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Thunderstorm ground enhancements—Model and relation to lightning flashes

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ABSTRACT

In the beginning of last century C.T.R. Wilson proposed that strong electric field of the thunderclouds might accelerate electrons to very high energies. However, this and many other electromagnetic processes in our atmosphere are poorly understood till now; the key questions about the thundercloud electrification and lightning initiation remain unanswered. During recent decades several observations of gamma ray, electron and neutron fluxes correlated with thunderstorms were reported. Nonetheless, the origin of these fluxes is under debate till now. The direct registration of the particle showers initiated by the runaway electrons (the most popular theory) was missing. We present the experimental evidence of the microsecond duration electron bursts originated from runaway electrons accelerated in thunderclouds. The electron acceleration downward becomes possible after creation of the Lower Positive Charged Region below the main negative charged layer in the middle of the thundercloud. Our analysis is based on the vast thunderstorm data from the Aragats Mountain in Armenia, 3200 m above sea level. Varieties of particle detectors located at Aragats Space Environmental Center are registering neutral and charged particle fluxes correlated with thunderstorms, so-called Thunderstorm Ground Enhancements. Simultaneously the electric mills and lightning detectors are monitoring the near-surface electric field and lightning flashes. In the paper we present the model of TGE initiation. We demonstrate the necessity of the Lower positive charge region development for the lower dipole operation and TGE initiation. Our observations establish direct relationship of the negative electric field strength and rain rate with TGE.

1. Introduction

One of the first particle physicists and researchers of the atmospheric electricity Nobel award winner sir C.T.R. Wilson in the beginning of last century recognized that “the occurrence of exceptional electron encounters has no important effect in preventing the acquisition of large kinetic energy by particles in a strong accelerating field” (Wilson, 1925a). It was the first publication introducing an enigmatic physical phenomenon of electron acceleration by the strong electric fields in thunderclouds called “runaway” electrons by the astronomer Eddington (1926).

Of course, in 1925 the particle cascade theory was not yet established, 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: “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” (Wilson, 1925a) and “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” (Wilson, 1925b). However, that is not possible, due to abundant radiation losses of electrons with energies greater than 50 MeV traversing the atmosphere. The first measured runaway electron spectrum in thunderstorm ground enhancements faded around 50 MeV (Chilingarian et al., 2010). The potential difference as large as 10^9 V also seems to be not feasible according to direct measurements of the intracloud electric fields with the balloon experiments (Stolzenburg and Marshall, 2008).

The first model of the structure of the electric field in thunderclouds anticipates a dipole between negative charged layer in the middle of the thundercloud and positive layer on the top. This, so called, main negative dipole[1] accelerated electrons upward. Wilson wrote: “In the central dipole region, where the downward-directed electric field is greatest, the electrons are accelerated upward to the positive layer but once above the positive layer, their motions are retarded by the electrostatic field

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[1] We adopt the “atmospheric electricity” sign convention: the positive field (E kV/m) accelerates electrons downward in the direction of the Earth; the negative field (−E kV/m) vice-versa accelerates electrons upward in the direction of space.

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and their trajectories bend downward again (Wilsons notebooks, cited by Williams (2009)) and "Fast beta rays can then reach the atmosphere or be bent around by magnetic field to reach Earth at varying distances according to energy and initial directions" (letter to B.F.J. Schonland, cited by Williams (2009)).

The more realistic tripole structure of the thundercloud electric field introducing the short leaving Lower positive charged region (LPCR) below the main negative was established only recently and till now its origin is not fully understood. The LPCR on the base of cloud with middle negatively charged layer constitute lower negatively charged dipole, which accelerates electrons downwards. Electrons accelerated by the lower dipole produce, so-called, thunderstorm ground enhancements—TGEs, intense fluxes of electrons, gamma radiation and secondary neutrons (Chilingarian et al., 2011). The idea of Wilson that accelerated electrons can reach the atmosphere find proof after launching of the orbiting gamma ray observatories. Numerous terrestrial gamma flashes (TGFs) are routinely observed at $\sim$500 km above Earth in correlation with strong equatorial thunderstorms (Fishman et al., 1994). The origin of TGFs is believed to be the electrons accelerated by the upper dipole as Wilson suggested in 1925.

The first attempts to observe the runaway electrons on the earth surface were carried out by Wilson's co-workers Schonland, Viljoen and Halliday in South Africa with the cloud chambers. However, due to low sensitivity of cloud chambers to low energy gamma rays (the majority of particles reaching the earth surface from the electron–photon avalanches unleashed by runaway electrons in the thunderclouds are gamma rays) the results of these experiments were discouraging. Looking for the electrons with energies up to 5 GeV incident to the earth surface following the force lines of geomagnetic field surely could not give a positive outcome (see Halliday, 1941). The observation of the runaway electron phenomena turns to be rather difficult. "In summary and as introduction to the present set of experiments, after 70 years of repeated theoretical and experimental investigations, it is still not clear whether or not the runaway electron acceleration mechanisms operates in a significant manner in either thunderstorms or lightning" (Suszcynsky et al., 1996). In last 2 decades there was significant progress in detection of the particles (mostly gamma rays) from thunderclouds (Parks et al., 1981; McCarthy and Parks, 1985; Aglietta et al., 1989; Eack et al., 2000; Brunetti et al., 2000; Alexeenko et al., 2002; Torii et al., 2002; Tsuchiya et al., 2007). However, till now there are numerous unsolved problems concern complicated TGE phenomena. Some of these problems, i.e., the model of TGE; the nature of emerging LPCR; TGE relation to atmospheric discharges will be presented and discussed in the paper.

2. Research made on Aragats Space Environmental Center (ASEC)

Cosmic Ray Division (CRD) of the A. Alikhanyan National lab (Yerevan Physics Institute) during recent 20 years commissioned and operated on the research station Aragats and Nor Amberd numerous particle detectors uninterruptedly registering fluxes of charged and neutral cosmic rays. The main topic of research was physics of the high-energy cosmic rays accelerated in our Galaxy and beyond. Surface arrays consisting of hundreds of plastic scintillator were measuring Extensive air showers (EASs), the cascades of particles born in interactions of primary high-energy proton or fully stripped nuclei with atoms of terrestrial atmosphere. Aragats physicists investigate the, so-called, knee region, where energy spectrum of protons and nuclei suddenly change the spectral index from -2.7 to -3. A new developed method of distinguishing between showers initiated by primary particles lead to possibility of measuring partial spectra and the exploration of the particle acceleration mechanism by the shock waves in vicinity of exploding super-novae stars. MAKET-ANI experiment proves very sharp knee in light nuclei energy spectrum at energies of 2–3 PeV and absence of knee in heavy nuclei energy spectrum up to 20 PeV (Chilingarian et al., 2004). This finding of charge dependent position of the knee was later confirmed by the KASCADE experiment (Antoni et al., 2005).

After finishing EAS experiments on Aragats was started a new excited topic—Solar physics and Space Weather. The neutron monitors located at 3200 and 2000 m and numerous new particle detectors measuring charged and neutral components of secondary cosmic rays making Aragats one of the largest centers for researching of solar-terrestrial connections. During 23-rd solar activity cycle were measured many important Solar energetic events, including largest series of GLEs (Ground level enhancements) and Forbush decreases in November 2003 (so-called Halloween events) and discovery of the highest energy solar protons at 20 January 2005 (Chilingarian, 2009). Culmination of the solar physics research was creation of the SEVAN (Space Environmental Viewing and Analysis Network) a network of particle detectors located at middle and low latitudes, which aims to improve fundamental research of space weather conditions and to provide short and long-term forecasts of dangerous consequences of space storms (Chilingarian and Reymers, 2008). The SEVAN network consists of hybrid detectors registering charged and neutral components of secondary cosmic rays. The network detects changing fluxes of different species of secondary cosmic rays at different altitudes, longitudes and latitudes, thus turning into a powerful integrated device used to explore solar modulation effects.

Starting from 2008 during very quiet 24-th solar activity cycle the CRD turns to investigations of the high-energy phenomena in the atmosphere. Existing and new designed particle detectors and unique geographical location of Aragats station allow to observe in 5 years more than 300 particle bursts, which were called TGEs—thunderstorm ground enhancements. TGEs observed on Aragats are not only gamma rays, but also sizable enhancements of electrons (Chilingarian et al., 2013b) and rarely also neutrons, usually lasting 10 min or more. Aragats physicists enlarge the possibilities for TGE research by coherent detection of the electrical and geomagnetic fields, rain rate, temperature, relative humidity and other meteorological parameters, as well as by detection of the lightning. Adopted multivariate approach of investigations allows connecting different fluxes, fields and lightning occurrences and finally establishing comprehensive model of the TGE.

The same approach allows unambiguously proving the existence of the neutron fluxes linked to the TGEs and well correlated with the gamma ray fluxes. The mechanism of the neutron generation by the photonuclear reaction of the gamma rays born in thunderclouds was suggested in Babich and Roussel-Dupré (2007) and observed at Aragats during the strongest TGEs (Chilingarian et al., 2012a). A new realistic simulation of the RREA process in the thunderstorm atmosphere helps to clarify contribution of the direct gamma ray production in a lead absorber to the Neutron monitor counts (NM, Tsuchiya et al., 2012). At any offset of the "emitting region" relative to the detector location the "direct neutron production" quickly diminished and the "atmospheric" neutron contribution enlarged (Chilingarian et al., 2012b). Therefore, both photonuclear processes in the air and in the lead absorber of NM should be considered to explain the neutron fluxes correlated with thunderstorms.

3. Extensive cloud showers—Experimental proof of the runaway process

Gurevich et al. (1992) developed a theory of the runaway process. They showed that when Møller scattering (electron–electron elastic scattering) is included, the runaway electrons described by Wilson will 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. Further development of the theoretic knowledge on the runaway process continued with intensive implementation of the Monte Carlo simulation. Sophisticated codes was used to model the propagation of energetic electrons in electric field; codes include energy losses from ionization and atomic excitation, Møller scattering and angular diffusion from elastic scattering with atomic nuclei and other (Lehtinen et al., 1999; Babich et al., 2001; Dwyer, 2003, 2007).

Recently the CERN based GEANT 4 code (Agnsotelli et al., 2003) is widely used for study of the propagation of the runaway electron avalanches in the atmosphere (Carlson et al., 2010; Chilingarian et al., 2012c). It is interesting to note that the runaway process is naturally embedded from the GEANT4 simulations: when you switch on appropriate electrical field and use incident cosmic ray electron flux as seeds; the electrons gain energy from field, knock-out atomic electrons and cascade process unleashed; it is another proof that simulation is a creative tool to discover new physical phenomena. The initial name of the cascade released by the runaway electron—the Runaway breakdown (RB, given by Gurevich et al. (1992)), pointed on the relation with lightning occurrence (not proven yet), is recently often replaced by the term RREA (Relativistic Runaway electron avalanches) without any relation to discharge process.

The first observation of the avalanches initiated by the runaway electrons was made at Aragats in 2009 (Chilingarian et al., 2010, 2011). An array of 16 plastic scintillators (Fig. 1, see details of experimental facility in Chilingarian et al. (2004)) was used for detection of extended atmospheric particle showers.

If signals from the first 8 scintillators covering $\sim 400\,\mathrm{m}^2$ area coincide within the trigger window time of 400 ns the amplitudes of all photomultiplier signals (proportional to the number of particles hitting each scintillator) are stored. At fair weather the surface array registered EASes initiated by the primary protons with energies above $\sim$50 TeV ($\sim$25 EAS per minute, 8-fold coincidences) and 100 TeV ($\sim$8 EAS per minute, 16-fold coincidences).

In Fig. 2 we demonstrate the detection of the largest TGE ever measured at Aragats. The significance of detection at energies above 7 MeV exceeds 350σ. Measuring electron flux with different thresholds allows recovering for the first time the electron integral energy spectrum (see details in Chilingarian et al. (2010)).

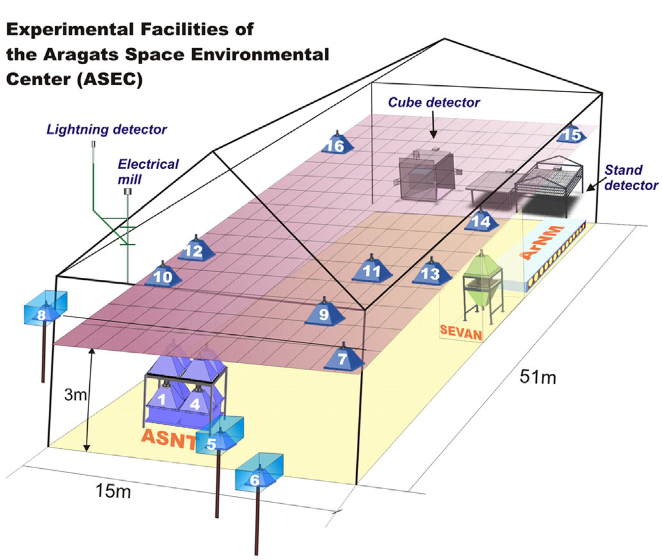

Fig. 1. Experimental facilities of the ASEC; 5 cm thick and 1 m^2 area plastic scintillators belonging to the MAKET surface array are denoted by numbers from 1 to 16. On the roof of building are located Electrical mill EFM 100 and lightning detector LD-250 of BOLTEK firm.

The time series of the surface array triggers also demonstrate huge enhancement, see Fig. 3. During 7 min of the TGE $\sim$200 additional triggers were registers; the count rate at 22:47, 19 September 2009 was enhanced $\sim$8 times for the 16-fold coincidences and 5 times for the 8-fold coincidences.

The minute of the maximal count of triggers coincides with maximal flux of particles registered by other detectors sensitive to electrons, gamma rays and neutrons. The statistical analysis of detected showers reveals their systematic difference from the EAS events (see for details Chilingarian et al. (2011)): the density of shower particles hitting the scintillators was much lower and spatial spread was much more uniform (spatial distributions of the EASes has characteristic bell-like form). Therefore, the showers of electrons and gamma rays from the thunderclouds constitute different from EAS physical phenomena —extensive cloud showers (ECSs, Chilingarian and Hovsepyan (2013)). ECS phenomenon is very rare: only 3 TGEs from 300 observed were accompanied by ECSes. ECSes originated from individual runaway electrons accelerated in the cloud just above the detector. Duration of ECS is expected to be very short: the arrival time of the shower particles from the thundercloud located not higher than few hundreds of meters above the detector could not be large. We do not measure shower particle arrival on microsecond scale; however the statistical analysis of particle second-by-second distribution within the minutes of maximal flux allows estimating the upper limit of ECS duration to be 50 ms (see for details Chilingarian et al. (2011)).

Like multiple EASs from the primary cosmic rays are sustaining stable flux of secondary cosmic rays, multiple ECSes provide transient enhancement of the TGEs lasting minutes. ECS phenomenon is very local and depends on the height of cloud above detector and on the strength of electric field in it. Both parameters are fast changing and only during several minutes cascades from runaway electrons can develope enough to cover several thousand square meters of surface. Only very suitable location and large sizes of the scintillators allow detecting ECSes on Aragats and for the first time directly proving existence of RREA phenomena.

The variety of particle detectors on Aragats allows also measuring the integral spectrum of TGE electrons and differential energy spectrum of gamma rays up to 100 MeV (before the gamma ray energy spectrum was measured only till 20 MeV). The energy spectra of the electrons have an exponential shape and extend up to 40–50 MeV. Recovered energy spectra of the gamma rays are power law and extend up to 100 MeV.

Prolonged up to 100 MeV gamma ray spectrum also was obtained by gamma ray observatory onboard of AGILE satellite (Tavani et al., 2011). Summed over 130 events fluence spectrum does not exhibit the exponential decay at 50–60 MeV as expected from the "pure" RREA mechanism.

Energy spectra of largest TGE events detected in 2009 and 2010 were recovered by the solving inverse problem of cosmic rays—fitting trial energy spectra by simulating the energy response of 60 cm thick plastic scintillator (see details in Chilingarian et al. (2012c)). After installing the network of large NaI crystals in 2011 the energy spectra of gamma rays were measured directly (Chilingarian et al., 2013).

Maximal flux of gamma rays exceeds background of secondary cosmic rays by $\sim$1000% in the energy range of 2–20 MeV and by 1–10% in the energy range up to 100 MeV. Very large enhancements can be explained only by invoking the RREA process. Ambient population of secondary cosmic ray electrons in the electric fields with strength greater than the critical value unleashes the electron-gamma ray avalanches and total number of particles on the exit from cloud can be multiplied by several orders of magnitude. A GEANT4 simulation helps to estimate characteristics of the thunderclouds

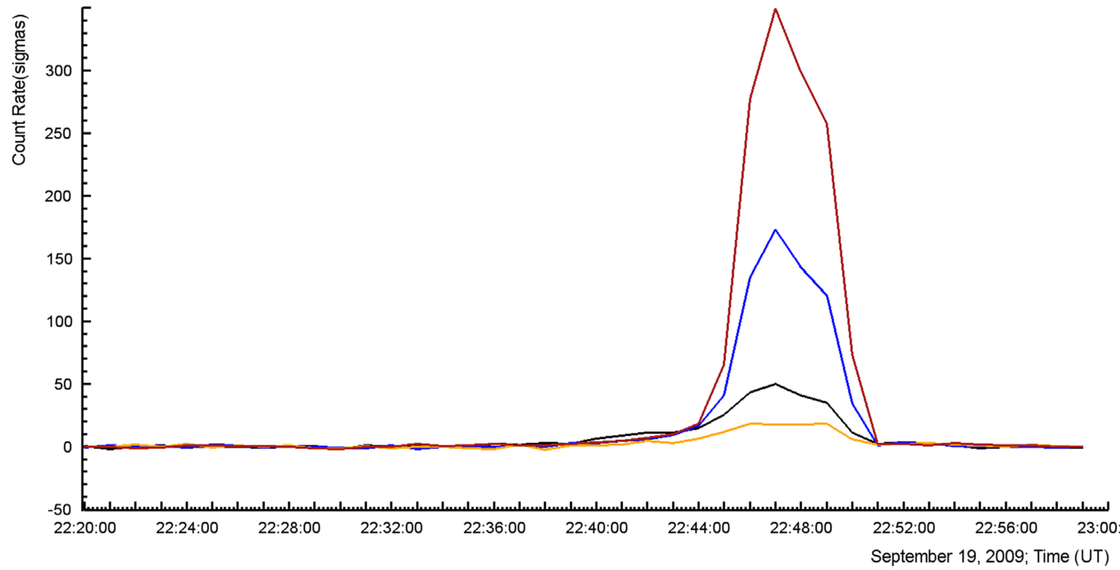

Fig. 2. The enhancements of ASEC detectors measured on 19 September 2009 (the maximum of flux at 22:47 UT) in numbers of standard deviations (number of σ). The 1 m^2 area 5 cm thick outdoor and indoor plastic scintillators measure electron flux with energies above 7 and 10 MeV (2 upper curves); the same type plastic scintillators of SEVAN – with energies larger that 15 MeV (next curve) and coincidence of 5 and 60 cm scintillators of ASNT – with energies above 30 MeV (lowest curve). Corresponding significance of peaks are 350, 170, 50 and 20 standard deviation.

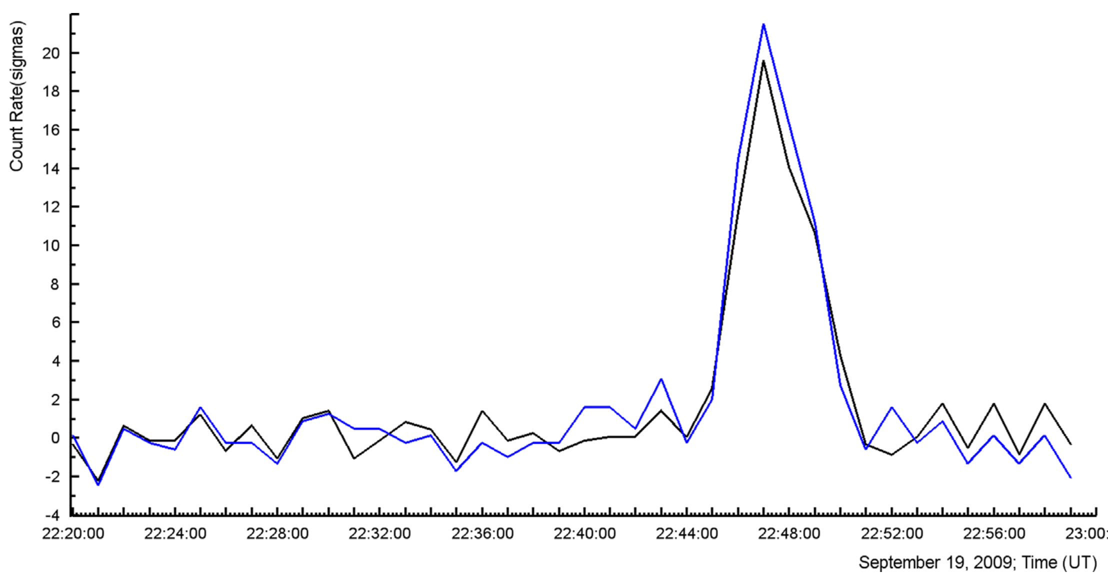

Fig. 3. Largest TGE event occurred on 19 September 2009; Minute time series of the triggers of MAKET surface array (16-fold – upper curve – and 8-fold – lower curve – coincidences).

responsible for TGE initiation (the strength of the electrical field and potential drop in the thundercloud, height of thundercloud above detector site). Estimated values of 1.8 kV/cm with elongation of 1–1.5 km and cloud height of 50–150 m for largest events are in good agreement with available measurements (Torii et al., 2011; Tsuchiya et al., 2011). However, the energy spectrum of gamma rays prolonged up to 100 MeV cannot be explained in the framework of the RREA process, as for assumed realistic parameters of the thundercloud maximal energy of the runaway electrons does not exceed 40–50 MeV. GEANT4 simulations demonstrate that these high-energy photons can be explained by the Modification of the energy Spectra (MOS) of charged particles in the electric field of thunderclouds (Muraki et al., 2004; Dorman and Dorman, 2005). The CR relativistic electrons entering prolonged electric field in thundercloud live longer and radiate more gamma rays thus enlarging the gamma ray flux from the thundercloud. The strength of the electric field not necessarily should exceed the RREA initiation threshold. MOS process has no threshold and amplitude of TGE events may be very small if field is weak or/and its elongation is short (see statistics of TGE events in Chilingarian et al. (2013a)).

4. The model of TGE; TGE amplitude and near-surface electric field

During milliards years of its evolution Earth was bombarded by the protons and fully striped ions accelerated in Galaxy in tremendous explosions of the supernovas and by other exotic stellar sources. This flux was changed during the passage of sun through the four galactic arms in its course around the center of Galaxy and, may be, was affected several times by huge explosions of nearby stars. Nonetheless, on the shorter time scales the galactic cosmic ray flux is rather stable. High-energy protons and fully stripped nuclei entering the terrestrial atmosphere and colliding

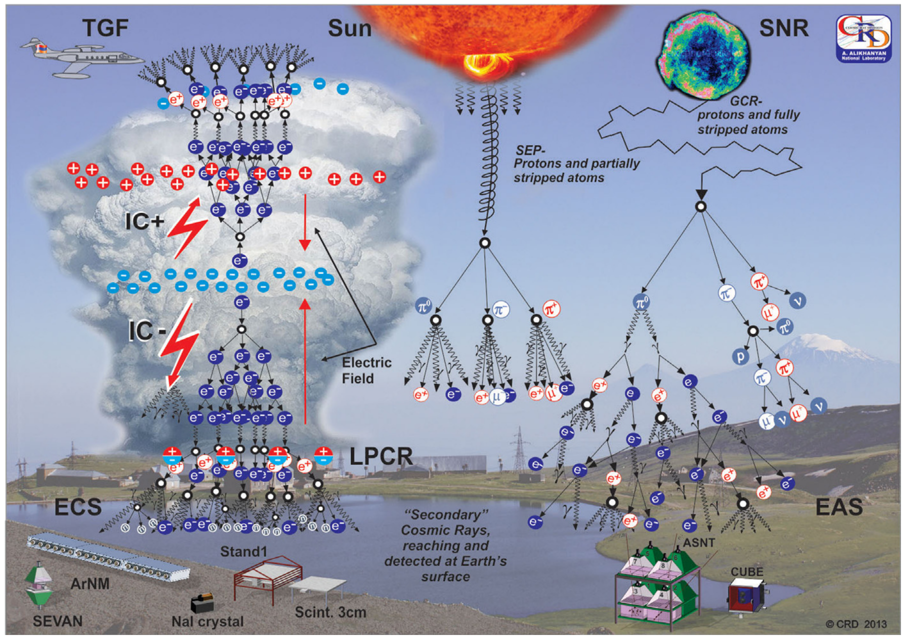

Fig. 4. Sources of the secondary cosmic rays detected on the Earth's surface.

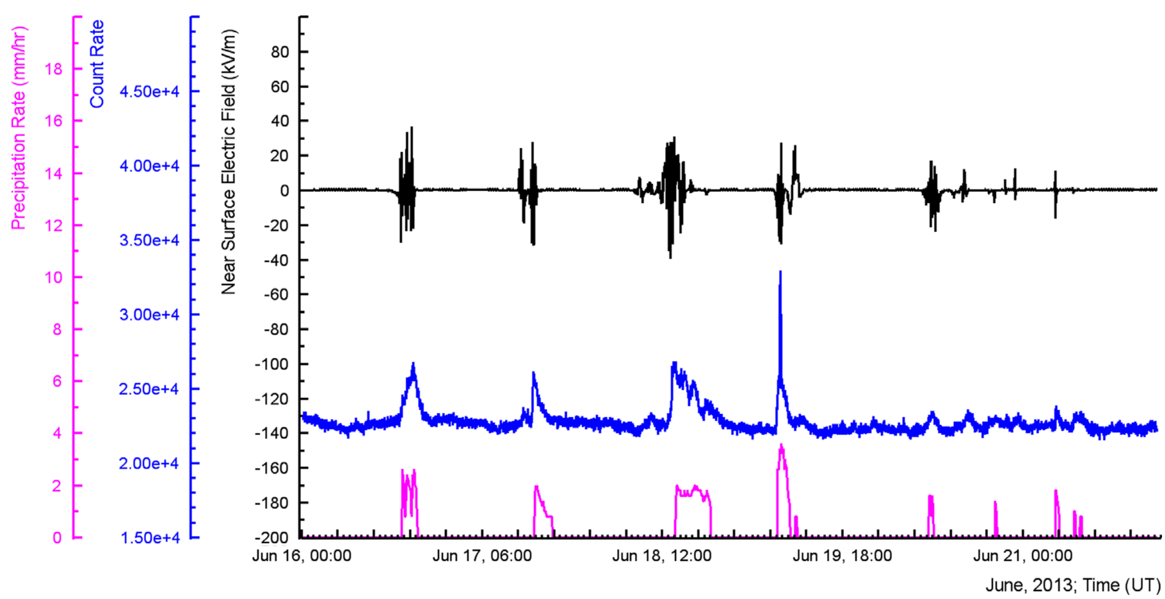

Fig. 5. Time series of the rain rate (bottom); time series of the count rate of outdoor plastic scintillator with energy threshold 1.5 MeV (middle); time series of the disturbances of near surface electric field. (Time series of numerous particle detectors, field meters and weather stations are available from the site of Cosmic ray division of Yerevan physics institute http://crd.yerphi.am).

with nitrogen and oxygen atoms generate extensive air showers—cascades of particles developing in atmosphere comprising secondary cosmic rays, see right side of Fig. 4.

Sun influences earth in different ways by emission of radiation, plasma clouds and high-energy particles and ions. Although the overall energy fraction of the high-energy particles is very small compared with visible light energy, nonetheless, on several occasions' solar particles if energetic enough can generate cascades contaminating stable flux of the secondary comic rays initiated by galactic primaries. Influence of sun on the secondary cosmic ray flux can be described as modulation of the stable cosmic ray "background" by the sun activity. The most energetic in the solar system flaring process releases up to 10^{33} erg of energy during few minutes. Along with broadband electromagnetic radiation the explosive flaring process results in ejection of huge amounts of solar plasma and in acceleration of the copious electrons and ions (so called solar energetic phenomena —SEP). Particles can be generated either directly in the coronal flare site with subsequent escape into interplanetary space, or they can be accelerated in the shocks that propagate through corona and interplanetary space (Aschwanden, 2004). These particles, along with neutrons, produced by protons and ions within the flare, constitute Solar cosmic rays (SCR). Only few of SEP events (usually not more than a dozen during solar activity cycle of $\sim$1 years) can be detected by surface monitors, see middle sketch in Fig. 4. Such events comprise, so called Ground Level Enhancement (GLE).

Another, newly discovered phenomenon modulated flux of secondary cosmic rays is the high-energy phenomena in thunderclouds. The identified drivers of the TGE are the Relativistic runaway electron

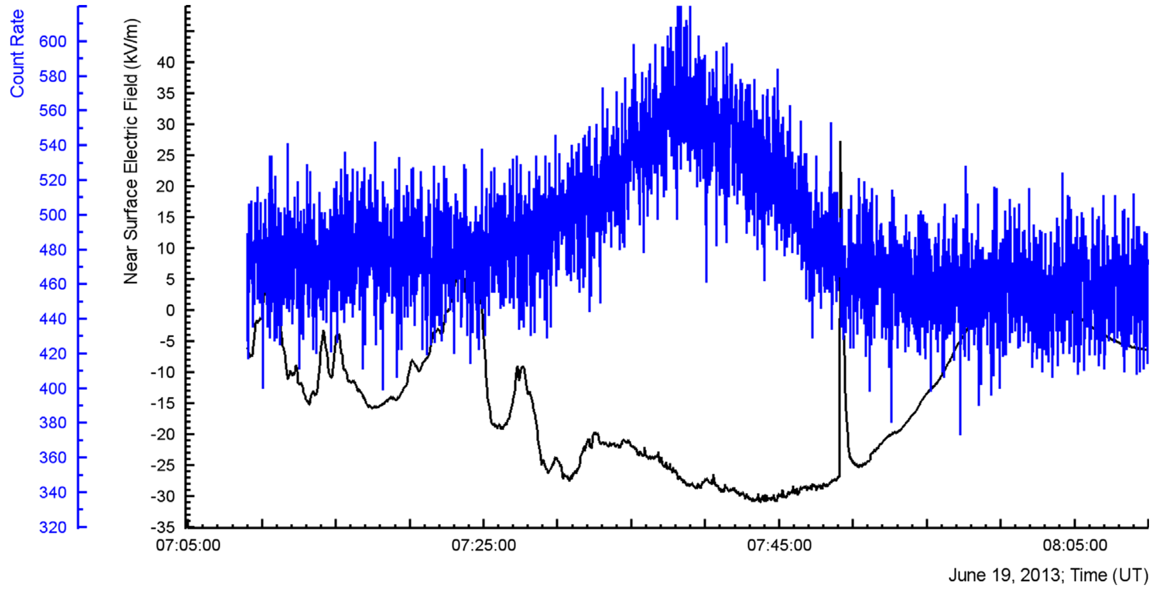

Fig. 6. The 2013 largest TGE of 19 June. Prolonged negative electric field initiates large TGE measured by 1-s time series of 3 cm thick outdoor scintillator.

avalanches (RREA) and Modification of energy spectra (MOS) processes (Chilingarian et al.,, 2012c).

The Lower positive charge region (LPCR, see left bottom of Fig. 4) with main negative layer in the middle of the cloud forms lower dipole, responsible for the downward electron acceleration and TGE origination. Many researchers outline the dominant role that LCPR plays in initiating/triggering an intracloud and cloud-to-ground lightning discharges (Pawar and Kamra, 2004; Nag and Rakov, 2009; Qie et al., 2005, 2009). The size of LPCR is much smaller than the size of the main negative charge layer. The transient character of LPCR can explain the duration of the TGE. LPCR's are short-lived because, being composed of precipitation, they fall out of the cloud and carry their charge to the ground (Holden et al., 1980). As one can see in Fig. 5, the all TGEs observed in June 2013 was accompanied by rain.

Rain started during TGE in progress and after it stops TGE fast declines. The TGE amplitude is approximately proportional to the rain rate.[2] Consequently, we can deduce that charge is resided on the rain droplets. The positive and negative ions can be separated in the droplet under the action of the ambient electric field, thus forming two residual stretched charged clusters (Gurevich and Karashtin, 2013, see left bottom side of Fig. 4). Therefore, the upper part of droplet forms with main negative layer of the thundercloud the lower dipole accelerated electrons downward; and the negatively charged bottom of the droplet is responsible for the large negative near surface electric field measured by the EFM-100 electrical mill.[3] The TGE amplitude should be proportional to the total positive charge in LPCR; and, therefore—to the amount of rain droplets (water) in the bottom of cloud. An estimate of amount of water in cloud is the rain rate. For the TGEs on June 20–21 (right side of Fig. 5) the charge accumulated in the droplets was not sufficient to provide strong electric field to unleash RREA process and we detect only modest enhancements of particle fluxes due to MOS process. On June 16–19 the rain rate was sufficient to stipulate large and prolonged TGEs. Zooming Fig. 5 we can investigate each TGE in more details. In Fig. 6 we post the 2013 largest TGE of 19 June.

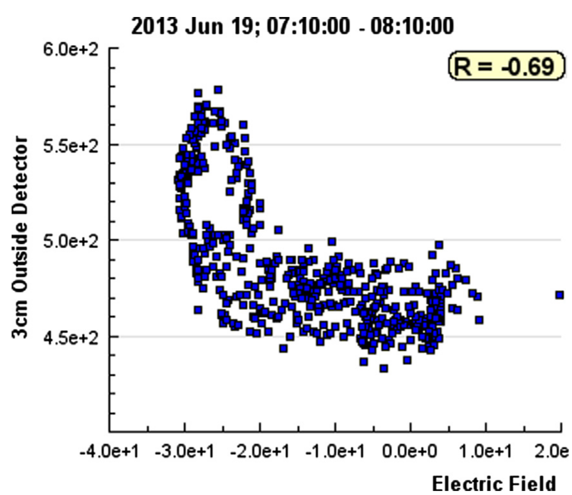

Fig. 7. The scatter plot of particle flux and near surface electric.

As we can see in Fig. 6 as electric field dipping to negative domain at ~7:25 the particle flux gradually enhanced, peaking at 7:36 when near surface electric field get the value of −30 kV/m. Rain consequently washed out the LPCR and particle flux started to decay, fully stopping at 7:50.

In Fig. 7 we can see the typical for the large TGEs pattern showing inverse dependence of the particle flux on near surface electric field strength. Apparent anti-correlation of 2 variables can be explained by enhancement of the positive charge of LPCR (resided on the rain droplets) and consecutive increase of negative charge (resided on the bottom of droplets and measured by the field mills located on Earth's surface). The larger is electric field of lower dipole—more electrons are accelerated and unleashing avalanches and more boost get TGE.

5. TGEs and lightning occurrences

TGE particle flux was often accompanied with intracloud lightning occurrences (IC−) and suppression of cloud-to-ground lightning occurrences (CG−). This structure of lightning occurrences supports creation of developed lower positive charge region as a fundamental

[2] Measured by Professional Davis Instruments Vantage Pro2, http://www.davisnet.com/.

[3] Boltek firm electrical mill EFM100, measurement accuracy 5%, http://www.boltek.com/efm100.html.

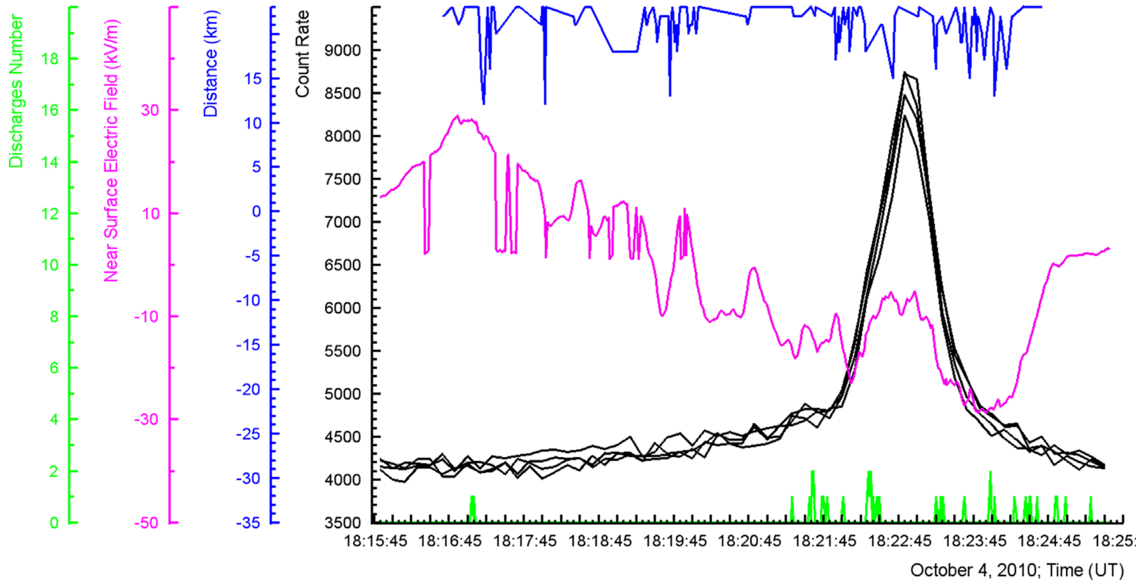

Fig. 8. The large TGE of October 4, 2010 measured by 41 m^2 area scintillators; electric field, distance to lightning and lightning occurrences registered by EFM 100 and Srorm tracker.

condition of TGE origination (Chilingarian and Mkrtchyan, 2012). Large fluxes of electrons and gamma rays detected on the Earth's surface are only possible when LPCR is well developed and, consequently, lower dipole is accelerated electrons downward. Lower dipole as well can initiate negative intraclaud lightning[4]; however TGEs and lightning are not obligatory correlated. Simultaneous measurements of the particle fluxes, electrical field disturbances and lightning occurrences at Aragats in the seasons of 2011–2013 do not give any evidence on causative relation of lightning occurrences to TGEs.

Lightning flashes are detected by 2 devices both produced by Boltek company. The electrical mill EFM-100 traced short-range (30 km) lightning flashes by the abrupt change of the near surface electrical field monitored by electric mill (only CG, cloud-to-ground lightnings are registered by EFM-100). Boltek's StormTracker[5] for each lightning stroke analyzes a signal waveform in real time. The discrimination between IC and CG is based on the shape and amplitude of the waveform, i.e., the rise and decline times. The direction is determined by looking at the magnetic field ratios for each stroke. The initial distance is determined by looking at the signal strength.

In Fig. 8 we present the large TGE event of 4 October 2010. The TGE amplitude measured by the four identic 1 m^2, 5 cm thick plastic scintillators belonged to ASNT detectors reached 150%. The duration of the TGE peak on the half-maximum (FDHM) was only 40 s, from 18:22:25 till 18:23:05. Lightning activity was modest during this event. In 5 km range Storm Tracker detects 12 IC− lightning flashes at 18:21:20–18:22:30; 8 IC− lightnings at 18:23:15–18:25:15; 2 IC+ lightning flashes at 18:24–18:25:20 and CG− lightning flash at 18:24:51 and CG± at 18:25:35. Only 1 lightning flash was detecting during FDHM of TGE. Distance to cloud-ground lighting flashes measured by EFM-100 was rather far —above 12 km.[6]

We do not expect that lightning flashes on the distances larger than 10 km can influence TGE. Based on the detection of the winter thunderstorms Tsuchiya et al. (2011) estimate the radii of the circle of intense RREA radiation to be 600 m. Another Japanese group (Torii et al., 2011) detects moving at the speed of 7 m/s energetic radiation source at the height of 300 m; the radiation was emitted from a downward hemispherical surface with radii of 700 m. Intracloud lightning flashes also are too rare to explain minutes long TGE.

Additionally, hundreds of nearby intracloud discharges and numerous cloud-to-ground lightning flashes was registered during the same thunderstorm at 22:00–22:10, October 4, 2010. Nonetheless, this very strong lightning activity was not accompanied by any significant enhancement of particle flux as it is demonstrated in Fig. 9.

From discussed above TGE event we may deduce that a causative relation does not connect large particle fluxes and lightning occurrences. Reported correlation of lightning signals and TGFs can be induced by the one and the same origin of TGFs and lightnings—strong electric fields in the thundercloud. Recently FERMI group infers that the detected VLF signals are from the relativistic electron avalanches that are responsible for the flash of gamma rays rather than are related to intracloud lightning (Connaughton et al., 2013). However, as we can see in Fig. 8 after the maximum of the particle flux enhancement on the stage of LPCR decaying few discharges occurred. Therefore, we cannot reject that the high-energy TGE electrons may create a conductive channel and "assist" lightning flashes to occur. The opposite hypothesis that lightning discharges themselves produce the observed particle flux seem not reasonable because the rise of TGE started far before the lightning occurrences.

6. Conclusion

Early in the last century Wilson made ingenious predictions, which still represent the frontiers of the new field of high-energy atmospheric physics (Dwyer et al., 2012a; Williams, 2010); some of them are still under debate. For instance: "By its accelerating action on particles the electric field of a thundercloud may produce extremely penetrating corpuscular radiation and this

[4] Large LPCR prevents negative CG− flashes from occurrence because abundant lower positive charges make an IC− discharge with negative charge region preferable, see for instance Qie et al., 2009.

[5] Boltek's stormTracker lightning detection system, powered by the software from Astrogenic systems, http://www.boltek.com/stormtracker.

[6] The EFM-100 detects near lightning flashes much more precise than Storm Tracker. Therefore, if any discrepancy on short distances EFM-100 detection is preferable.

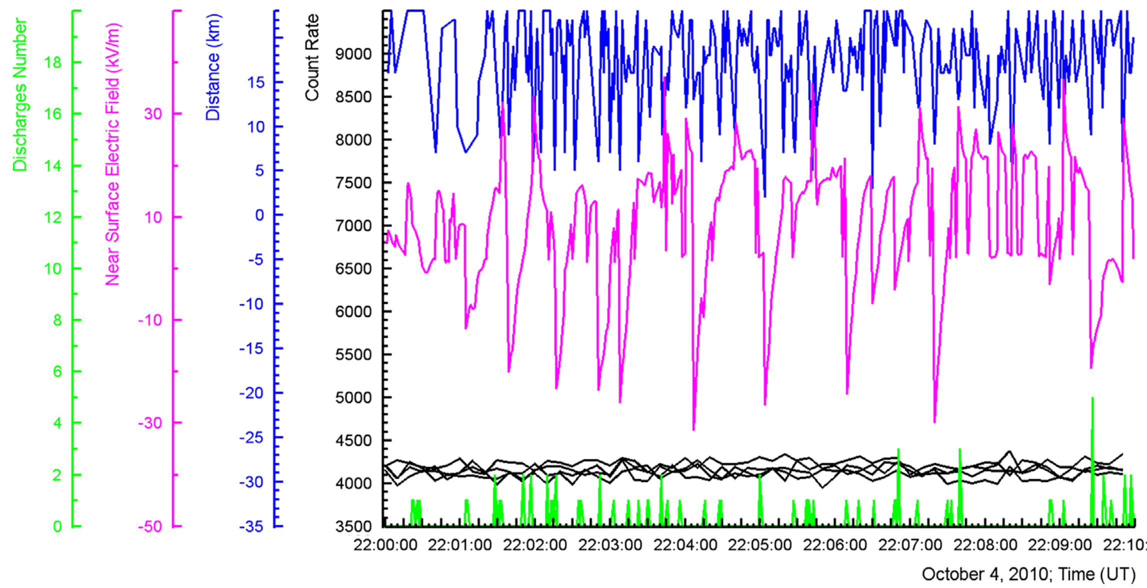

Fig. 9. Huge thunderstorm on October 4, 2010 along with electric field disturbances and lightning occurrences; no significant TGE is detected.

may occur even when there is no thunder" (Wilson, 1925b). This statement concerns one of the hottest topics of the modern research. Are the particles from the clouds due to electric field only (Torii et al., 2011; Chilingarian and Mkrtchyan, 2012) or lightning occurrence is mandatory for emerging particle fluxes (Gurevich et al., 2012)?

Our observations support first hypothesis. Although lightning itself can produce electrons and gamma rays (Dwyer et al., 2012b), the TGE observations prove that lightning is not necessary condition for the particle fluxes initiation. Residing on the rain droplets in the bottom of thundercloud LPCR with main negatively charged layer form a lower dipole. Electrical field of lower dipole effectively transfer field energy to electrons; electrons generate gamma rays and gamma rates by photonuclear reaction born neutrons. Runaway electrons generate secondary electron bursts of microsecond duration; overall duration of TGE is usually ~10 min and more; during tens of minutes large amount of short bursts happen. Large TGEs occur during large negative near surface electric field. Amplitude of TGE is proportional to the absolute value of the electric field strength. Atmospheric discharges and TGEs are competitive processes and at maximal TGE flux usually no discharges are detected. However, ECSes provide ionization of atmosphere continuously on the minute time-scale and intracloud negative lightning (IC−) may use the conductive path opened by multiple ECSs. Only when the LPCR is degraded the lightning leader can propagate till the earth surface and classical negative cloud-to-ground lightning flashes (CG−) can occur.

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