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Lightning origination and thunderstorm ground enhancements terminated by the lightning flash

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Abstract – Proceeding from the measurements of the lightning occurrences, slow and fast electric-field disturbances, particle flux enhancements and their abrupt terminations, we formulate a lightning origination model. Registration of the extensive air shower simultaneously with lightning detection allows us to propose a solution to the long-standing problem of its role in the lightning initiation. Our analysis is based on the numerous Thunderstorm Ground Enhancements detected in 2012–2014 at Mt. Aragats in Armenia.

Introduction. – The problem of how lightning is initiated inside thunderclouds is not only one of the biggest unsolved problems in lightning physics, it is also probably one of the biggest mysteries in the atmospheric sciences [1]. The relationship between thundercloud electrification, lightning activity, wide-band radio emission and particle fluxes has not been yet unambiguously established. One of the most intriguing opportunities opened by the observation of the high-energy processes in the atmosphere [2] is their relation to lightning initiation. The basic charge structure of a thundercloud can be viewed as a vertical tripole consisting of three charge centers (regions), the main positive region at the top, the main negative region in the middle, and a transient lower positively charged region (LPCR) below the main negative one. Thus a positive field extends from the LPCR in the cloud base up to the main negative-charge region in the middle of the cloud, and it is transformed into a negative field that extends to the main positive-charge region on the top of the thundercloud. Consequently, the lower dipole accelerates electrons of the ambient population of secondary cosmic rays downward in the direction of the Earth and the upper dipole accelerates electrons in the direction of the open space. Wilson postulated the acceleration of the electrons in the strong electric fields inside thunderclouds in 1924 [3]. In 1992 Gurevich *et al.* [4] developed the theory of the runaway breakdown, now mostly referred to as relativistic runaway electron avalanches (RREA, [5]). The separation of positive and negative charges in the thundercloud and the existence of a stable ambient population of the MeV electrons (secondary cosmic rays) in the atmosphere enables the acceleration of the electrons in the direction of the Earth's surface (thunderstorm ground enhancements, TGEs, [6,7]) and to open space (terrestrial gamma flashes, TGFs, [8]. Recent measurements of the TGEs shed light on the size of the particle-emitting region [9,10], energy spectra of electrons [11] and gamma rays [12]. The vast amount of TGE events registered by facilities of the Aragats space environmental center (ASEC, [13]) at an altitude of 3200 m in 2009–2014 allows us to develop a comprehensive model of TGE initiation [14]. The energy of accelerated electrons can reach ∼40–50 MeV and gamma rays 100 MeV. The flux of electron and gamma rays with energies above few MeV registered on the Earth's surface can exceed the cosmic-ray background up to 20 times.

TGEs are often associated with the negative polarity of the near-surface electric field [15] and with the suppression of the cloud-to-ground lightnings [7,9,10].

When the LPCR is vertically deeper and has a large horizontal extent, a descending negative leader would likely change its direction of propagation to predominantly horizontal; consequently the negative cloud-to-ground (−CG) lightnings will be suppressed and mostly negative intracloud (−IC) lightning will occur [16]. TGFs are believed to be generated during thunderstorms by the upper dipole and are associated with the initiation of the strong positive intracloud (+IC) lightning (see discussion in [17]). Thus, both TGEs and TGFs precede the lightning activity and can be used for the research of poorly understood lightning initiation processes, providing a new research tool —the flux of elementary particles originated in the thunderclouds. Information acquired from the time series of TGEs and TGFs along with the widely used information on the temporal patterns of the radio emission waveforms will help to develop a reliable model of lightning initiation. Copiously measured during thunderstorms bipolar pulses known as preliminary breakdown (PB) pulse trains are thought to be an intra-cloud process that initiates or leads to the initiation of the stepped leader [18]. Nag and Rakov [16] claim that it is likely that the PB pulse trains provide a manifestation of the interaction of a downward-extending negative current with the LPCR; *i.e.* the pulse train occurs when a descending negative leader encounters a LPCR. Another indication of the LPCR existence is the enhanced particle flux detected on the Earth's surface —thunderstorm ground enhancement (TGE). The temporal pattern of the TGE, lightning and PB pulse train provide a unique information on the processes of the lightning initiation.

We select several TGE events detected in 2012–2014 by the ASEC facilities, which were terminated by the cloud-to-ground (CG) lightning flash. The measurements include one-second and one-minute time series of the elementary-particle count rates, gamma-ray energy spectra, meteorological conditions, fast and slow disturbances of near-surface electric field and others. Simultaneous registration of these parameters allows us to investigate their causal relation to lightning initiation.

Instrumentation. – The new emerging field of high-energy physics in the atmosphere involves measuring as many parameters as possible, such as particle fluxes, electric-field disturbances, radio emissions from the thunderclouds, and meteorological environments.

TGEs analyzed in the present study were observed by 3 cm thick scintillators with a sensitive area of $1\,m^2$ operated in the particle counter mode. The light collection is implemented by 84 spectrum-shifter fibers with a diameter of 1 mm. Light from the scintillator is re-radiated by the optical spectrum-shifter fibers to the long-wavelength region and passed to the FEU-115M photomultiplier. The scintillator is manufactured by injection molding in the form of $120 \times 100 \times 5\,mm^3$ dimensions plate with grooves for the spectrum-shifter fibers. The maximum of luminescence is at $\sim$420 nm and the luminescence time is 2.3 ns. The registration efficiency is $\sim$99% for electrons and $\sim$5% for gamma rays, the energy threshold is $\sim$1 MeV.

Extensive air showers are registered by the Aragats Solar Neutron Telescope (ASNT), see details in [6]. The ASNT consists of 4 upper (5 cm thick) and 4 lower (60 cm thick) scintillators, each having an area of $1\,m^2$. The distance between the layers is 1.2 m. All scintillators are located in iron lightproof housings and are overviewed by the FEU-49 photomultipliers. The data acquisition system registers all coincidences of the detector signals from the upper and lower layers and energy releases (number of particles) in the lower 60 cm thick scintillators. The signals ranging from 0.5 mV to 5 V, from each of the 8 photomultipliers, are passed to the programmable threshold discriminators. The output signals are fed in parallel to the 8-channel logical OR gate triggering device and to a buffer. The ASNT trigger condition is defined by detecting at least one signal in the 8 data channels. The duration of the entire data readout and the signal processing procedure is less than 10 μs.

A 52 cm diameter circular flat-plate antenna followed by a passive integrator is used to record the fast electric-field waveforms. The output of the integrator is directly connected to a 8-bit digitizing oscilloscope (Picoscope 3206) with a 60 cm long RG58 coaxial cable. The sampling rate is 10 ns, and record duration 5 ms, including 1 ms pre-trigger time. The recording system has a frequency bandwidth of 16 Hz–50 MHz and is triggered by a signal from a commercial MFJ-1022 active whip antenna that covers a frequency range from 300 kHz to 200 MHz.

The static electric field between the thunderclouds and the ground and the distance to the nearby lightning are measured with the EFM-100 electric-field mills of the Boltek company installed on the roofs of the buildings where the particle detectors are located. The electrical-field measurements are taken 20 times per second. The electric-field mill detects the net charge directly above in the atmosphere; the sensitivity range extends up to $\sim$30 km. Comparisons of measurements made by the network of three identical EFM-100 electrical mills prove reliability and rather high accuracy ($\sim$20%) of near-surface electric-field estimation.

Simultaneous detection of the lightnings and enhanced particle fluxes. – Amid numerous TGEs detected by the ASEC facilities (see statistical analysis of the TGEs observed on Aragats in [19]) we select those abruptly terminated by the lightning analogical to the selection reported in [20]. Duration of TGE usually lasts from a minute to ten minutes with rather flat beginning and slow decay. However, in some cases smooth changes of the particle flux are sharply terminated by the lightning, see figs. 1 and 2.

Lightning very rarely occurs in the beginning of TGE (left side of fig. 1(b)) and at the maximum of TGE (fig. 1(c)). Usually, lightning terminates particle flux at the declining phase of TGE, when LPCR is dissipating due to the movement of the cloud or fading of the electric field in the cloud (fig. 1(a); right side of fig. 1(b); fig. 1(d); and fig. 2).

Table 1 contains the essential parameters of the selected TGEs. In the first column, we list the date of the event, in the second the time of the TGE maximum and relative amplitude (importance) of the particle flux peak in percent of the fair weather value and in number of standard deviations (p-value). In the third column we list the full width at half-maximum (FWHM) of the TGE. In the fourth–sixth columns we list the times of the lightning

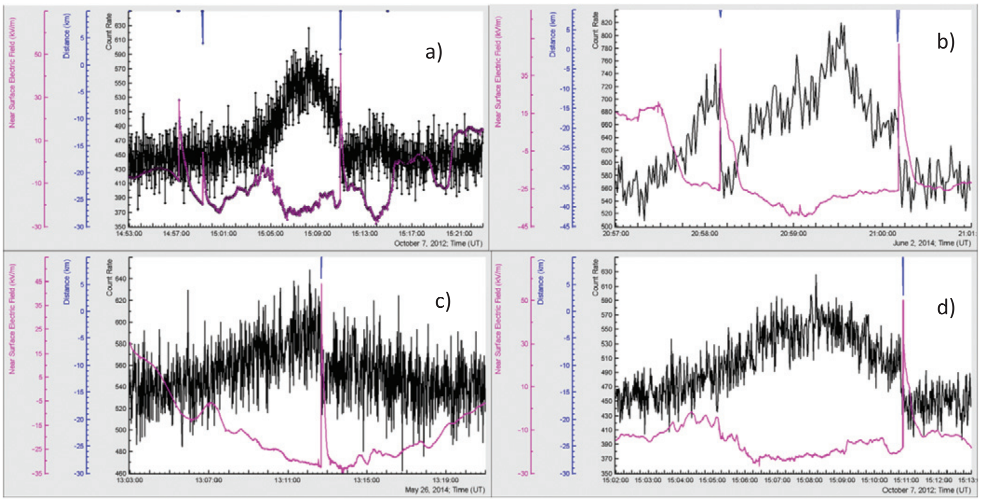

Fig. 1: (Colour on-line) Time series of the 1 second count rates of the outdoor 3 cm thick scintillator sharply terminated by the lightning and disturbances of the near-surface electric field; in the top of figures the distance to lightning from particle detectors is shown.

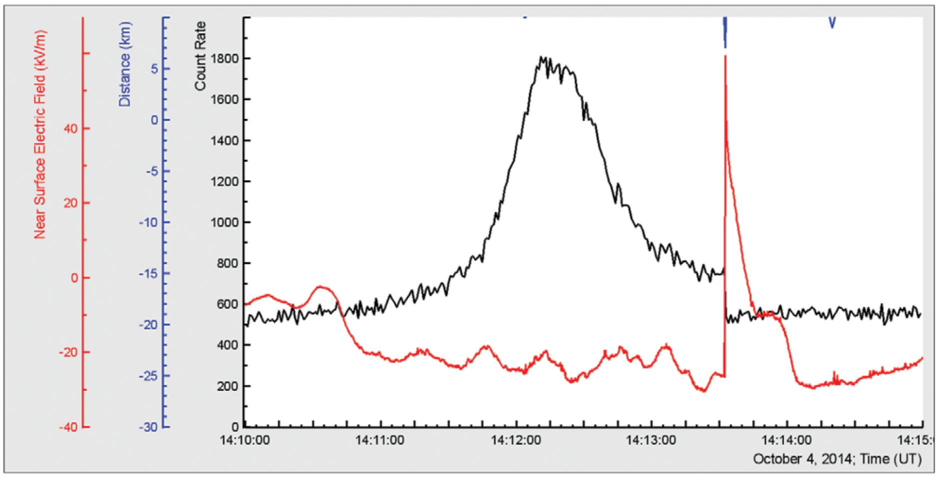

Fig. 2: (Colour on-line) Time series of the 1 second count rates of the outdoor 3 cm thick scintillator abruptly stopped by lightning and disturbance of the near-surface electric field; in the top of the figure the distance to lightning from particle detectors is shown.

start (sharp increase of the near-surface electric field), the time of the near-surface electric-field maximum and the time of FWHM along with the corresponding strengths of the near-surface electric field. In the seventh column, we list the fall of the particle detector count rate due to lightning occurrence. The eighth column shows the distance to lightning estimated by the electric-field mill EFM-100 and in the last column we list the time of the detection of the nearest extensive air shower (EAS), initiated by the high-energy primary hadron in the atmosphere above particle detectors.

As we can see from table 1 the statistical significance of the selected TGE events is rather high. TGE's maxima have mean enhancement above the background fluxes of $35 \pm 12\%$. The mean fall of the count rate caused by lightning is $21 \pm 7\%$.

From the table 1 we can outline the typical features of the negative cloud-to-ground lightning occurred on Aragats:

1) mean electric field before the start of the lightning $\sim -24.7 \pm 2.9\,\text{kV/m}$;

2) the mean maximum value of the enhanced electric field $\sim 51 \pm 2.7\,\text{kV/m}$ (after reaching the maximum the near-surface electric field slowly returns to pre-lightning values due to continuous charge separation processes in the cloud);

3) mean FWHM $\sim 4.8 \pm 3.1$ min;

4) mean electric field at FWHM $\sim 13.1 \pm 3\,\text{kV/m}$;

Table 1: Main parameters of the TGE events terminated by lightnings.

Date (UT)	Time and importance of TGE	FWHM TGE min.	Start of lightning (UT); El. field (kV/m)	El. field maximum time (UT) and maximum value (kV/m)	FWHM (UT) El. field (kV/m)	Time (UT) and drop of γ-ray flux (%)	Dist. (km)	EAS, ASNT (UT)
07/10/2012	15:08 35% (5.7σ)	6	15:10:53 −17.9	15:10:53.15 50.2	15:10:59.5 16	15:10:48–15:10:52 22	2.9	15:10:52.7
26/05/2014	13:12 18% (3.4σ)	8	13:12:41.5 −32	13:12:41.7 44	13:12:48.2 6	13:12:42–13:12:44 13	6	13:12:41.5
02/06/2014	20:58 33% (8σ)	0.5	20:58:10.2 −23.7	20:58:10.35 49.5	20:58:13.6 13	20:58:10–20:58:11 24	8	20:58:09.4
02/06/2014	20:59:30 46% (11σ)	1.5	21:00:10.7 −23.2	21:00:10.9 52.2	21:00:13.9 14.5	21:00:10–21:00:11 22	2	21:00:10.7
04/10/2014	14:12:15 45% (8.5σ)	0.5	14:13:32.4 −26.6 kV/m	14:13:32.5 59.5	14:13:37.5 16	14:13:32–14:13:33 31	6.8	14:13:31.3

5) mean time from the start of the electric-field sharp enhancement till its maximum $\sim 160 \pm 50$ ms;

6) mean distance to lightning $\sim 4.8 \pm 3$ km.

The very large amplitude of the negative lightning field changes (∼75 kV/m) achieved in very short time (∼160 ms) and the large recovery time of the electric field (tens of seconds) indicate strong discharge processes at nearby distances (∼10 km and less) in the thunderclouds above Aragats. The time delay between the EAS registered by all the 8 scintillators of the ASNT detector (see details of the detector in [6]) and the start of lightning is 0.3 ± 0.05, 0.8 ± 0.05 and 1.1 ± 0.05 seconds for the events with lightning occurred at the decay phase of the TGE. Thus, we conclude that for these events the lightning occurrence is not connected with high-energy EAS. For both events occurred at the beginning and at the maximum of the TGE the time delay was 0 ± 0.05 seconds. We may connect the lightning initiation for these events with large EAS hitting occasionally the thundercloud and initiate step leaders to breakthrough ever "deep" LPCR.

Waveforms of fast and slow disturbances of the electric field related to October 4, 2014 event. – On 4 October 2014, 14:11:10 UT thunderclouds completely covered the sky at Aragats and the near-surface electric field abruptly goes down, reaching −22 kV/m. Simultaneously the particle count rate of 3 cm thick outdoor plastic scintillator starts to increase and reaches a maximum of 1808 counts per second at 14:12:14 (mean value with fine weather is 525 counts per second, MSD ∼23). The TGE particle flux enhancement was enormous; reaching 340% at the maximum flux second which is equivalent to the *p*-value of 53σ, see fig. 2. At 14:13:31.5 the electric field starts its sharp increase, in 100 ms changing from −26.6 kV/m up to 59.5 kV/m. The large potential drop of the near-surface electric field of 86 kV/m occurred in 100 ms with consequential very long recovery of the pre-lightning electric field (the near-surface electric field returns to the negative domain after 40 seconds and reaches −27 kV/m at 14:13:53) indicates a huge negative charge deposited on the ground, *i.e.* the negative CG flash. In the same second the scintillator count rate decreases by 30% from 779 counts to the value of 541.

Fast electric-field waveform observed on October 4 at 14:13:31 is shown in fig. 3. The first of the two strong and short pulses of the same polarity with FWHM of $\sim 1\,\mu$s each, and amplitudes of 200 mV and 300 mV, separated by $10\,\mu$s triggers the data acquisition system. Prior to the strong signal, there are two weak nanosecond scale pulses observed at $\sim -8.4\,\mu$s and at $\sim -41\,\mu$s at the pre-trigger time with a single negative bipolar pulse in between at $-24\,\mu$s.

Nanosecond scale pulses that have the shape of a distorted sine wave with an average period of oscillation of ∼20–30 ns and typical full duration of 0.1–$2\,\mu$s were frequently observed in the course of studying the wide-band

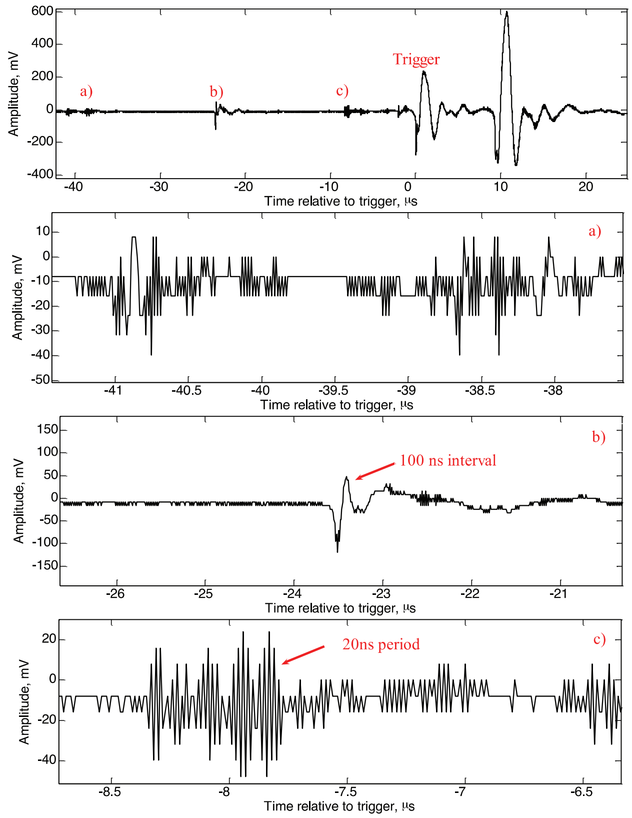

Fig. 3: (Colour on-line) Fast electric-field waveforms recorded on 4 October and associated with −CG lightning, which terminates the TGE shown in fig. 2. Panels (a), (b) and (c) are magnifications of the corresponding areas in the entire waveform.

electric fields connected with atmospheric discharges in the sky above the Aragats mountain. The preliminary stage of a −CG flash develops in a large positive electric field between the main negatively charged region in the middle of the cloud and the transient lower positively charged region (LPCR) in the bottom of the cloud. Probably, nanosecond scale pulses followed by large-amplitude electric-field disturbances can be considered as a precursor to the main lightning event (return-stroke).

Conclusion. – Electron and gamma-ray fluxes from the thundercloud are originated in the lower dipole formed by the main negatively charged region in the middle of the cloud and the transient lower positively charged region (LPCR). The LPCR prevents the lightning leader from reaching the ground and usually no −CG lightning occurs during mature LPCR when the particle flux is sizable. Only after decaying of the LPCR lightning the stepped leader makes its path to the ground.

TGEs and lightning are concurrent processes both discharging high potential difference in the cloud and switching off the electric field [21]. Continuous attempts to start the stepped leader produce a large number of low-energy (few eV) electrons by ionizing the air [22]. The low-energy electrons then drift in the thunderstorm electric field producing electric currents and radiofrequency emissions. The current resulting from the high-energy particles and their associate ionization could be some of the largest produced by the thunderstorm [23]. Therefore, this current will certainly increase the conductivity of the particular region of the thundercloud, facilitate its discharge and lead to the creation of a propagating hot leader channel [1,4]. Weak bipolar nanosecond scale radiofrequency pulses (fig. 3(a)) possibly originated from these discharges represent an early stage of formation of the conducting channel in the thundercloud (initial breakdown). Further development of the −CG lightning depends on the degradation of the LPCR. We adopted the hypothesis that the LPCR resides on water droplets (hydrometeors —HMs). The strong electric field polarizes and stretches water droplets and enhances the electric field in the bottom of the thundercloud. Our observations show that only at high humidity the TGEs at Aragats are possible and rains terminate the particle fluxes [14]. Local discharges on HMs stimulated by electrons [24] and propagation of the lightning step leader may generate a series of bipolar radiofrequency pulses (fig. 3(b) and (c)) reflecting a preliminary breakdown process of the lightning flash (fig. 3).

* * *

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