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On the origin of particle fluxes from thunderclouds

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ABSTRACT

We present the observational data on registration of atmospheric discharges simultaneously with the detection of elementary particles obtained during thunderstorms at an altitude of 3200 m above sea level on Mt. Aragats in Armenia. Throughout the 2016 summer and 2018 spring campaigns on Aragats, we monitored lightning occurrences and signals from NaI spectrometers, plastic scintillators and Neutron Monitor proportional counters, and analyzed the shape of registered pulses. Particle detector signals were synchronized with lightning occurrences at a few nanoseconds level.

Analysis of shapes of the simultaneously detected pulses of the fast wideband electric field produced by a lightning flash and pulses from particle detectors discloses that all additional detector pulses registered during lightning flash were the electromagnetic interference signals and not particles originated directly from the lightning bolt. Thus, we observe no evidence of the direct production of electrons, neutrons or gamma rays during a lightning flash. We conclude that the entire particle fluxes detected on Aragats research station (more than 250 TGEs) can be explained by the generation of MeV electromagnetic cascades in the strong atmospheric electric fields.

1. Introduction

Copious observations of the thunderstorm ground enhancements (TGEs) [7,8], i.e. enhanced fluxes of electrons, gamma rays and neutrons detected by particle detectors located on the Earth's surface and related to the strong thunderstorms overhead, posed the question of their origin. According to the TGE initiation model [11,16], the electrical field of the lower dipole effectively transfers field energy to secondary cosmic ray electrons. Electrons generate copious gamma rays by a runaway breakdown (RB) [21], now referred mostly as relativistic runaway electron avalanches (RREA) [4,5,18]. High-energy gamma rays (with energies above 10 MeV) in interaction with atmosphere atoms generate neutrons by photonuclear reaction [10]. Large TGEs usually occurred during large negative electric fields observed near the earth's surface [9]. Multiyear observations of particle fluxes and lightning occurrences on Aragats prove that during large TGEs the lightning activity is suppressed; lightning reduces particle fluxes and does not accelerate them [12,15].

Observation of numerous TGEs by the Japanese, Chinese, and Slovakian groups [6,26,27,30,31] proves that RB/RREA process reliably accelerates and multiplies electrons producing numerous TGEs.

In contrast, there are observations of an alternative source of thundercloud particles.

Physicists performing experiments at the Tien-Shan Mountain Cosmic Ray Station, Kazakhstan (altitude of 3340 m) in several papers reported the existence of high-energy emissions, i.e. electron, gamma and neutron fluxes that are directly connected with yet unknown processes in the lightning bolt. Gurevich et al. [23] "report for the first time about the registration of an extraordinary high flux of low-energy neutrons generated during thunderstorms. The measured neutron count rate enhancements are directly connected with thunderstorm discharges". Gurevich et al. [25] confirm that "the intensity both of electrons and gamma rays in lightning discharge prevail the background emission by 1.5 to 2 orders of magnitude"

Another group from the Lebedev Institute in Moscow, Russian Federation, reported the emission of neutrons in the energy range up to tens of MeV in a one-meter long high-voltage discharge produced in laboratory [2]; and that "neutrons were registered within the range from thermal energies up to the energies above 10 MeV. It was found that the neutron generation takes place at the initial phase of electric discharge and is correlated with the generation of x-ray radiation" [3].

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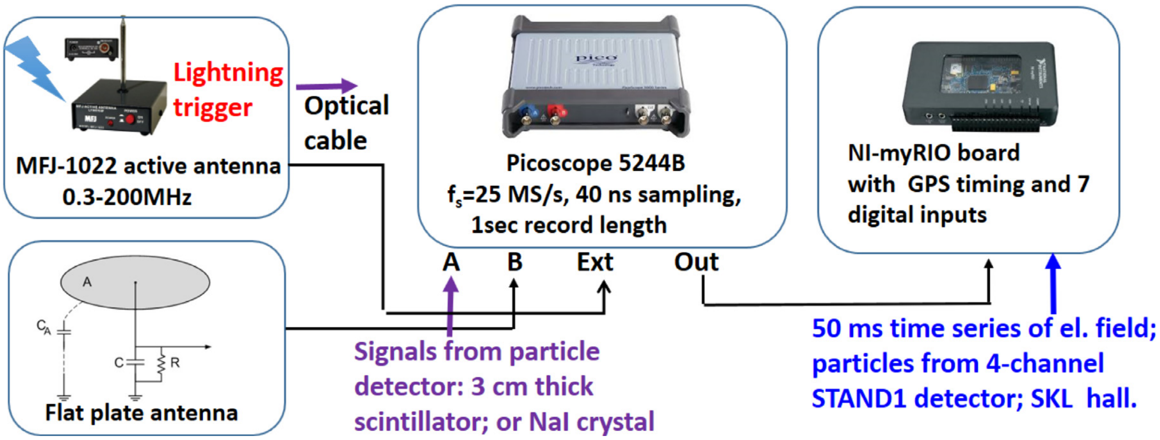

Fig. 1. The fast synchronized data acquisition (FSDAQ) system for the research of particle flux–lightning relations.

Another observation of the lightning-induced gamma ray flux was reported by the group from the International Center for Lightning Research and Testing (ICLRT) [20] in north central Florida. The gamma ray flux intensity was able to saturate the electronics throughout 50 µs following the system trigger. The authors claim that the primary factor that triggered the very intensive gamma ray flux was the upward positive leader approaching a negative charge region.

Despite these pieces of evidence, the physical model of the particle origination in the thunderbolt is not yet well explained. Usually, the physical model is not formulated at all; the only detection of particles is described:

Ref. [24]: it is established that “the neutrons are generated during thunderstorm atmospheric discharges. Often the neutrons are emitted in short bursts; the burst width is 200–400 µs.”

Ref. [2]: “Currently, there is no reasonable model or mechanism to explain the generation of neutron bursts during atmospheric discharge in air. A special mystery is the origin of the neutrons with energies above 10 MeV.”

The systematic research of the lightning-related X-ray radiation was made at the lightning observatory in Gainesville (LOG), Florida [29]. The 7.6 cm long cylindrical NaI (Tl) scintillator, circular flat-plate antennas were used for correlated measurements of the X-ray photons, electric field, and electric field derivative. Measured X-ray radiation, lightning leader and return-stroke onset times, helped to establish a correspondence between leader steps and X-ray pulses. For 23 (8 first and 15 subsequent) strokes within 2 km of the lightning observatory in Gainesville; X-rays were detected 88% of the time. The authors present the time series of gamma ray count rates before the lightning (Fig. 5 of [29]) on a microsecond time scale.

During a thunderstorm on 6 February 2017 in Japan, a γ-ray flash with duration of less than 1 ms was detected at monitoring sites 0.5–1.7 km away from the lightning. The subsequent γ-ray afterglow subsided quickly, with an exponential decay constant of 40–60 ms, and was followed by prolonged line emission at about 0.511 MeV, which lasted for a minute [19]. Authors claim a conclusive evidence of positrons and neutrons being produced after the lightning.

Few bursts of gamma ray showers have been observed in coincidence with downward propagating negative leaders in lightning flashes by the telescope array surface detector (TASD) [1]. The authors claim that observed energy deposit is consistent with forward-beamed showers of 10^{12}–10^{14} or more primary photons above 100 keV, distributed according to a RB/RREA spectrum. However, no model was presented to justify such a huge amount of high-energy particles associated with a lightning flash.

In summary, two models are suggested in the literature:

(a) The RB/TGE model—electrons from the ambient population of CR accelerated in the strong electric field in the lower part of the cloud, runaway, generate bremsstrahlung gamma rays and the gamma rays produce neutrons via photonuclear reactions;
(b) The lightning model—the electron, gamma, and neutron fluxes originate in the lightning flashes. The model of particle generation in the lightning bolt, or around the lightning bolt is yet not well specified.

To solve this controversy, we need to unambiguously answer the question: do lightning flashes emit high-energy electrons, positrons, gamma rays and neutrons with single energies of several tens of MeV? [28]. Therefore, we perform experiments with simultaneous recording of the pulse shape from particle detectors and from atmospheric discharges. During the summer 2016 to spring 2018 campaigns on Aragats completed by the staff of cosmic ray division (CRD) of Yerevan Physics Institute (YerPhI) hundreds strong storms with numerous lightning flashes were observed, and some of the most violent ones produced electromagnetic interferences (EMI) in some of the particle detectors and data acquisition electronics (DAQ). Taking as examples the huge storms occurred on Aragats we demonstrate that with new fast electronics we can reliably distinguish EMI from genuine particle registration in a variety of particle detectors that are in operation on Aragats. No particle fluxes correlated with lightning flashes were detected at Aragats during the whole time of observations.

2. Instrumentation

The correlation analysis of the TGEs and lightning discharges poses stringent requirements on the time resolution and synchronization of the data flow from particle detectors, near surface electric field sensors and sensors of the fast electric field. The recently developed fast synchronized data acquisition (FSDAQ) system (see Fig. 1) is triggered by a commercial MFJ-1022 active whip antenna that covers a frequency range from 300 kHz to 200 MHz. A flat-plate antenna followed by passive integrator is used to record fast electric field waveforms. The output of the integrator is directly connected to the digital oscilloscope (2-channel Picoscope 5244B) with 60 cm long RG58 coaxial cable. The data capture length is 1 s, including 200 ms pre-trigger time and 800 ms post-trigger time. The sampling rate is 25 MS/s, corresponding to 40 ns sampling interval, and the amplitude resolution is 8 bit.

The trigger output of the oscilloscope is connected to the input of GPS timing system of the national instrument’s (NI) MyRiO board. Any event recorded by the oscilloscope generates an output trigger, causing the GPS card to trigger at the same instant and produce a timestamp.

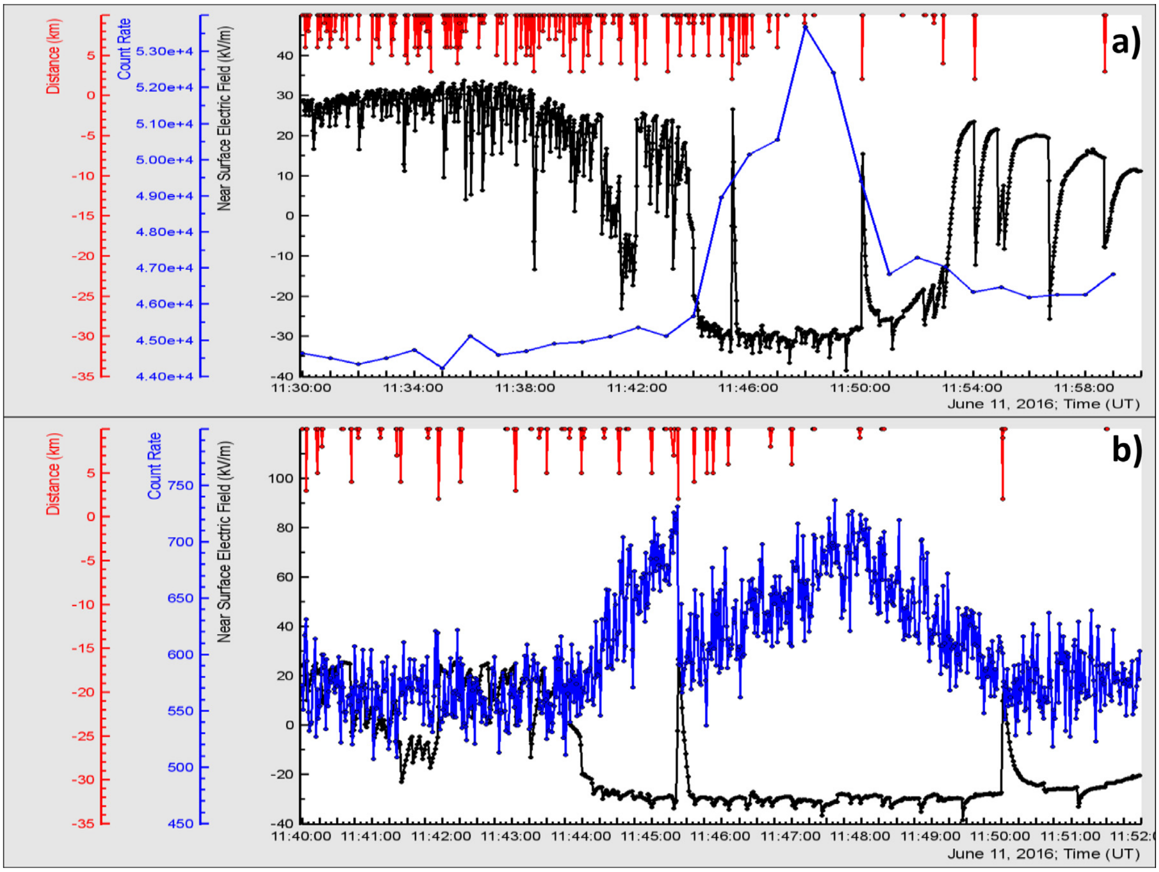

Fig. 2. (a) Disturbances of the near surface electrostatic field, distance to lightning and 1 min count rate of STAND1 (MAKET) upper scintillator; energy threshold ~1 MeV; (b) 1 s time series of the 3 cm thick plastic scintillator of the same detector. A strong lightning discharge is seen as a vertical line interrupted TGE.

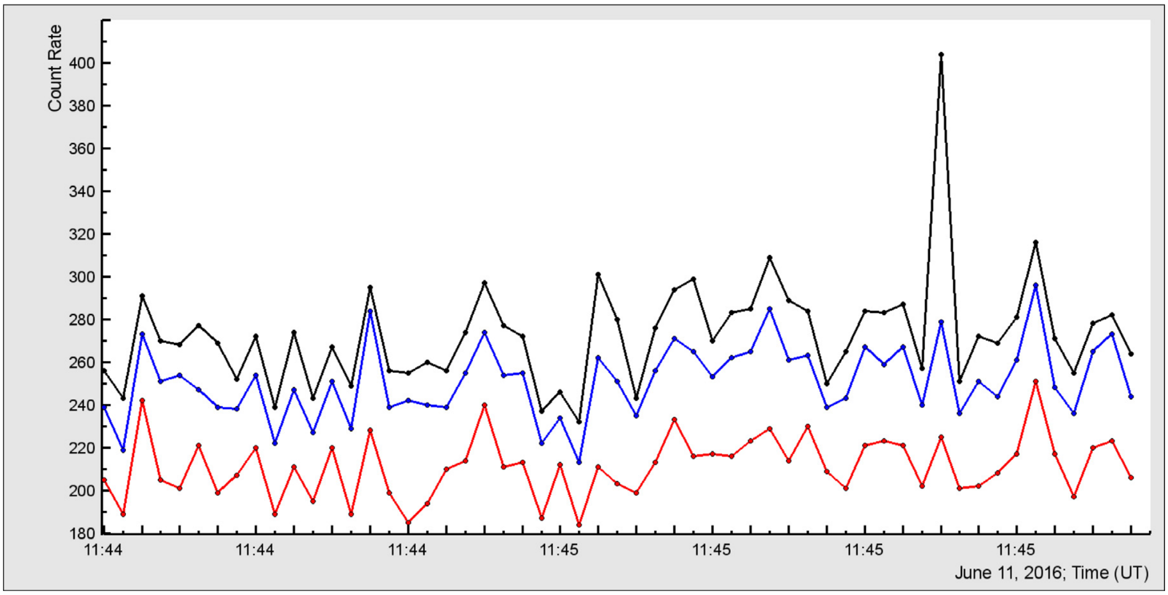

Fig. 3. Event on 11/6/2016, 11:44 UT. The 1 s time series of ArNM. Only time series corresponding to 0.4 µs dead time (upper curve) demonstrates large peak due to counting multiple secondary neutrons coming within time span ~1 ms; the time series corresponding to 750 and 1200 µs dead time demonstrate no peak.

The heart of the DAQ system is the NI-myRIO board. It includes eight analog inputs, four analog outputs, 32 digital I/O lines, programmable FPGA, and a dual-core ARM Cortex-A9 processor (a high-performance processor implementing the full richness of the widely supported ARMv7-A architecture). With reconfigurable FPGA technology, we perform high-speed signal processing, high-speed control, inline signal processing, and custom timing and triggering. For the control systems, one can also run advanced control algorithms directly in the FPGA fabric to minimize latency and maximize loop rates. “LabVIEW FPGA Module”, which extends the LabVIEW graphical development platform, provides an alternative to HDL (Hardware description language) graphical programming

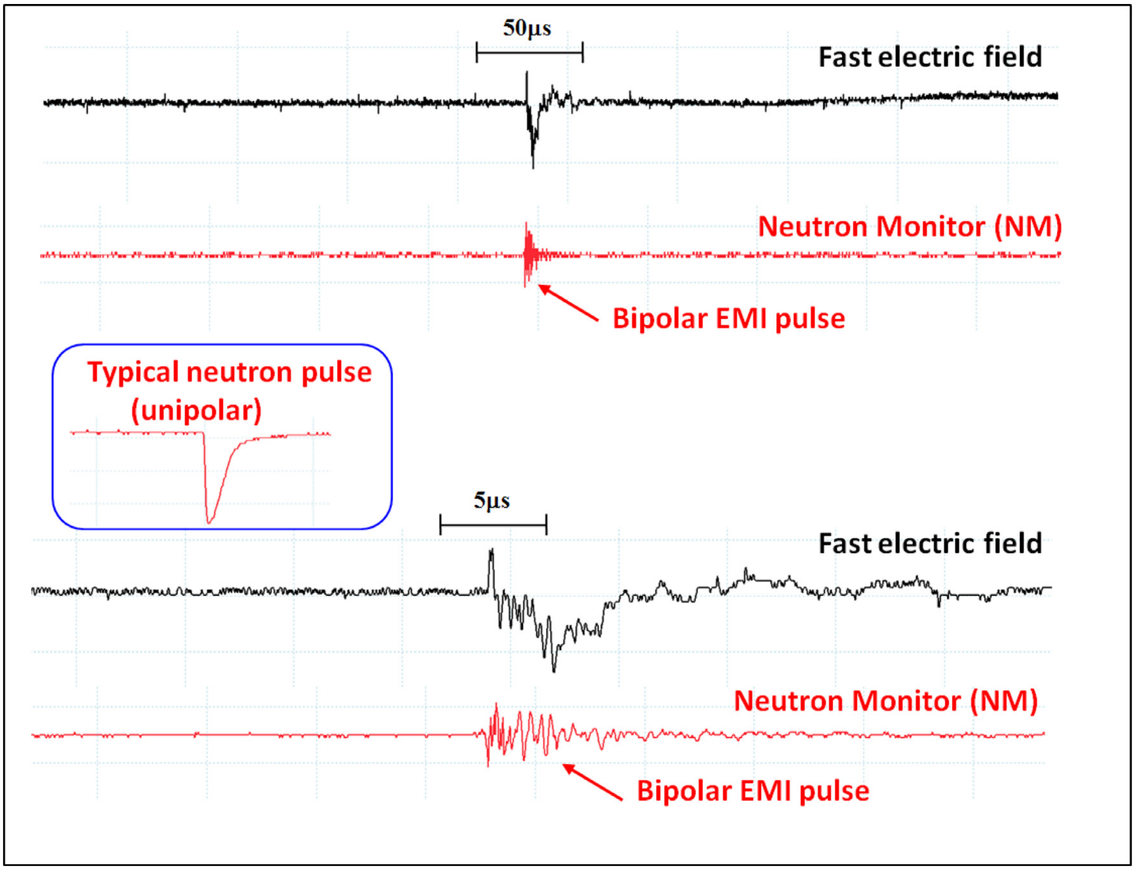

Fig. 4. Synchronized waveforms of fast electric field and neutron monitor shown in different time scales along with a typical waveform of neutron signal from the proportional counter of NM. Lightning flash occurred on 11 June 2016 at 11:44 UT.

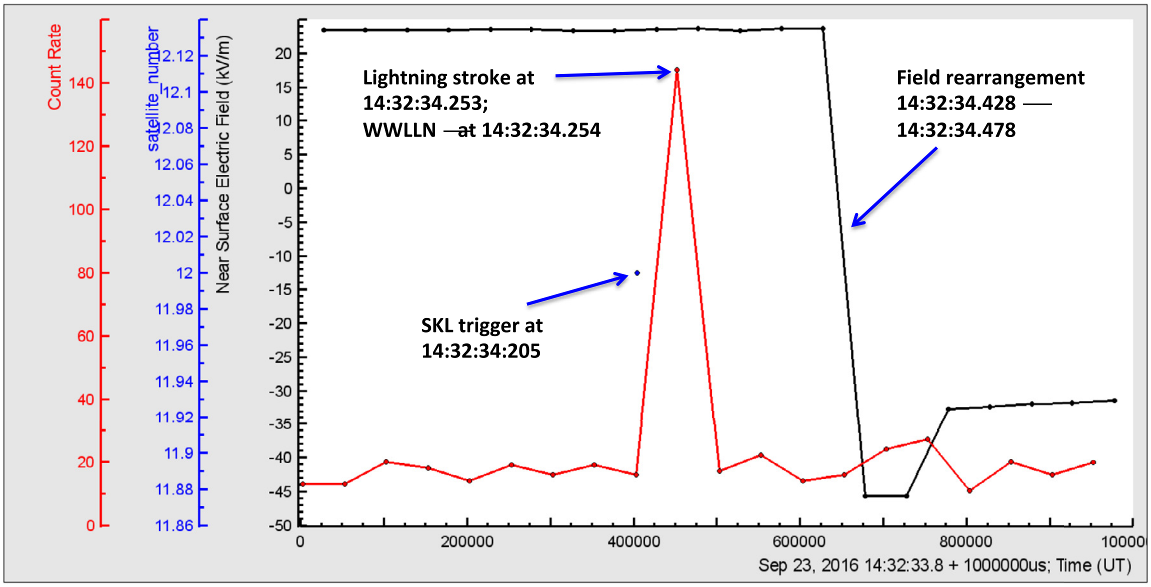

Fig. 5. 50 ms time series of the bottom scintillator of STAND1 detector and electrostatic field disturbances. The negative change of electrostatic field of 69.3 kV/m is produced by an inverted-polarity lightning flash.

approach that simplifies the task of interfacing to I/O and communicating data.

The commercial GPS receiver sends two types of data-stream to the board. The first is RS-232 ASCII data telling what time it is, at what latitude, longitude, and altitude the receiver is, and information about the satellites the receiver is using. An embedded 25 MHz counter on FPGA gives the exact time of the trigger. The 1PPS (one pulse per second) stream of the 5 V, 100 ms pulses resets this counter at each second. The leading edges of 1PPS signals from GPS receivers are synchronized within the accuracy of the non-military GPS system (about 100 ns). This feature allows time synchronization with 100 ns resolution.

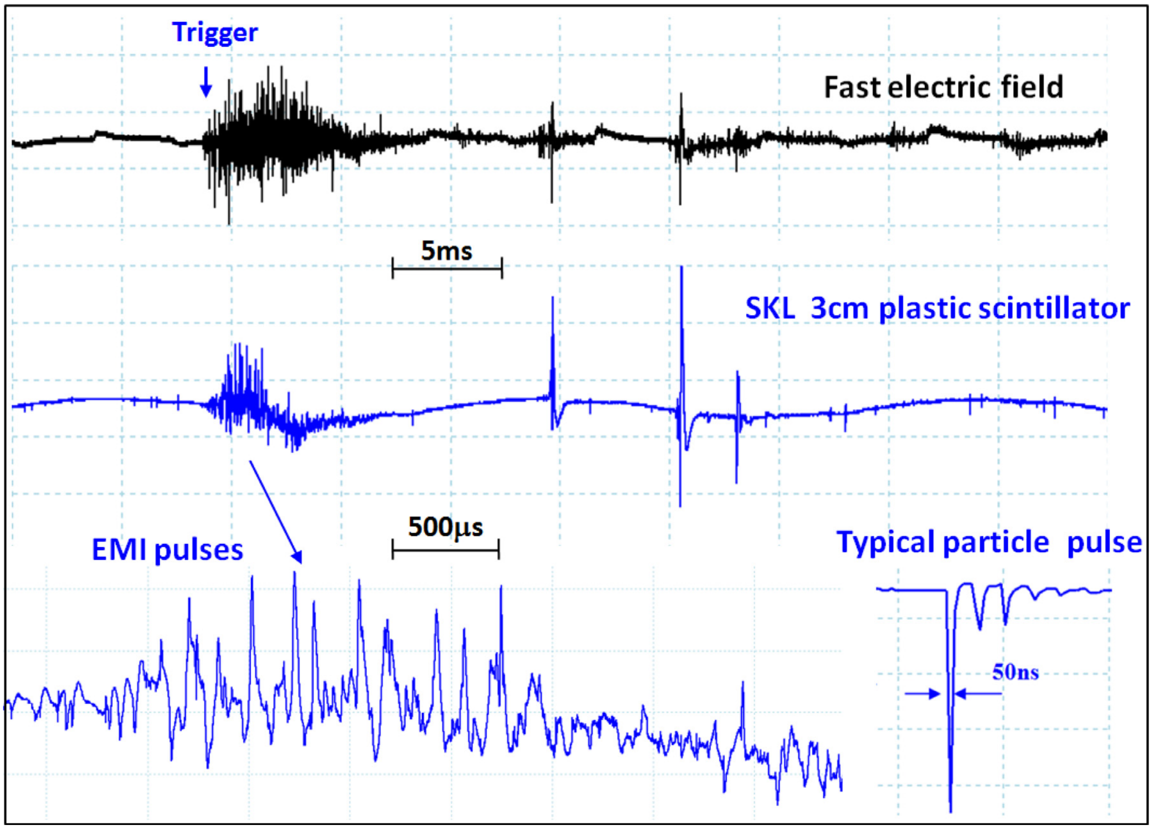

Fig. 6. Typical EMI signature from atmospheric discharges in the particle detector waveform. Synchronised time-series of the pulses of fast electric field and signals from the plastic scintillator. SKL trigger occurred on 23 September 2016 at 14:32:34.205 UT.

Eight digital inputs of myRIO board are used for feeding signals from the variety of particle detectors operated on Aragats. Since the 2016 summer season, we connected to myRIO the STAND1 detector comprised of three vertically stacked plastic scintillators (thickness = 1 cm, area = 1 m^2, energy threshold ~0.8 MeV) and one stand-alone plastic scintillator (thickness = 3 cm, area = 1 m^2, energy threshold ~2 MeV), proportional counters of Aragats neutron monitor (ArNM) and NaI crystal based spectrometers (energy threshold ~0.3 MeV). Details on the performance of these particle detectors can be found in [13,14].

The myRIO pulse counting system can provide registration of very short time series (down to 1 ms) that enables the investigation the dynamic of TGE development and its relation to the lightning initiation (50 ms time series are stored currently).

Signals from the electric field sensor (electric mill EFM-100) were fed to the myRIO board via the TCP-IP connection (WiFi). The electrostatic field changes were recorded at a sampling interval of 50 ms; the amplitude resolution of electric field measurement was 0.01 kV/m, and the lightning location accuracy was ≈1.5 km. The firmware application provided by Boltek has a feature to share the electric field data via a network (it acts as a server for a client running under myRIO). The 8th channel is reserved for the synchronization pulse (the trigger) from a fast waveform recording device or from any of particle detectors.

At any triggering signal, the MyRio board generates a special output containing current value of particle detector counts, near-surface electric field value and precise time of arriving of the trigger signal. Thus, the fast waveform patterns are synchronized with particle fluxes and with slow (20 Hz) near surface electric field measurements.

The time series of particle detector count rates, electrostatic field measurements and service information (status of myRIO, time delays, a number of satellites used for GPS timing), as well as the files containing digital oscilloscope data, are transferred via online PC to the mySQL database on CRD headquarters in Yerevan. All information is available via ADEI multivariate visualization code at the website http://adei.crd.yerphi.am; explanations are located in the WiKi section [17].

Two DAQ systems are operated independently in MAKET and SKL experimental halls on Aragats; triggers issued by both fast DAQ systems usually coincide within few ms. However, an optical link can transfer the trigger signal from SKL to MAKET experimental hall located at a distance of 100 m for the joint triggering of 2 networks of particle detectors and field meters.

3. *In situ* measurements of the thunderstorm particles on Aragats

Throughout this paper, we use the atmospheric electricity sign convention, according to which the downward-directed electric field or field change vector is considered to be positive. On 11 June 2016, large disturbances of the near-surface electrostatic field started at 10:45 UT (see Fig. 2(a)). The atmospheric pressure was 690.8 mbar; relative humidity—75%; wind speed 3—4 m/s; temperature ~5 °C; no rain was registered. In Fig. 2(a) and (b) we show disturbances of the near-surface electric field; 1 min and 1 s time series of plastic scintillators of STAND1 array and distance to lightning in the top of both Fig. 2(a) and (b). Note the difference in the horizontal axes of Fig. 2(a) and (b): for 1 min time series, it is half of the hour, for 1 s time series it is 12 min. The typical shape of the electrostatic field disturbances (the electrostatic field in the deep negative domain for several minutes possibly accompanied by several short “bursts” touching positive domain and 1–2 negative lightning flashes with large amplitude) shown in Fig. 2(a)

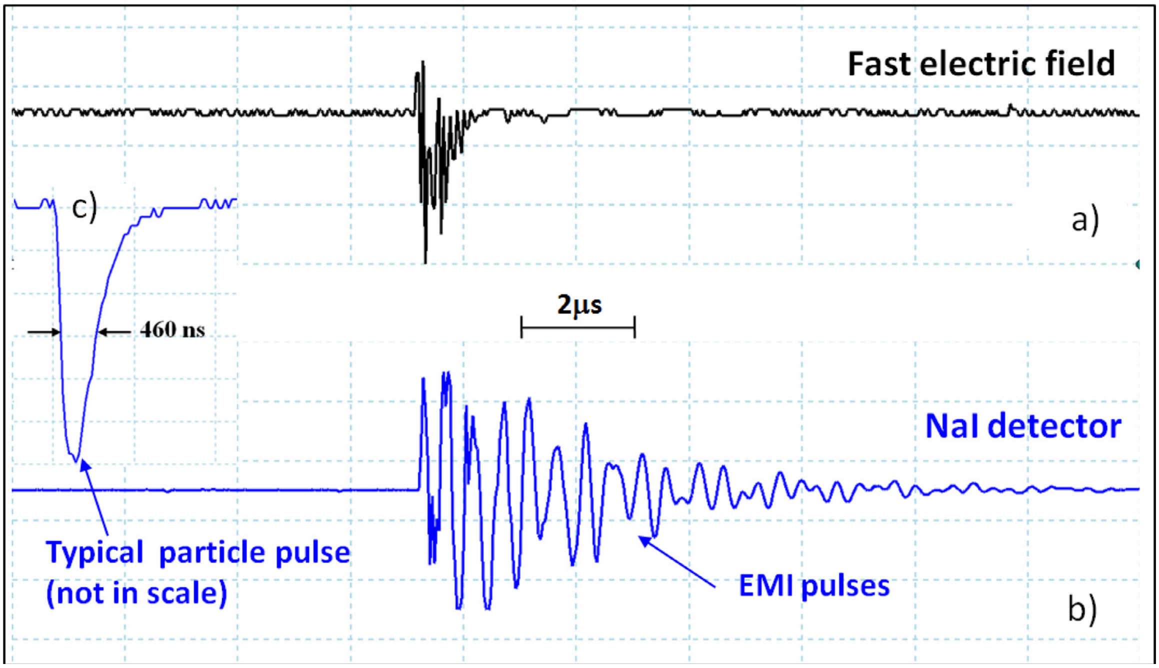

Fig. 7. Registration of the lightning flash occurred on May 15, 2016, 12:48:25. Waveforms of the fast electric field (a); NaI detector output (b); in the inset (c) is shown a typical shape of NaI detector response to an incident particle.

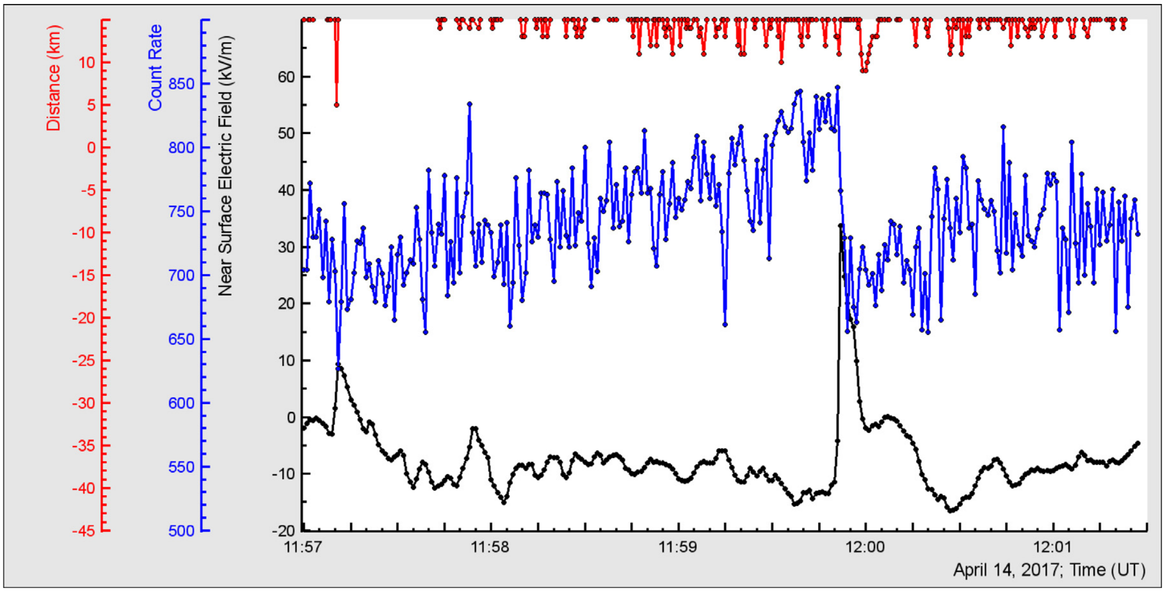

Fig. 8. TGE abruptly terminated by the lightning flash at 11:59:51.82; trigger was registered in MAKET and SKL hall at 11: 59:51.75; a surge of the electrostatic field started at 11:59:51.94; a decline of particle flux started at 11:59:51.83.

indicates the establishment of the lower dipole, which accelerates the CR electrons downwards. Accelerated electrons unleash multiple relativistic runaway avalanches measured on the earth's surface [7,8]. The enhanced particle flux (TGE) is shown in Fig. 2(a) by the 1 min time series of count rate of 1 cm thick plastic scintillator of STAND1 detector located nearby MAKET experimental hall (upper detector of 3 stacked above each other). The count rate enhancement was ≈25% corresponding to more than 35 standard deviations. From the recovery of the differential energy spectrum of TGE (see for instance Fig. 5 in [16]) it is apparent that after lightning flashes high-energy particle flux is totally terminated, whereas the flux of low energy particles (below 3 MeV) continues.

A strong lightning discharge that occurred at 11:45:22 abruptly terminated the TGE. However, the TGE restarted and was continuing ~4.5 min until 11:50, when second strong lightning discharge finally terminated particle flux. The electrostatic field change caused by the lightning has a rise time of few hundreds milliseconds and recovery time of several seconds. Abrupt termination of particle flux caused by first lightning is shown in Fig. 2(b) with 1 s time series of the 3 cm thick scintillator of the same STAND1 detector. Count rate decreases from 731 at 11:45:22 down to 592 (19%) at 11:45:23. The electrostatic field starts to rise from an initial value of −30.6 kV/m at 11:45:22.48, and shows a maximum of 39.7 kV/m at 11:45:22.58; the amplitude of field change was

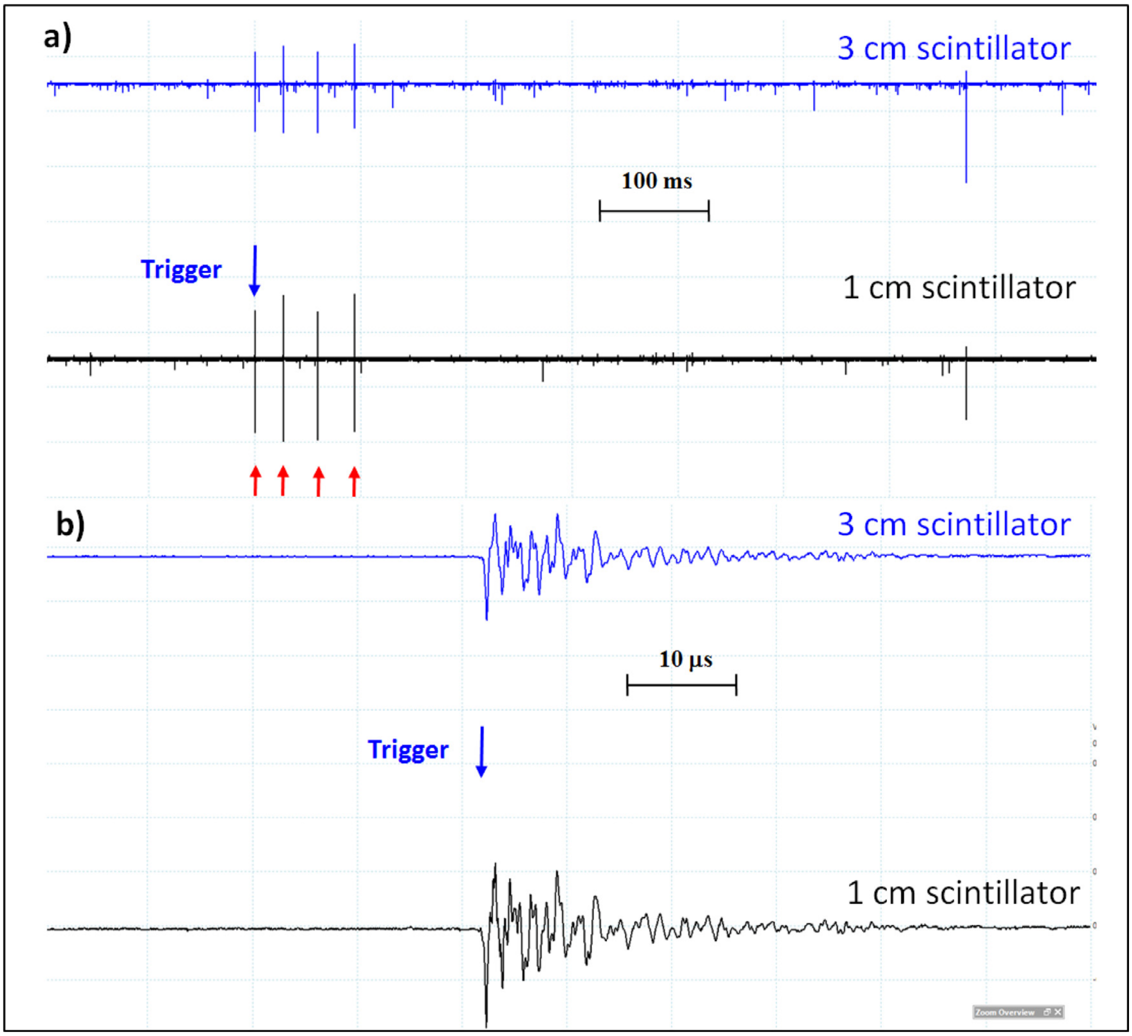

Fig. 9. The “Shower Burst” event detected on 14 April 2017 by 1 cm thick and 3 cm thick 1 m area plastic scintillators located in the experimental hall MAKET. The signal shapes were synchronized with lightning flash (atmospheric discharge trigger was detected at 11: 59:51.75). The “bursts” are denoted by 4 small arrows in (a). The zoomed version of the first burst is shown in (b).

70.3 kV/m reached in 100 ms. Field recovery took much longer time ~10 s.

The lightning discharge is a powerful wideband radio-wave emitter, which produces electric pulses in the cables, DAQ electronics, and power lines. To check if the registered pulses are electromagnetic interferences (EMI) or signals from relativistic particles born in the lightning bolt we performed synchronized measurements of the waveforms of fast electric field caused by atmospheric discharges and signals from particle detectors. The Aragats neutron monitor (ArNM, see details in [14]) measures the 1 s time series of count rates from 16 proportional counters filled with Boron gas. Neutrons and protons incident the detector’s 5 cm thick lead absorber generate in nuclear reactions numerous secondary neutrons, which are detected by the proportional counter.

In Fig. 3 we show three time series of detector count rates recorded with 3 different dead times. For the shortest dead time of 0.4 µs, all secondary neutrons that enter the proportional counter are detected. For larger dead times of 750 µs and 1250 µs the particle count is suppressed after detecting the first neutron. Thus, a hypothetic particle burst from the lightning will be registered by ArNM as a large peak in the 1 s time series of ArNM count rate corresponding to 0.4 µs dead time, and will not be registered with 750 µs and 1250 µs dead times, as it is shown in Fig. 3.

To prove that detected peak is due to burst of neutrons we need to examine the pulse shapes recorded by the oscilloscope. In Fig. 4, we demonstrate fast electric field waveforms from flat plate antenna and pulses from one of the proportional counters of ArNM and their zoomed versions. As a reference, a typical shape of the genuine neutron pulse is also shown.

By detecting the large peak at 11:45:23 in time-series of ArNM shown in Fig. 3 only, we can erroneously conclude that simultaneously with atmospheric discharge a large number of neutrons is generated in the lightning bolt. However, comparing the detailed pattern of the detected lightning bipolar pulses with the typical unipolar pulse that neutron generates on the output of the proportional counter (Fig. 4) we should reject the hypothesis of neutron production in the lightning bolt. All additional counts detected by the proportional counter at 11:45:23 are due to EMI.

On 23 September 2016 on Aragats station, a severe storm was observed with strong lightning activity and heavy rain at 13:50–14:50 UT. The temperature dropped from 3.6 °C to 1.3 °C; relative humidity was very high—98%, rain rate for 20 min touched a level of 1 mm/h. In Fig. 5 we show the trigger time, the estimated lightning flash time (by the large EMI pulse registered by one of the particle detectors) confirmed by the World-Wide Lightning Location Network (WWLLN) observation and the time series of the electric field rearrangement.

During the time span of several tens of ms after the trigger and before the lightning stroke, numerous atmospheric discharges induce plenty of pulses in a 52 cm diameter circular flat-plate antenna and simultaneously we observe bipolar pulses from particle detector (Fig. 6). A large number of bipolar "fake" signals ("trains" of pulses) from the 3 cm thick plastic scintillator of STAND1 detector mimicked a particle burst correlated with lightning. If one counts the number of particles in a burst only, it is possible to come to an erroneous inference that a registered peak is due to particles from the lightning bolt. However, the pulse from the charged particle registered by the scintillator has a typical unipolar shape (right bottom corner of Fig. 6). Using a fast digital oscilloscope, we can reliably distinguish bipolar pulses from atmospheric discharges and unipolar pulses from the particle detectors.

In Fig. 7(b) we show bipolar pulses registered by another detector, NaI crystal based spectrometer [13] produced by the strong atmospheric discharge (Fig. 7(a)). Signals from charged or neutral particles detected by NaI spectrometer are always unipolar.

Thus, we observe that all examined particle detectors (plastic scintillators, NaI crystals and proportional counters) can be triggered by a strong nearby lightning. However, by examining the shape of registered pulses we can easily discriminate EMI from the genuine particle pulse.

To confirm our results on the nature of "bursts" in the particle detectors we perform the pulse shape analysis from 3 particle detectors operated on Aragats Mountain. Two FSDAQ systems located in MAKET and SKL experimental halls separated by a distance of ∼100 m were triggered by two independent whip antennas. Several particle detectors were connected to both FSDAQ systems; data files with 1 s capture length and 40 ns sampling intervals were stored after each trigger (200 ms before and 800 ms after trigger). In April–June 2017 we detected numerous lightning flashes, which triggered the both FSDAQ systems; ∼250 joint triggers of MAKET and SKL DAQ system were registered. Careful examining of the shapes of output signals from flat plate antenna and from particle detectors proves that there was no genuine signal from any of the 3 particle detectors. All output "bursts" were bipolar and can be easily distinguished from the unipolar signals from particles traversing the detector. As an example of 2017 observations, we present the April 14 TGE, the first TGE of 2017 abruptly terminated by a lightning flash (Fig. 8). The outputs of the 2 plastic scintillators synchronized with trigger worked out by the whip antenna are shown in Fig. 9. We can detect 4 "Shower Bursts" in the Fig. 9(a); however, examining of the zoomed version shown in Fig. 9(b) proves that bi-directional signals from the DAQ electronics are EMIs and not genuine unipolar particle signals.

4. Discussion and conclusion

New emerging field of atmospheric high-energy physics is still lacking firmly established theoretical model. Our paper is an attempt to clarify one of the often-discussed problems: the origin of extremely rare particle "bursts" coinciding with a lightning flash.

During numerous storms observed from 2016 summer to 2018 spring we did not observe any lightning producing relativistic particles in any of continuously monitored detectors. There were no intense particle bursts in monitored particle detectors within 200 ms before atmospheric discharge trigger and 800 ms after. However, as we mentioned, in our previous papers, we do not exclude that propagation of lightning leaders and emerging of strong electric fields around leader tips can produce X-rays and additional seed electrons involved in the runaway process.

For many years of observations, there are not more than a half-of-dozen reported events of possible lightning origin. In contrast, only on Aragats we detect hundreds of TGE events comprising of millions and millions of "ECSs"—extensive cloud showers [11]; or Micro Runaway Breakdowns ("MRBs") [22]. All these alternative terms (Shower Burst [1], Inverse TGF [20], ECS [8], and MRB [22]) are related to one and the same entity—a runaway cascade developed in the strong electric field in the thunderstorm atmosphere. Continuum of gamma rays detected in Japan, China, Armenia, Slovakia and other countries can prolong till the return stroke and obviously include as well few gamma ray showers that coincide with the stepped leader propagation. Routinely observed copious gamma ray bursts integrated into a prolonged TGE can be explained by a standard RB/RREA theory with cosmic ray electron seeds [11,16,21].

If thunderclouds are high above particle detectors (1–2 km), like in Utah and Florida most gamma rays and all electrons are absorbed in the atmosphere. This is why the detection of TGEs at such sites is so rare. In contrast, thunderclouds at Aragats can be as low above particle detectors as 25–50 m. Only when the electric field in the cloud is extremely large the runaway electrons can collect from the electric field energy enough to unleash cascades so large, that gamma rays from RB/RREA cascades can be observed 1–2 km below the cloud on the earth's surface. It is why the reported "lightning origin" events are so rare and so short.

To finally resolve the enigma of the lightning correlated high-energy particles we need more observation at many sites with various particle detectors and improved time resolution.

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The data for this paper are available on the WEB page of the Cosmic Ray Division (CRD) of the Yerevan Physics Institute, http://adei.crd.yerphi.am/adei. Figures from the paper can be easily reproduced with embedded multivariate visualization on-line program ADEI [17].

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