Maximum strength of the atmospheric electric field

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Particle detectors of the European Space Environment Viewing and Analysis Network (SEVAN) network located on mountain peaks in Aragats (Armenia), Lomnicky Stit (Slovakia), and Musala (Bulgaria) are well suited for the detection of thunderstorm ground enhancements (TGEs). The modulation of charged particle 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. The relation between electric-field strength and changes of particle-flux count rates is nonlinear and depends on many unknown parameters of the atmospheric electric field and meteorological conditions. Nonetheless, employing tremendous TGEs as a manifestation of the strongest 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 approximately 3 km, we study the extreme strength of the atmospheric electric field. With the simulation of propagation of charged particles in a uniform electric field using the CORSIKA code, we estimate the maximum potential difference in the thunderous atmosphere, which can reach approximately 500 MV.

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I. INTRODUCTION

Understanding the maximum potential difference (voltage) inside thunderstorms is one of the fundamental problems of atmospheric physics directly connected with the enigma of the lightning initiation and electron acceleration. The history of the problem is described in Ref. [1] and references therein. In his famous paper, Dwyer derived a fundamental limit on the maximum electric field that a thundercloud can sustain [2]. When the electric field in the cloud is significantly higher than the threshold field used to initiate an electromagnetic avalanche on runaway electrons (runaway breakdown or relativistic runaway electron avalanche, RB or RREA [3]), the electron flux makes enough ionization to initiate a lightning flash. Numerous measurements on balloons, aircraft, and on mountain peaks confirm that particle fluxes are usually abruptly terminated by a lightning flash. More than 100 thunderstorm ground enhancements (TGEs) observed on Aragats were terminated by the lightning flash when the magnitude (absolute value) of the near-surface electric field (a proxy of the intracloud electric field) was sufficiently high [4,5]. Thus, the energy spectra of TGE electrons and gamma rays measured at the flux maximum just before lightning contain information on the strength of the electric field that initiates TGE and then stops it to initiate a lightning flash. We perform the simulation of the RREA process in the atmosphere to test conditions leading to maximum attainable electric fields that are directly connected to maximum particle fluxes and maximum energies of particles in RREA. However, the RREA simulation codes do not include the lightning initiation mechanism; thus, one can exceed the strength of the electric field above any real value to get billions and billions of avalanche particles, but it is not physically justified. Thus, in our comment [6] on the estimate of the atmospheric electric potential of 1.3 GV reported in Ref. [7], we mentioned that the potential within a gap of 2 km at 8–10-km altitude above sea level was highly overestimated. Any physical inference based only on data from one detector and on only one particular species of cosmic rays, and neglecting corresponding atmospheric phenomena, is highly risky.

Direct monitoring of the intracloud electric field with any spaceborne or ground-based technologies is not feasible yet; hence, we suggest using the monitoring of particle

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fluxes modulated by the electric field to estimate the attainable value of the potential drop. Measurements of the modulation of the cosmic-ray flux traversing the electrified cloud provide a new type of evidence on cloud electrification and, possibly, allow us to obtain a tighter estimate of the maximum potential difference in thunderclouds. The big advantage of our approach is the multiyear 24/7 monitoring of different species of cosmic rays available from the measurements at the high-mountain research stations. In contrast, accidental balloon flights cannot provide continuous observations of a thunderous atmosphere, and they 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 the background flux of cosmic rays up to 100 times [8]. The same field that accelerates electrons downward in the direction of the Earth will reduce the flux of muons because of the excess of positive over negative muon flux. Simultaneous monitoring of these species of secondary cosmic rays with the Space Environment Viewing and Analysis Network (SEVAN) East-European network of particle detectors [9] gives the possibility to select from the multiyear observations on Aragats in Armenia, Musala in Bulgaria, and Lomnicky Stit in Slovakia the most violent TGEs corresponding to extreme values of the electric field. Recently, we published the analysis of the 13-year largest TGE observed on Aragats on 4 October 2010 and estimated the upper boundary of maximum potential difference to be 350 MV [10]. In the present paper, analyzing the world's largest TGEs registered in Slovakia (observed at the Lomnicky Stit mountain peak on 20 June 2017 [11]) and using the CORSIKA [12] simulation of the RREA process in the strong electric field, we show that the voltage can reach 500 MV.

II. MODULE OF THE SEVAN NETWORK

A network of particle detectors known as SEVAN 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 detector allows us to estimate the solar modulation effects posed on different species of Galactic cosmic rays and fluxes of charged and neutral particles during solar energetic proton events (SEP). SEVAN modules located on mountaintops are actively used 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. Observational data from SEVAN particle detectors located on mountaintops Musala (altitude −2925 m, latitude −42°11′, longitude −23°35′) in Bulgaria,

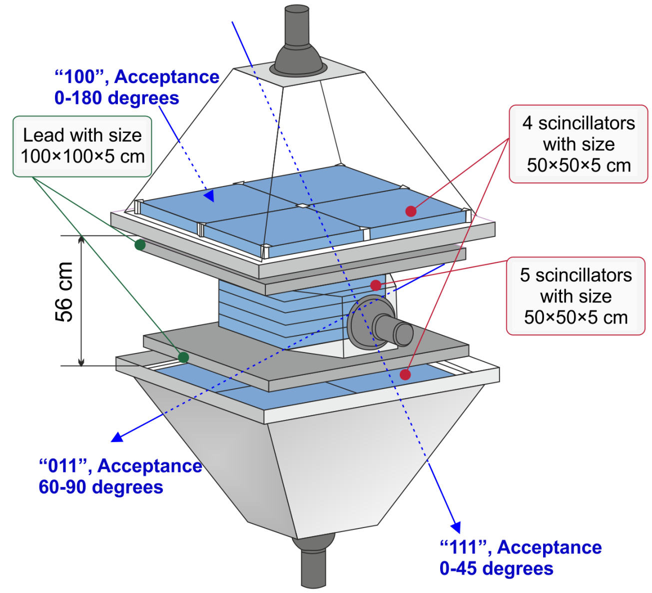

FIG. 1. Module of the European "Space Environmental Viewing and Analysis Network" (SEVAN).

and Lomnicky Stit (altitude −2634 *m*, latitude −49°12′, longitude −20°12′) in Slovakia reveal extreme TGE events. They comprise enormous enhancement of the electron and gamma-ray fluxes and a simultaneous decrease of the muon flux. In Fig. 1, we show the chart of the SEVAN detector. The detector is assembled from standard slabs of plastic scintillators of $50 \times 50 \times 5\ \mathrm{cm}^3$ size. Thick $50 \times 50 \times 20\ \mathrm{cm}^3$ scintillator assembly (5 stacked slabs) and two $100 \times 100 \times 5\ \mathrm{cm}^3$ lead filters are located between two identical assemblies of $100 \times 100 \times 5\ \mathrm{cm}^3$ scintillators (four slabs). The data streaming from the SEVAN comprise 1-min count rates (or 1-sec count rates) from three scintillator layers. All combinations of signals from detector layers are stored as well: The "100" combination means that the signal is only in the upper layer (low-energy particles); the "111" combination, that the signal comes from all three layers (high-energy muons); and the "011" combination, thenear-horizontal muons). The "010" combination selects mostly neutral particles—gamma rays and neutrons.

The purity of particle selection by SEVAN coincidences was estimated by simulations; see Fig. 4 in Ref. [9]. The purity of muon selection is rather high, about 95%, because of a 10-cm-thick lead filter between first and third scintillators. The energy threshold of the upper detector is about 7 MeV. The minimum energy of muons ("111" combination) is about 250 MeV. The efficiency to register charged particles by the upper scintillator is approximately 95%, and gamma rays, approximately 6%.

III. MEASUREMENT OF PARTICLE-FLUX COUNT RATES WITH SEVAN COINCIDENCES

The atmospheric electric field, which is especially large during violent thunderstorms, accelerates and decelerates charged particles, depending on the field direction and particle charge. The extreme TGEs occur when the electric field accelerates electrons in the direction of the Earth's surface, resulting in an enormous burst of the counts of the upper scintillator and a "100" combination of the SEVAN detector, sometimes enhancing the fair-weather count rate 100 times. Simultaneously, the same field that accelerates electrons downward causes muon-flux depletion ("111" combination) due to the excess of positively charged muons upon negative ones (the "muon stopping effect"; for a discussion and references, see Ref. [10]). More evidence of the large electric field in the thundercloud is the large depletion of the inclined trajectories, "011" combination—inclined high-energy muons traversing more distance in the electric field than vertical ones. Because of the vertical orientation of the atmospheric electric field, the TGE particle arrives at the near-vertical direction; from the near-horizontal direction, only high-energy muons can arrive, as they can traverse large distances in the atmosphere without absorption. The above modulation effects, registered by SEVAN detectors in Slovakia and Bulgaria, are shown in Figs. 2 and 3.

The extreme event was recorded in Slovakia on 10 June 2017 [11]; the enhancement of the count rate of the "100" combination during the minute 13:12–13:13 was enormous and reached 12 860% [Fig 2(a)] of the fair-weather value. This world's largest TGE reaches its maximum in one minute. The enormous, runaway, electron flux initiates a lightning flash that stops TGE. TGE was terminated by complicated multiple-stroke discharge registered by the EUCLID network at 13:14:35 [13]; 5 flashes from 7 occurred within 1-km distance from the detector.

The muon flux depletion at the same minute was 13.5% [see Fig. 2(b)], twice as large as the strongest event ever observed on Aragats on 4 October 2010 [14]. The depletion of inclined muons was much larger, 45%; see Fig. 2(c). As we can see in Figs. 2 and 3, the maximum enhancement of TGE particles coincides with the minimum of the muon flux.

A very large TGE event was recorded in Bulgaria on 20 May 2019 [15]. The shape of the event was more complicated, demonstrating three peaks in 10 minutes (due to three 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 the "100" combination during one minute, 12:41–12:42, reaches 6400% [see Fig. 3(a)] of the fair-weather value. The muon flux depletion at the same minute was 8.7% [Fig 3(b)]. The depletion of inclined muons was 20% [see Fig. 3(c)].

In Table I, for convenience, we show the mean of both 1-min and 1-sec count rates measured just before the extremely large event at Lomnicky Stit and the count rates measured at the maximum flux. As we can see from Table I, 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

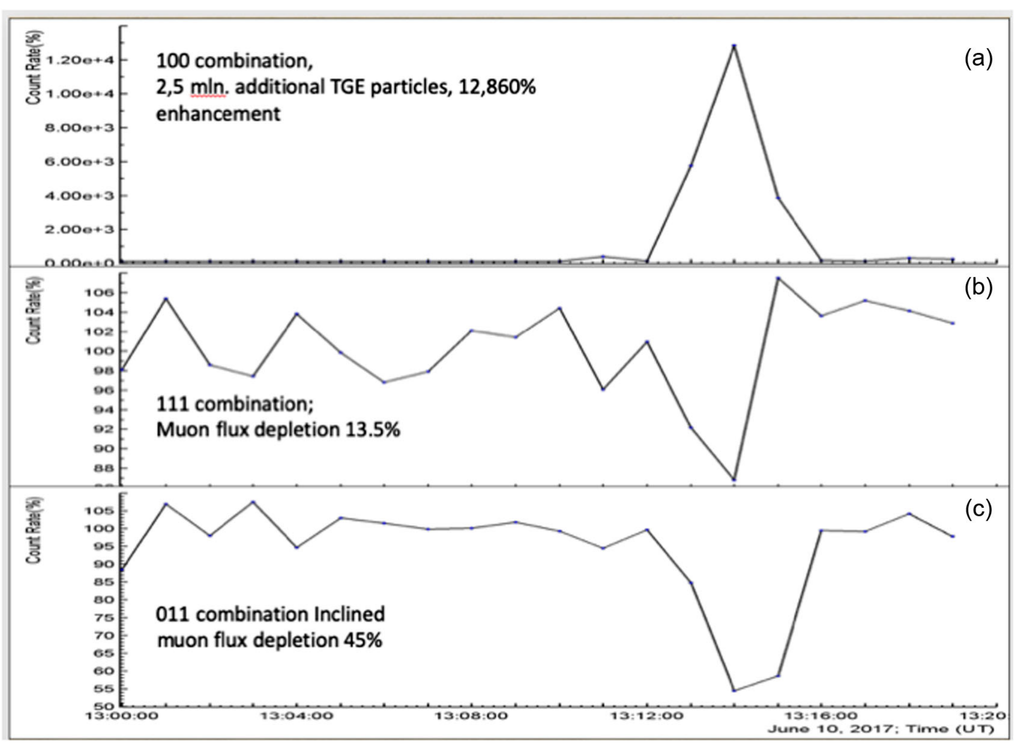

FIG. 2. Extreme TGE event detected by the SEVAN detector located on Lomnicky Stit mountain: (a)–TGE particles—electrons and gamma rays; (b) high-energy muons; (c) inclined muons.

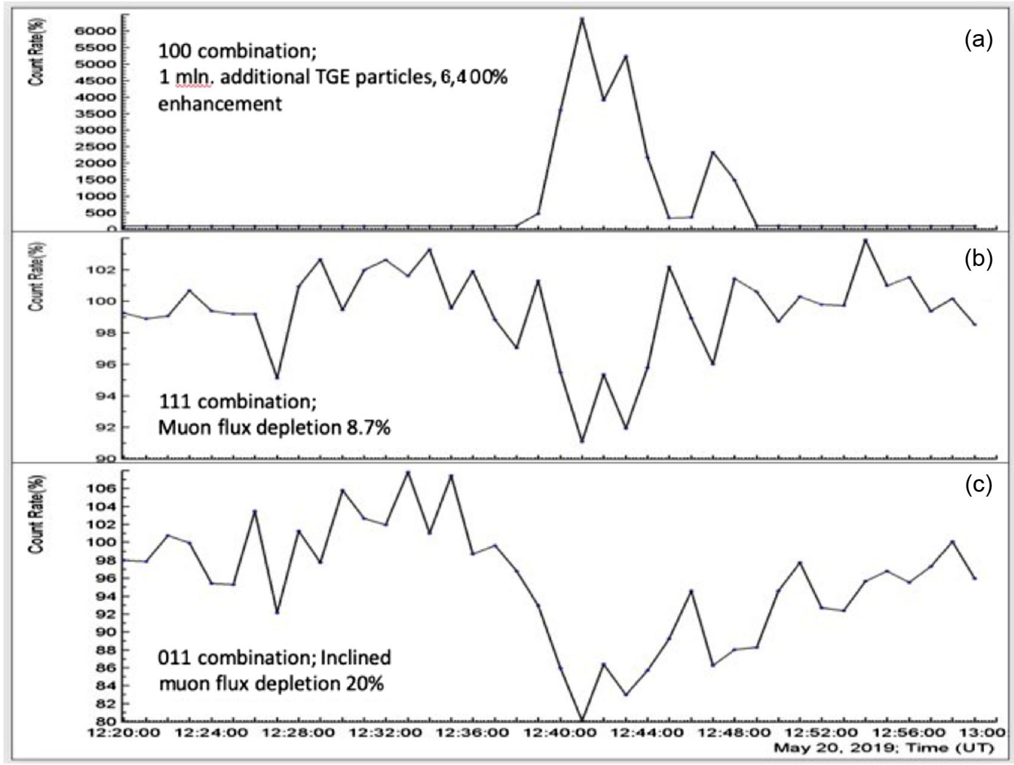

FIG. 3. Very large TGE event detected by the SEVAN detector located on Musala mountain: (a) TGE particles—electrons and gamma rays; (b) high-energy muons; (c) inclined muons.

more than 100 times (N) (last column of Table I). The enhancement of SEVAN 010 and neutron monitor (NM) counts does not reach these extreme values but is also much larger than measured on Aragats. Importantly, the large count enhancement was observed for combination "010" and NM, which indicates the detection of energetic gamma rays and neutrons [16]. A tremendous enhancement of neutron flux (140%) was measured by the neutron monitor at the same location and at the same time. Neutron-monitor evidence is very important as an independent observation and as a proof of photonuclear reactions of high-energy gamma rays born in the TGE (the previous highest flux detected by the neutron monitor on Aragats was only 5.5% [17]).

As usual, along with the enhancement of the electromagnetic component of the TGE, we register the depletion of the muon flux due to the muon-stopping effect ("111" combination, Ref. [10]).

Measured high-energy gamma-ray and neutron fluxes (combination "010") are also the largest ever measured by the particle detectors located on the Earth's surface. In Fig. 4, we compare the largest enhancements obtained in the 010 combination of SEVAN at three mountains. The enhancement observed at Lomnicky Stit (approximately 125%) is much larger than at Musala and Aragats (both approximately 15%). SEVAN's "010" combination measures neutrons and gamma rays. It is very difficult to separate fluxes because the SEVAN detector's "010" combination counts are due to gamma rays and neutrons; the neutron monitor is also sensitive to gamma rays (see discussion in Ref. [16]). To disentangle neutron and gamma-ray fluxes, we need to measure the energy spectra

TABLE I. Mean values of the count rates of particle detectors located at Lomnicky Stit and extreme values at the maximum flux minute registered on 10 June 2017.

Name	Mean 1/ min	σ	Mean 1/ sec	13:14 1/ sec	13:14 1/ min	%	N
Upper	25 047	171	417	42 233	2 534 000	10 013	101
Coincidence 111 muons	1929	48	32.2	27.8	1666	87	
Coincidence 100	19 550	142	326	42 100	2 526 000	12 890	130
Coincidence 010	1468	39	24.5	55.5	3326	25	2.7
Neutron monitor	29 640	265	494	1187	71 220	140	20

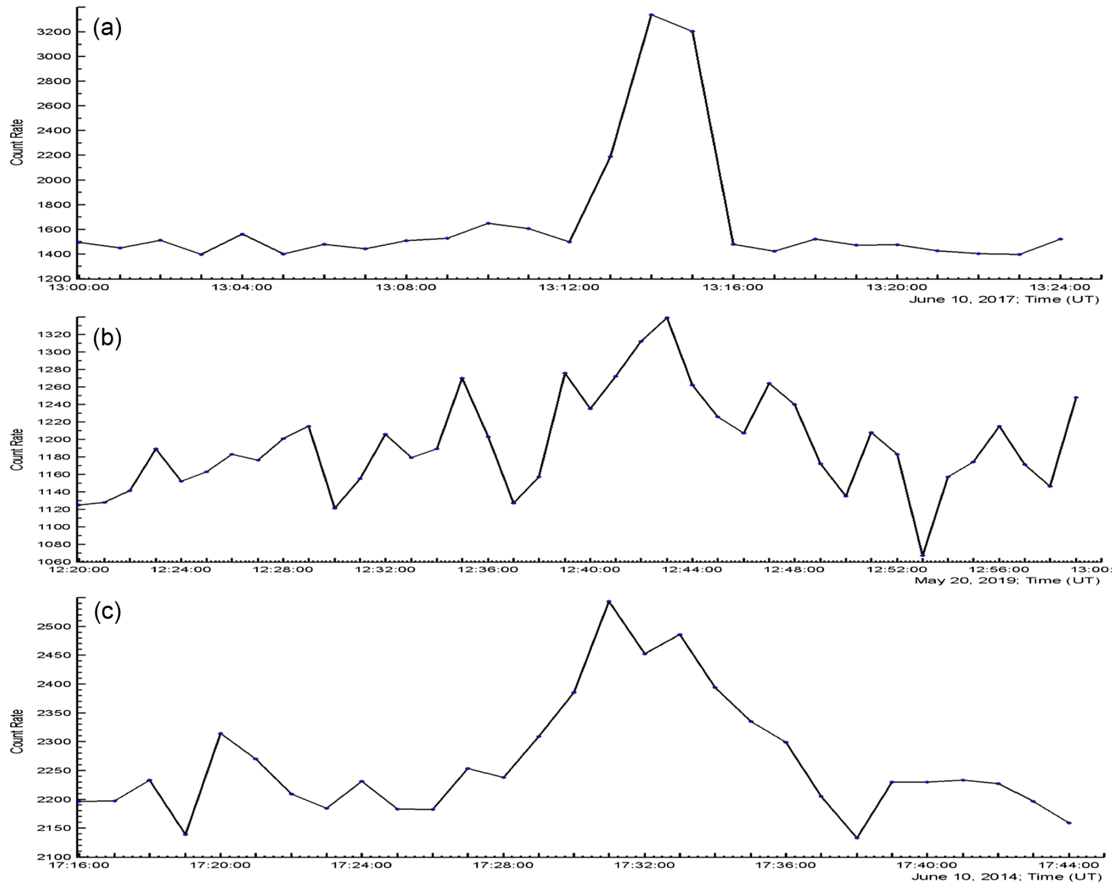

FIG. 4. Extreme TGE events detected by the SEVAN 010 combination detector located on Lomnicky Stit (a), Musala (b), and Aragats (c).

of TGE gamma rays. Unfortunately, gamma-ray spectrometers have not been installed on Lomnicky Stit yet.

IV. ESTIMATION OF THE MAXIMUM ATMOSPHERIC ELECTRIC FIELD AT LOMNICKY STIT

By measuring the maximum enhancement of particle flux at Lomnicky Stit, we estimate the atmospheric electric field that can enable such a huge RREA, which reaches the Earth's surface and generates such an enormous TGE. We recognize that the relation between the electric-field strength and TGE particle fluxes is nonlinear and depends on many unknown parameters of the atmospheric electric field and meteorological conditions (structure of charged layers, the height of the cloud, wind speed, etc.). However, extremely large-particle fluxes measured by the SEVAN detector allow us to obtain a reasonable estimate of the maximum electric field, choosing the appropriate field strength and its spatial extent from a number of alternatives obtained in the simulation trials. CORSIKA version 7.7400 [18], which takes into account the effect of the electric field on the transport of particles, was used in the simulations. As already demonstrated in our previous simulations [19] with CORSIKA and GEANT4 codes [20], the multiplication and acceleration of seed electrons, namely, the RREA process [3], is a threshold process, and avalanches start when the atmospheric electric field reaches the critical value that depends on the air density. The extent of the electric field should also be sufficiently large to ensure avalanche development. The simulation of the RREA was done within heights of 2.6–4.6 km where the uniform electric field was introduced with strength exceeding the runaway breakdown threshold by 10%–40%. Uniformity of the electric field extending 2 km leads to the change of the surplus to critical energies at different heights according to a particular air-density value. Thus, the 2.4 kV at a height of 4.6 km is approximately 32% larger than the critical energy, and at a height of 2.6 km, it is only approximately 15% larger. At the exit from the electric field, the electromagnetic avalanche continued propagation over 400 m in the dense air above the detector before registration.

To avoid contamination of high-energy gamma rays generated by the modification of electron energy spectra (MOS; see details in Ref. [21]), simulations were performed with vertical beams of 1-MeV electrons (seed particles for the RREA). The MOS process generated high-energy bremsstrahlung gamma rays from high-energy electrons of the ambient population of cosmic rays which can artificially enlarge the maximal energy achievable in the RREA. Simulation trials included 10000 events for the electric-field strengths 1.8–2.3 kV/cm and 1000 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, as well as the number of electrons and gamma rays (normalized to one seed electron) calculated every 300 m in the electric field, and at distances 50, 100, 200, and 400 m after exiting from it [see Figs. 5(a) and 5(b)]. In Figs. 5 and 6 and Table II, the number of electrons and gamma rays was integrated from 7 MeV to be compared with the SEVAN upper scintillator count rate (energy threshold of approximately 7 MeV). We can see from the figures that for large electric-field strengths, the number of electrons exceeds the number of gamma rays; however, after the exit from the electric field, and the electron flux rapidly attenuates [see Fig. 5(b)], and at 100 m below the electric field, the number of gamma rays exceeds the number of electrons by an order of magnitude.

To estimate the number of expected counts of the SEVAN detector for different electric-field configurations, we need to know the number of seed electrons entering the electric-field region. Using the well-known energy spectrum of the secondary cosmic-ray electrons (obtained from the calculator EXPACS [22]), we integrate the number of cosmic-ray electrons at a height of 4600 m from 1 to 300 MeV and obtain 455/m^2 sec. Proceeding from this number and taking into account the efficiencies of particle registration in the upper scintillator of the SEVAN detector (≈95% for electrons and ≈6% for gamma rays), we obtain the expected number of counts for the different configurations of the electric field. We show, in the first three columns of Table II, the number of particles per one seed electron to be registered by the upper SEVAN scintillator, and in the last column, for all 455 seed electrons incident on 1 m^2 per second at a height of 4600 m. In the last row of Table II, we show the number of TGE particles measured by the upper scintillator of SEVAN at 13:14 UTC.

The count rate of the upper detector of SEVAN was 42,223 (see Table I); from simulations, we estimate the

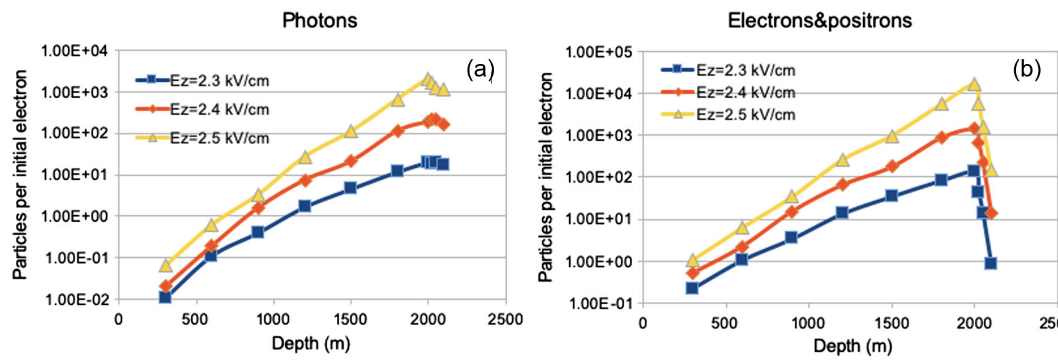

FIG. 5. Development of the electromagnetic avalanche in the atmosphere. The avalanche started at 4600 m, 2 km above the SEVAN detector. The number of avalanche particles is calculated each 300 m. After exiting from the electric field, the avalanche is followed an additional 100 m.

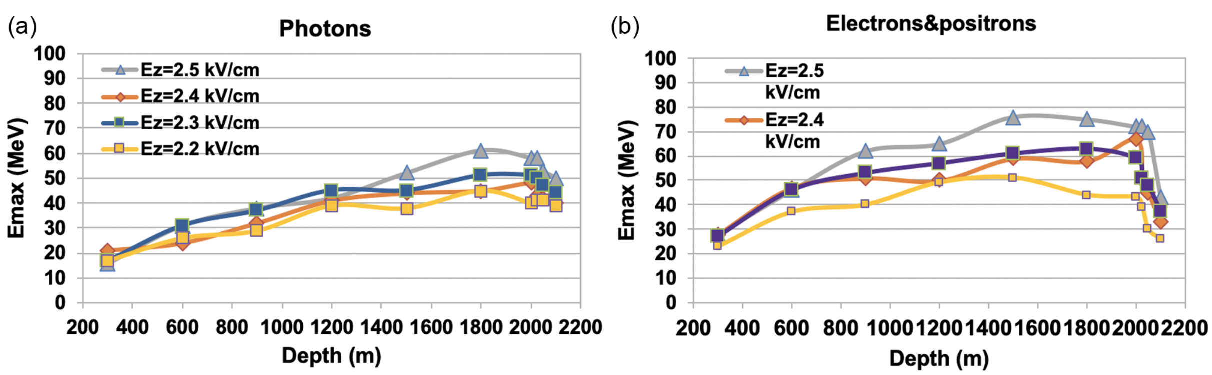

FIG. 6. Maximum energies of RREA electrons and gamma rays. The avalanche started at 4600 m, 2 km above the SEVAN detector. The maximum energies of the avalanche particles are calculated each 300 m. After exiting from the electric field, the avalanche is followed an additional 400 m. Simulations were performed with a fixed energy of seed particles (1 MeV) to avoid large gamma-ray energies due to MOS and not the RREA process.

TABLE II. Simulated count rates in the upper scintillator of the SEVAN detector for different configurations of the atmospheric electric field.

	Electron counts $/\mathrm{m}^2$ sec	Gamma − ray counts $/\mathrm{m}^2$ sec	Sum el.+ gamma $/\mathrm{m}^2$ sec	Total expected counts (x 455)
2.4 kV/cm 50 m	175	13	188	85,540
2.4 kV/cm 100 m	11	10	21	9555
2.5 kV/cm 50 m	1268	76	1344	611,520
2.5 kV/cm 100 m	119	68	187	85,085
SEVAN L.S. 10.6.2017 upper				42,223

expected count rate of approximately 85,000 for 2.4 kV/cm if the electric field terminated at 50 m above the Earth's surface, and, for 2.5 kV/cm, if the electric field terminated at 100 m above the Earth's surface. We cannot establish a one-to-one relation between the electric-field strength and the expected count rate because of the uncertainty in the extent the electric-field accelerated electrons downward. Nonetheless, the information from Fig. 5 and Table II allows us to limit the maximum electric field by 2.5 kV/m (a conservative estimate assuming the termination of the electric field at the height of 100 m above the Earth's surface). The number of electrons increases very fast when the electric-field strength increases above 2.4 kV/cm, and the lightning flash will inevitably stop further multiplication of electrons in the RREA avalanches. It is well known that RREAs might limit thunderstorm electric fields [23]. In Ref. [24], ten electric-field soundings were selected (from sensors located at balloons) near lightning initiation locations. For all cases, the electric field exceeds the runaway breakdown threshold by factors of 1.1–3.3 in the few seconds before the flash. The RREA above Lomnicky Stit was also terminated by the lightning flash, as well as numerous large TGEs observed at Aragats [5]. We made many simplifications in the simulation trials, and we are still very far from expecting exact numerical coincidences. However, the huge enhancement of the obtained count rate with the increase of the electric-field value from 2.4 to 2.5 kV/cm allows us to conclude that for the world's largest TGE measured at Lomnicky Stit, the electric field does not reach 2.5 kV/cm; consequently, the potential difference in the atmosphere is not larger than 500 MV. Numerous other simulations with lower strengths of the electric field produce 10–100 times fewer particles reaching the SEVAN detector (see Fig. 5).

In Fig. 6, we show another characteristic of the RREA energy spectra, namely, the maximum energy of particles reached in the RREA development. This parameter does not depend on the absolute calibration of the seed particle spectrum.

In Fig. 6, we can see that the maximum energies of electrons and gamma rays at Lomnicky Stit obtained from simulations are approximately 30% larger than the ones measured at Aragats for the largest TGEs (see Figs. 7 and 11 in Ref. [10]). 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 exceeded 2 times the fair-weather count rate, and the maximum energy of particles in the RREA cascade was approximately 50 MeV. The corresponding enhancement of SEVAN located in Slovakia exceeded the fair-weather count rate 100 times. Consequently, the maximum energy of the RREA particles can reach 80 MeV [see Fig. 5(b)] for the largest TGE event ever observed.

V. POSSIBLE SYSTEMATIC ERRORS DUE TO ASSUMPTIONS IN THE SIMULATIONS

The strengths and spatial extent of the electric field, the cloud height, and the seed electron energy spectrum assumed in the simulation, although in overall agreement with *in situ* measurements, can significantly deviate from the conditions of the particular thunderstorm, which give rise to the detected TGE event. Therefore, the energy spectra obtained in simulation trials provide only an overall understanding of the dependence of particle yield and maximum energy on the intracloud electric-field parameters. However, the dependence of RREA on the critical energy, avalanche development in the atmosphere, and the muon stopping effect is well reproduced in the simulations. We plan to develop a more realistic RREA model, which also includes positrons as seed particles and energies from 1 to 300 MeV for seed particles initiating the runaway avalanche in the thunderous atmosphere. Also, we plan to introduce a gradient in the vertical electric-field profile instead of a uniform electric field.

We also made some assumptions on the cloud height at Lomnicky Stit. The staff there explained that clouds are usually very low above detectors; therefore, we continue simulation of avalanche development an additional 50 and 100 meters before reaching the detector. The assumption of a 2-km-long electric-field region is justified by a very large depletion of the muon flux (both vertical and inclined), which is an indicator of an extended electric field above the detector, and it emphasizes that this TGE can be used for the estimation of the maximum electric field in the thundercloud.

We consider, measure, and show count rates of all combinations of the SEVAN detector and compare them with similar parameters of SEVAN operated at Aragats. We use this information to reveal the uniqueness of the TGE considered for the maximum field estimation and to demonstrate the universality of the "stopping muon" effect. For comparison with simulation and for the estimation of the maximum potential drop, we use counts of the upper layer of SEVAN. The sum of the TGE gamma-ray and electron flux, measured by the upper layer of SEVAN, is directly related to RREA simulations, in which we follow the number of electrons and gamma rays every 300 m and also after exiting from the electric field.

VI. CONCLUSIONS

We confirm that TGE observations are frequent and routine not only on Aragats (where approximately 95% of the published TGE world collection is observed) but also on other mountaintops where thunderclouds are near to the Earth's surface. The characteristics of measured particle fluxes, electric fields, and lightning occurrences confirm the physical effects connected with TGE origination. At a sharp mountaintop at Lomnicky Stit, the electric field reaches larger strengths, and enhancements of count rates are much bigger. The muon stopping effect [10], first observed by the particle detectors at Aragats, was also detected at Lomnicky Stit with a much "deeper" decline of the count rate of high-energy muons. Both the muon depletion measured at Lomnicky Stit and a much larger enhancement of the low-energy electron and gamma-ray flux than on Aragats led to a larger potential difference (voltage) during extreme TGEs, derived from the comparison with simulation trials. The observed enhancements of gamma-ray and electron fluxes measured by the upper scintillator of SEVAN as compared with CORSIKA simulations of the RREA imply the maximum ≈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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