 cm^3 scintillator assembly (5 slabs) and two 100 x 100 x 5 cm^3 lead filters are located between 2 identical assemblies of 100 x 100 x 5 cm^3 scintillators (4 slabs). The data stream from the SEVAN comprises 1-minute count rates (or 1-sec count rates) from 3 scintillator layers. All combinations of signals from detector layers are stored as well: "100" combination means that the signal was only in the upper layer (low energy particles); "111" – that signal comes from all 3 layers (high-energy muons), "011" – near-horizontal muons). The "010" combination selects mostly neutral particles – gamma rays and neutrons.

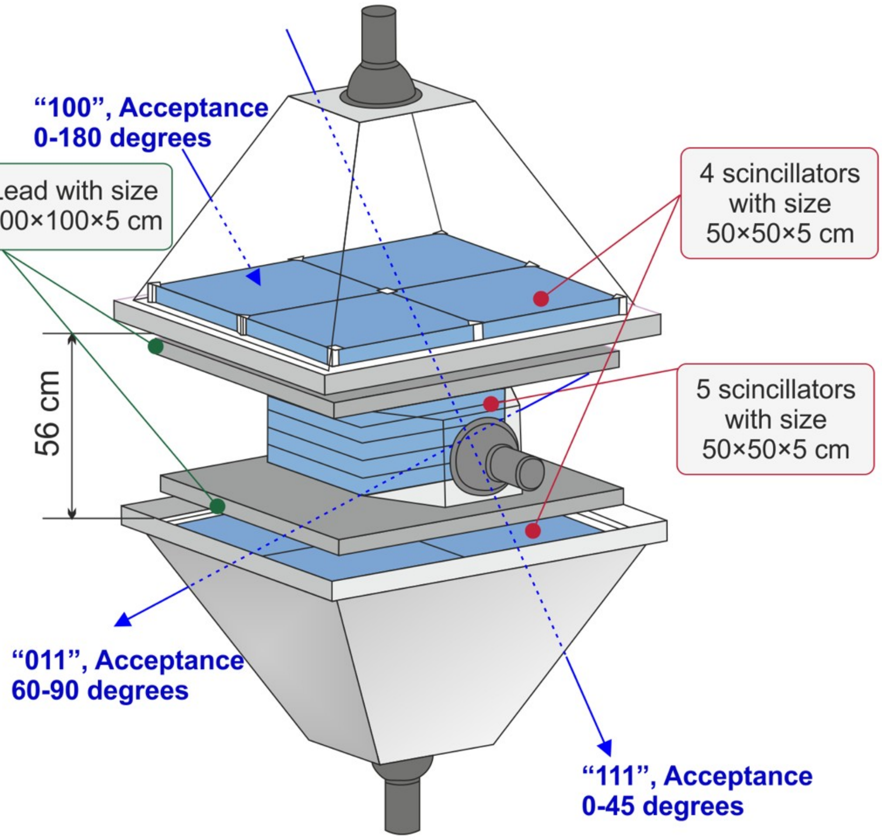

Figure 1. The module of the European "Space Environmental Viewing and Analysis Network" (SEVAN).

The purity of particle selection by SEVAN coincidences was estimated by simulations, see Fig. 4 in [11]. The purity of muon selection is rather high ~95%, due to a 10 cm thick lead filter between first and third scintillators. The energy threshold of the upper detector is ~ 7 MeV. The minimum energy of muons ("111" combination) is ~250 MeV. The measurement of changing fluxes of different species of the ambient population of cosmic rays, all of which are modulated by the solar activity and by the atmospheric electric field provides the possibility to investigate correlations between different species of cosmic rays and the electrified atmosphere. The atmospheric electric field, which is especially large during violent thunderstorms accelerates and decelerates charged particles dependent on the field direction and particle charge. The extreme TGEs occurred when the electric field accelerates electrons in the direction to the earth's surface; thus, the counts of "100" combination of SEVAN get enormous bust, enhancing the fair-weather count rate 250 times! Simultaneously, the same field that accelerates electrons downwards causes muon flux depletion ("111" combination) due to an abundance of positively charged muons upon negative ones (see for discussion and references [12]). Another evidence of the large electric field in the thundercloud is the large depletion of the inclined trajectories, "011" combination comprises inclined high energy muons. The TGE particle, due to the vertical orientation of the atmospheric electric field arrives in the near-vertical direction; from the near-horizontal direction can arrive only high-energy muons, that can traverse large distances in the atmosphere without absorption. Described above modulation effects registered by SEVAN detectors in Slovakia and Bulgaria are shown in Figs. 2 and 3.

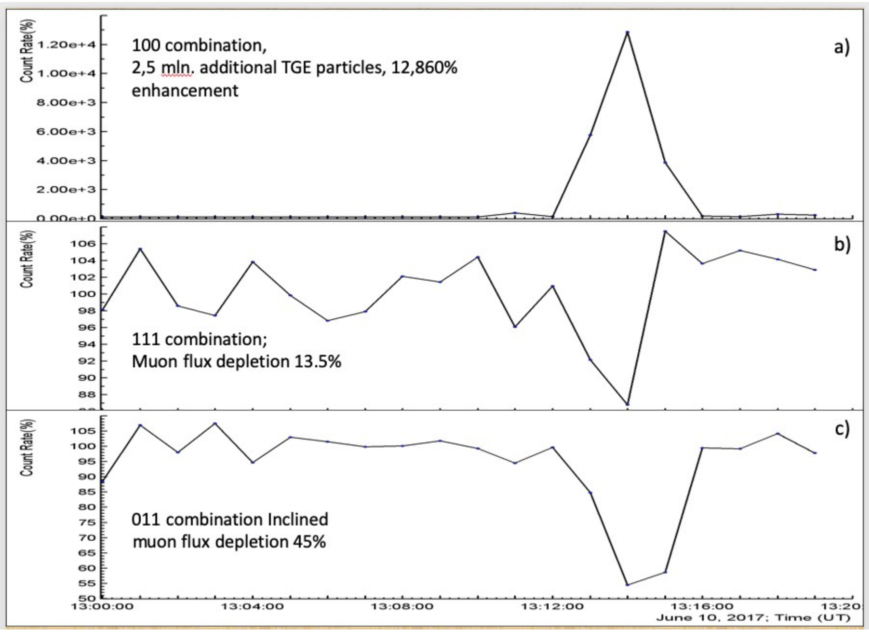

Figure 2. Extreme TGE event detected by SEVAN detector located on Lomnicky Stit mountain: a) – TGE particles – electrons and gamma rays; b) high energy muons; c) inclined muons.

The extreme event was recorded in Slovakia on 10 June 2017 [13]; the enhancement of the count rate of “100” combination at the minute 13:12-13:13 was enormous and reached 12,860% (12 thousand 860 percent, Fig 2a) of the fair-weather value. TGE was terminated by multi-stroke discharge at 13:14:35.5. This world ever-largest TGE was reached only in one minute, the electric field was enormously large, unleashing a huge electromagnetic avalanche; sure, such an enormous potential drop initiates a lightning flash that stops TGE. In the balloon flights adversely impacted by lightning, the electric field before the flash exceeded the runaway breakdown field by factors of 1.1 to 3.3 [7].

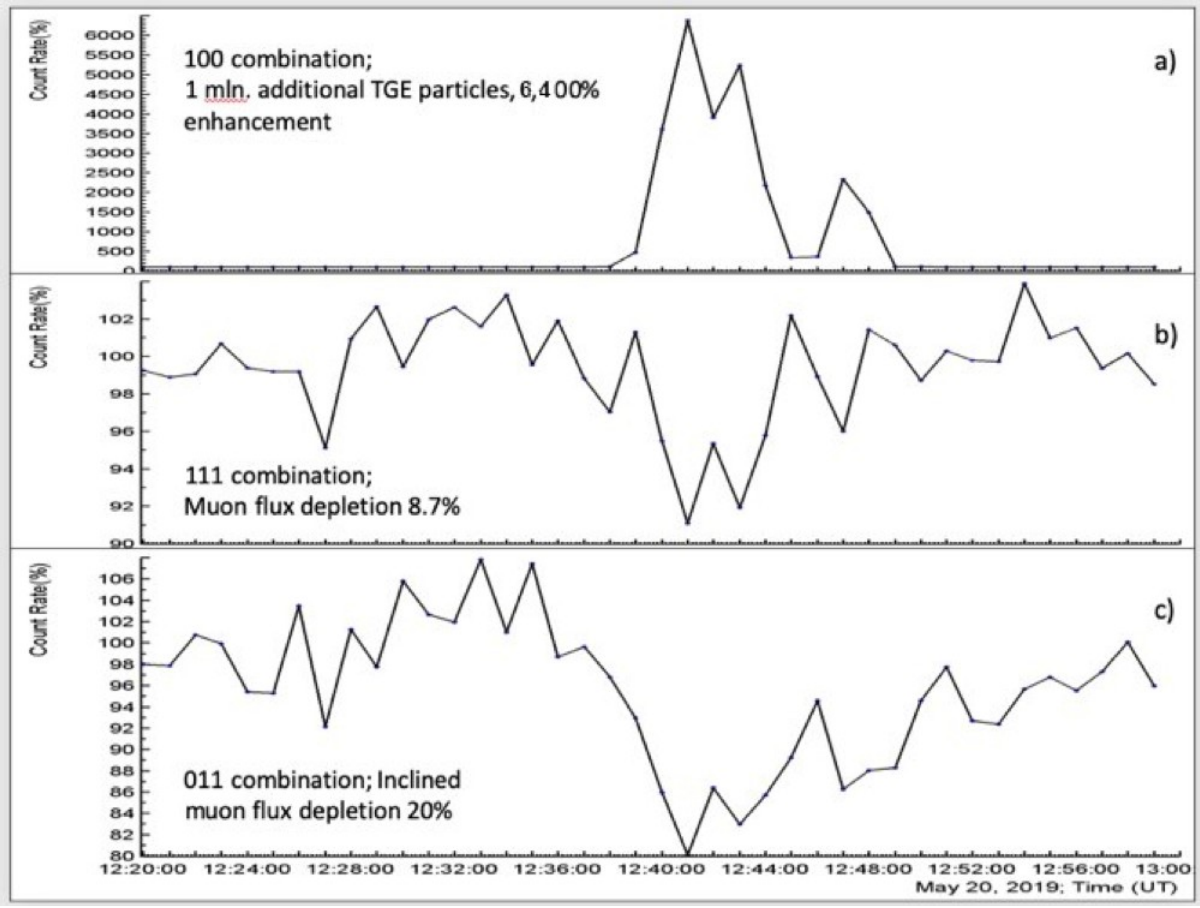

Figure 3. Extreme TGE event detected by SEVAN detector located on Musala mountain: a) – TGE particles – electrons and gamma rays; b) high energy muons; c) inclined muons.

The maximum electric field occurred a few seconds before the flash. These very large values of the electric field support the idea that the TGE may initiate lightning flashes [14]. The muon flux depletion at the same minute was 13.5%, (see Fig. 2b), it was twice larger than for the strongest event ever observed in Aragats on 4 October 2010 [12]. The depletion of inclined muons was much larger 45%, see fig. 2c. For the one-minute time series, the maximum enhancement of TGE particles coincides with the minimum of the muon flux; for one-second time series, the extreme values of fluxes can be shifted from each other because fast-changing electric field on the second time-scale can influence differently fluxes of near-vertical avalanche particles and the flux of cosmic ray muons coming within much broader angular acceptance.

Importantly, the count enhancement of about 50 times was observed for combination "010", which indicates neutrons and high energetic gamma-rays [15]. A tremendous enhancement of neutron flux (130%) was measured by the neutron monitor at the same location. Neutron monitor evidence is very important as an independent observation and as a prove of intense photonuclear reactions of high energy gamma rays born in the TGE (previous highest neutron flux detected on Aragats was only 5.5% [4].

Extreme, however, a bit smaller, event was recorded in Bulgaria on 20 May 2019 [16]. The shape of the event was more complicated demonstrating 3 peaks in 10 minutes (due to 3 terminations of TGE by the lightning flashes at 12:42:18, 12:46:13, and 12:50:07). The increase of the count rate of “100” combination during one minute, at 12:41-12:42 reaches 6,400% (6 thousand 400 percent, see Fig. 3a) of the fair-weather value. The muon flux depletion at the same minute was 8.7%, Fig 3b. The depletion of inclined muons was 20%, see fig. 3c. A highly enlarged count rate of the Luilin detector [17] located in the same place confirms this extreme event.

3. Estimation of the atmospheric electric field

In Table 1 for convenience we show both the mean 1-minute and 1-second count rates measured just before the extremely large event at Lomnicky Stit and count rates measured at the minute of the maximum flux. As we can see from the Table the count rates of the upper SEVAN scintillator and combination “100” (signal only in the upper scintillator) highly exceed fair-weather count rates, the enhancement is more than 100 times (N) or 10,000% (2 last columns of Table 1).

Table 1. Mean values of the count rates of Lomnicky stit SEVAN and extreme values at maximum flux minute registered on June 10 2017

Name	Mean 1/ min	σ	Mean 1/sec	13:14 1/sec	13:14 1/ min	%	N
Upper	25047	171	417	42233	2,534000	10,013	101
Coincidence 111 muons	1929	48	32.2	27.8	1666	87	
Coincidence 100	19550	142	326	42,100	2,526000	12,890	130
Coincidence 010 gamma	1468	39	24.5	55.5	3326	225	2.3

As usual, along with the enhancement of the electromagnetic component of the TGE, we register depletion of muon flux due to, so-called, muon stopping effect (“111” combination, [12]). Measured high-energy gamma ray and neutron fluxes (combination 010) were also the largest ever measured by the particle detectors located on the earth’s surface.
Proceeding from the maximum enhancements of particle fluxes we pose the problem of estimation of the atmospheric electric field that can enable such a huge multiplication and acceleration of the seed electrons from the ambient population of cosmic rays. We recognize, that the relation between electric field strength and disturbances of particle fluxes is nonlinear and depends on many unknown parameters of atmospheric electric field and meteorological conditions (topology of charged layers, the height of the cloud, wind speed, etc). However, extremely large particle fluxes measured by SEVAN detector allows us to make, as we think, relevant estimate by the detailed modeling of experiment with well-known GEANT4 and CORSIKA codes widely used in the high-energy physics and astrophysics communities. CORSIKA version 7.7400, which takes into account the effect of the electric field on the

transport of particles was used in simulations. As it was already demonstrated by CORSIKA and GEANT4 simulations [18], the multiplication and acceleration of electrons of cosmic rays, the RREA process [3]is a threshold process and avalanches started when the atmospheric electric field reaches the threshold value that depends on the air density (for instance ≈1.63 kV/cm at 4600 m). The extent of the electric field also should be sufficiently large to ensure avalanche development. The simulation of the RREA was done within the vertical region of the uniform electric field with strengths exceeding the runaway breakdown threshold on 2.6-4.6 km height in the atmosphere. Uniformity of the electric field extending 2 km leads to the change of the surplus to threshold energies at different heights according to particular air density value. Thus, the 2.4 kV at 4.6 km height is ≈32% larger than critical energy, and at 2.6 km height is only ≈15% larger. Therefore, we provide a smooth decrease of the electric field (in sense of critical energy) with enlarging of the depth in the atmosphere. The largest TGEs occurred when the distance to the cloud base (a proxy of electric field lower boundary) was 25 – 100 m (see Fig 17 in [10]), thus the electromagnetic avalanche continued propagation in the dense air above the detector 25, 50 and 100 meters before registration. To avoid contamination by the MOS process (modification of electron energy spectra, see details in [19]) simulations for simplicity were performed with vertical beams of 1 MeV electrons, as seed particles for the relativistic runaway avalanche. In this way we obtain a reliable estimate of the maximum energy achieved by the RREA gamma rays; the MOS process generates additional high-energy bremsstrahlung gamma rays from high energy electrons of the ambient population of cosmic rays. The electron energy spectrum at energies corresponding to the minimum of ionization losses is rather flat, thus our approximation does not introduce large bias.

Simulation trials include 10^4 events for the electric field strengths 1.8-2.3 kV/cm and 200 for the strengths – 2.4 and 2.5 kV/cm. Electrons and gamma rays were followed in the avalanche until their energy decreased down to 0.05 MeV. The energy spectra of RREA electrons and gamma rays were obtained as a result of each simulation trial. We perform, as well, the calculation of the SEVAN detector response function with the GEANT4 package. We consider all species of the secondary cosmic ray incident the upper scintillator, calculate efficiencies of registration (≈0.06 for gamma rays and ≈0.8 for electrons and positrons), and, assuming the energy threshold of 7 MeV we obtain the rate 413 counts per second for the upper scintillator that well coincide with a measured count rate of 417 per second. In simulation trials we follow the development of the RREA where we show the number of electrons and gamma rays in RREA per 1 seed electron on different stages of avalanche development in the electric field and after leaving the electric field region, see Fig.4 a) and b). From figures we can see that for large electric field strengths the number of electrons exceeds the number of gamma rays, however, after the exit from the electric field electron flux rapidly attenuates (see Fig. 4b) and, at 100 m below the electric field number of gamma rays exceeds the number of electrons by an order of magnitude.

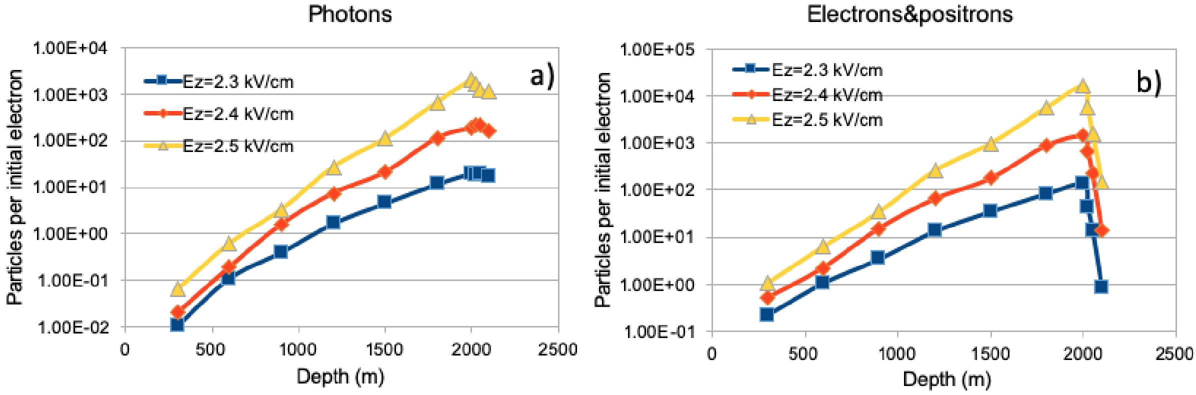

Figure 4. Development of the electromagnetic avalanche in the atmosphere. Avalanche started at 4656 m, 2 km above the SEVAN detector. The number of avalanche particles is calculated each 300 m. After exiting from electric field avalanche is followed additionally 100 m.

To estimate the number of expected counts of SEVAN detector for different electric field configurations we need to calculate the number of seed electrons entering the electric field region. We integrate the number of cosmic ray electrons at the height 4600 m from 0.1 to 3 MeV (the “runaway” energies) and obtain 228 per second per m^2. Proceeding from this number and taking into account the efficiencies of particle registration we obtain the expected number of counts for different strength of the electric field to be compared with the measured count at 13:14 on June 10, 2017, namely 42,233 (see Table 1). We show in the first 3 columns of Table 2 the number of particles per one seed electron obtained in simulations and in the last column - for all 228 seed electrons incident on 1 m^2 per second on the height of 4600m.

Table 2. The simulated intensity of electromagnetic avalanche with SEVAN response function (vertical efficiencies) for different configurations of the atmospheric electric field. The electric field is introduced 2 km above Lomnicky stit at 4659 m to heights 25, 50, and at heights 100 m below (energy threshold 7 MeV).

	El+Pos Counts	Gamma counts	Sum	Total counts (x228)
2.4kV/m 50 m	175	13	188	42864
2.4kV/m 100 m	11	10	21	4788
2.5kV/m 50 m	1268	76	1344	306432
2.5kV/m 100 m	119	68	187	42636

In Table 2 we can see a very strong influence of the electric field strength on the expected count rate. Also, we can see that the electric field with a spatial extent of 2 km and a strength

above 2.4 kV/cm can sustain the flux providing the number of particles similar to the measured one. Thus, we can conclude that for the measured at Lomnicky Stit extreme TGE the potential difference in the atmosphere should be 480 - 500 MV.
However, we need an additional confirmation (besides balloon flight measurements) that our simulation is relevant. Computer codes does not “initiate” lightning flash and can generate infinite number of particles for enhanced electric field strengths. Therefore, to compare simulation results with available experimental measurements (at Aragats, where maximal energy of gamma rays and electrons reach and exceed 60 MeV) we show in Fig. 5 more robust characteristic of the RREA energy spectra than number of particles, namely, – the maximal energy of particles reached in the RREA development. This parameter does not depend on absolute calibration on the seed particle spectrum.

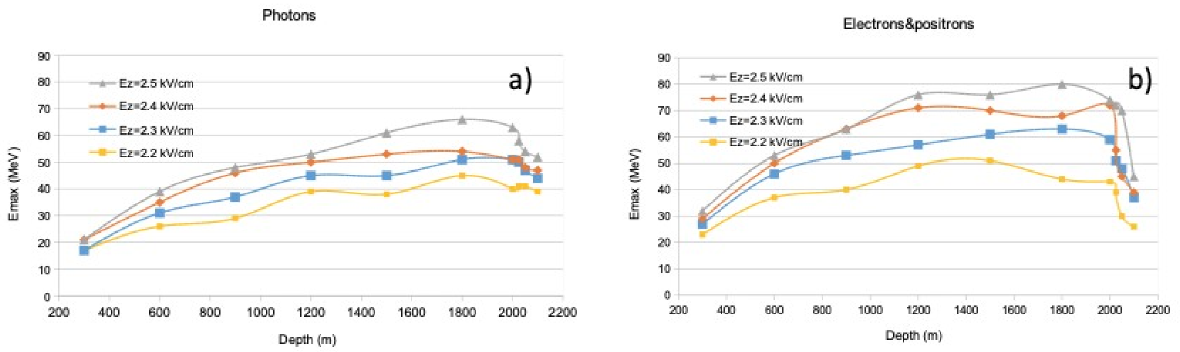

Figure 5. Maximal energies of RREA electrons and gamma rays. Avalanche started at 4656 m, 2 km above the SEVAN detector. The maximal energies of avalanche particles are calculated each 300 m. After exiting from electric field avalanche is followed additionally 100 m. The maximal energy for the RREA developing in 2.4 and 2.5 kV/m electric fields was obtained by 1000 RREA simulations, for 2.2 and 2.3 kV/m – for 10000 simulation trials.

In Picture 5 we can see that the expected maximal energies of electrons and gamma rays at Lomnicky Stit are larger than ones measured at Aragats for the largest TGEs (see Figs. 7 and 11 in [7]). Unfortunately, at Lomnicky Stit there were no particle spectrometers for direct comparison with experimental spectra. The enhancement of the count rate of the upper scintillator of the SEVAN detector at Aragats never exceeds 2 times the fair-weather count rate and the maximal energy of particles in RREA cascade was ≈50 MeV. The corresponding enhancement of SEVAN located in Slovakia exceeds the fair-weather count rate 100 times. Consequently, the maximal energy of the RREA particles can reach 80 MeV (see Fig 5b) for the observed ever largest TGE event.

Conclusions

The emergence and evolution of the intracloud electric field govern both the high-energy particle flux and lightning occurrences. The atmospheric electric field modulates charged particle fluxes enormously enhancing electron and gamma ray fluxes and depleting muon flux. The muon stopping effect [12], observed by the particle detectors at Aragats, Musala, Lomnicky Stit implicates the abrupt decline of count rate of high energy muons (at near-vertical and at inclined incidences). The muon depletion measured at Lomnicky Stit and Musala was much larger than on Aragats, therefore we expect a larger potential difference (voltage) during extreme TGEs measured in Slovakia and Bulgaria. Analyzing TGE measured in Slovakia we use the enormous enhancement of gamma ray and electron flux for revealing correspondent potential difference. The observed enhancements of gamma ray and electron fluxes were compared with CORSIKA simulations of the relativistic runaway electron avalanches and imply ≈500 MV potential difference present in the atmosphere during the minute of the highest flux (and consequently highest strength of the electric field) measured by the SEVAN detector at Lomnicky Stit on 10 June 2017.

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