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The synergy of the cosmic ray and high energy atmospheric physics: Particle bursts observed by arrays of particle detectors

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A B S T R A C T

Particle bursts detected on the earth's surface during thunderstorms by various particle detectors originated from the relativistic runaway electron avalanches (RREAs) initiated by free electrons accelerated in the strong atmospheric electric fields. Two oppositely directed dipoles in the thundercloud accelerate electrons in the direction of the earth's surface, and to the open space. The particle bursts observed by orbiting gamma ray observatories are called terrestrial gamma ray flashes (TGFs, with energies of several MeV, only sometimes reaching tens of MeV); ones registered by particle detectors located on the ground – are called thunderstorm ground enhancements (TGEs, with energies, usually reaching 40-50 MeV). Balloons and aircraft in the troposphere register gamma ray glows (with energies of several MeV). Recently, high-energy atmospheric physics includes also, so-called, downward TGFs (DTGFs), intense particle bursts with a duration of a few milliseconds.

Well-known extensive air showers (EASs) originate from the interactions of galactic protons and fully-stripped nuclei with the atmosphere atoms. EAS particles have very dense cores around the shower axes. However, high-energy particles in the EAS cores comprise a very thin disc of (a few tens of ns), and a particle detector traversed by an EAS core will not register a particle burst, but only one very large pulse. Only neutron monitor, by collecting delayed thermal neutrons from EAS core particle interactions with soil, can register particle bursts. We discuss the relation between short particle bursts available from the largest particle arrays with EAS phenomena. We demonstrate that the neutron monitors can extend the EAS "lifetime" up to a few milliseconds, a time comparable with DTGFs duration. The possibility to use the network of neutron monitors for high-energy cosmic ray research is also deliberated.

Plain Language Summary: Short and extended particle bursts are registered in space, the troposphere, and the earth's surface. Coordinated monitoring of the particle fluxes, near-surface electric fields, and lightning flashes makes it possible to formulate a hypothesis on the origin of intense bursts and their relation to extensive air showers and atmospheric discharges. Analysis of the observational data and possible origination scenarios of particle bursts allows us to conclude that the bursts can be explained by the electron acceleration in the thunderous atmosphere and by gigantic showers developed in the terrestrial atmosphere by high-energy protons and fully-stripped nuclei accelerated in Galaxy.

1. Introduction

After the discovery of terrestrial gamma flashes (TGFs, Fishman et al., 1994) the high-energy physics in the atmosphere (HEPA) is gaining increasing attention by both measurements with gamma-ray instruments onboard satellites and by numerous theoretical and modeling studies (Dwyer et al., 2012). Though, a very complicated experimental arrangement (particle detectors are located 300–500 km from the radiation source on the fast-moving satellites) and the absence of an online trigger for particles coming from the earth's direction make the research of the TGF origin a rather complicated problem. The runaway breakdown (RB) model introduced in Gurevich et al. (1992) and afterward mostly cited as relativistic runaway electron avalanche (RREA, Babich et al., 2001; Dwyer, 2003) did not provide gamma ray beams enough intense to describe satisfactorily the TGF observations (Mailyan et al., 2016). The experimental situation drastically improved when observation of enhanced fluxes of electrons, gamma rays, and neutrons start to be performed on the earth's surface with numerous particle detectors located just below electron-photon avalanches (Chilingarian et al., 2010). Registration of numerous thunderstorm ground enhancements (TGEs Chilingarian et al., 2011, 2017, 2020, 2021) produced by electron accelerators operating in the thunderous atmosphere, made it possible to measure the energy spectra of TGE particles and develop adequate models of the electron acceleration. Simulations with GEANT4 (Chilingarian et al., 2012) and CORSIKA codes (Chilingarian et al., 2018) confirm that the origin of the TGEs observed on Aragats can be explained by the RB/RREA process. Assuming several vertical profiles of the atmospheric electric fields above the critical value (from 1.8 to 2.1 kV/cm extended for 1-2 km), it was possible to find models that provide energy spectra, which were compatible with measured in direct experiments (Marshall et al., 1995; Stolzenburg et al., 2007). There is no need to introduce additional complications to the RB/RREA process, particle multiplication naturally emerges by introducing the strong electric field in the atmosphere above particle detectors. Certainly, in

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order to obtain the energy spectra alike measured in the experiment, several appropriate combinations of the electric field strength and its spatial extension should be examined (Chilingarian et al., 2020). Simulations confirm that free electrons from extensive air showers (EASs), entering strong atmospheric electric fields, generate multiple electron-photon avalanches, which cover sizable areas on the ground and can induce surface array triggers, as EASs do. Naturally, the density and energy of TGE particles are much smaller than EASs (see Figs. 3–5 in Chilingarian et al., 2011 and Fig. 5 in Chilingarian et al., 2017).

The key approach in TGE research is the correlated measurements of particle fluxes, fast wideband electric field records, and a variety of meteorological parameters, including near-surface electric fields. The facilities installed on Aragats station for the measurements of atmospheric discharges are synchronized on a nanosecond time scale with particle detectors making it possible to study the interrelation of TGEs and lightning flashes (Chilingarian et al., 2015, 2017, 2020, 2021). Multiyear measurements allow us to claim that atmospheric discharges do not originate from particle fluxes, but abruptly terminate them (Chilingarian et al., 2019).

Recently, the research groups using large arrays of particle detectors deployed for the registration of EASs, became interested in the unusual triggers (particle bursts, so-called the downward TGFs -DTGFs) and their possible correlations with lightning activity. Special attention was paid to establishing a combined monitoring technique of high precision registration of particle fluxes and atmospheric discharges. Coordinated monitoring of the lightning flashes and particle bursts, as well as, the modeling of the avalanche transport in the electrified atmosphere, make it possible to formulate hypotheses on the origin of particle bursts and their relation to atmospheric discharges.

However, in spite that "lightning discharges are now recognized as powerful particle accelerators" (see Wada et al., 2022, and references therein) the physical mechanism of how a discharge produces an enormous number of relativistic particles, is still in debate (see the suggested scenarios in Dwyer (2012), Celestin and Pasko (2011). In this paper, we discuss the possibility of the DTGFs origination by the EAS core, using the recent particle burst observations by the High Altitude Water Cherenkov Observatory (HAWC, Abeysekara et al., 2012), and Telescope Array (TA, Abu-Zayyad et al., 2013) experiments. We show how the registration of EAS cores can extend the "life" of the EAS ≈100,000 times, from a few tens of ns to a few milliseconds, and originate the particle bursts, which can mimic the DTGFs.

2. Neutron monitors as EAS burst detectors

The Aragats neutron monitor (ArNM) consists of 18 gas-filled cylindrical proportional counters of CHM-15 type (length 200 cm, diameter 15 cm) enriched with borontrifluoride ($^{10}BF_3$). The proportional counters are surrounded by 5 cm of lead and 2 cm of polyethylene. The cross-section of the lead above each section has a surface area of 6 m2, and the total surface area of the three sections is 18 m2. The high-energy hadrons and gamma rays from EASs produce multiple neutrons in the lead. Then, the neutrons were thermalized in the polyethylene, enter the sensitive volume of the proportional counter, and yield Li7 and α particles via interactions with borontrifluoride (Moraal et al., 2000). The α particle accelerates in the high electrical field inside the proportional counter and produces a pulse registered by the data acquisition electronics. If all pulses need to be counted, the dead time of the NM should be maintained very small. If only the incident hadrons need to be counted (a one-to-one relationship between count rate and hadron flux), the dead time must be be equal to the secondary neutron collection time (≈1250 μs), to avoid double-counting. Stenkin et al. (2007) for the first time, described the detection of the neutron bursts in the NM related to occasional hitting of the detector by a core of a high-energy EAS (Moraal et al., 2000). Hadrons and gamma rays from the EAS core generate numerous thermal neutrons and enormously increase the ArNM count rate (neutron multiplicity). This option of EAS core detection by NM was almost not recognized in the past, because the usually used long dead time does not permit counting the neutron multiplicity. By establishing 3000 times shorter dead time of 0.4 μs we detect EASs hitting ArNM, several of which provide bursts with a neutron multiplicity exceeding 2000 (see Figs. 20–22 of Chilingarian et al., 2016). The primary particle energies corresponding to these events are very high (>10 PeV).

In Fig. 1 we show the 1-s time series of one from 10 neutron bursts with multiplicities above 100 that occurred on the fair-weather day of 26 November 2016. To see the neutron burst in much more detail we monitor ArNM signals with a high frequency digitizing oscilloscope. The sequence of the amplitudes of pulses from proportional counter N2 of the ArNM recorded by a Picoscope 5244B is shown in Fig. 2. The record length was 100 ms including 20 ms pre-trigger time and 80 ms post-trigger time (the trigger time corresponds to 0 on the X-axis). The sampling rate was 250 Mb/s, corresponding to a sampling interval of 4 ns, and the amplitude resolution was 8 bits. The signal of the ArNM was also relayed to the MyRIO board (National Instruments) which produced a pulse for the oscilloscope triggering when the count rate of the detector exceeds a preset threshold value (usually a 20% enhancement above the running average). Bursts were observed as sequences of microsecond pulses temporally isolated from other pulses on a time scale of at least 100 μs.

The typic single signal shape is shown in Fig. 3. The observed burst is rather "dense" in the beginning (interval between pulses is a few microseconds) and much sparser at the end (interval between pulses is from tens to hundreds of microseconds). Most frequently, the pulse amplitude is the largest at the beginning of a burst. The interval between pulses varies during the burst: it is the shortest (about 3–5 μs) in the beginning and increases to tens and hundreds of microseconds at the end of the burst. The rise time of the neutron signal is ≈300 ns and the duration ≈500 ns.

Exhausting information on EAS core hitting ArNM can be found in the dataset of 50 high-multiplicity events published in the Mendeley repository (Soghomonyan et al., 2021). In Fig. 4a we show the distribution of neutron burst durations for 50 selected events from the Mendeley dataset; in Fig. 4b - the distribution of the multiplicities of these events registered by the proportional counter of the ArNM.

A large number of identical particle detectors (usually plastic scintillators) covering square kilometers of the area are used for detecting high-energy primary particles by registering huge EASs. High-energy particles from the EAS core comes within a few tens of nanosecond and a single plastic scintillator from the surface array with a usual dead-time of 1 μs will generate only one large pulse in response to multiple EAS core particles. The neutron monitor is enlarging the very short EAS time profile (20–30 ns) by ≈ 5 orders of magnitude (2-3 ms) making it possible to use rather a slow device (neutron monitor) for the registration of EAS cores. In Fig. 5 we show the 24 h time distribution of the neutron multiplicities. During the same day fine-weather day 26 November 2018, ArNM registered 10 bursts with multiplicities above 100. Each of these events corresponds to the high-energy EASs, which core hit the earth's surface nearby the detector. Measured multiplicity is proportional to the EAS energy and the closeness of EAS core to the detector. Thus, the distribution of multiplicity amplitudes can be related to the energy spectrum of the primary cosmic ray hadrons.

After the detailed simulation of the detector response function by modeling the interactions of primary particles in the atmosphere above the detector it will be possible to estimate the energy spectra of primary cosmic ray flux. Sure, the relation "multiplicity – primary energy" is statistical one, however, due to the high location (3200 m) and large surface (18 m^2) of ArNM during multiyear operation it is possible to collect enough events to recover the energy spectrum. In Fig. 23 of Chilingarian et al. (2016), we show the energy spectra of primary cosmic rays obtained by the relation of the frequency neutron multiplicities to the integral energy spectrum measured by MAKET array in the energy range near the "knee" of all particle spectra – 3–5 PeV (Chilingarian et al., 2016).

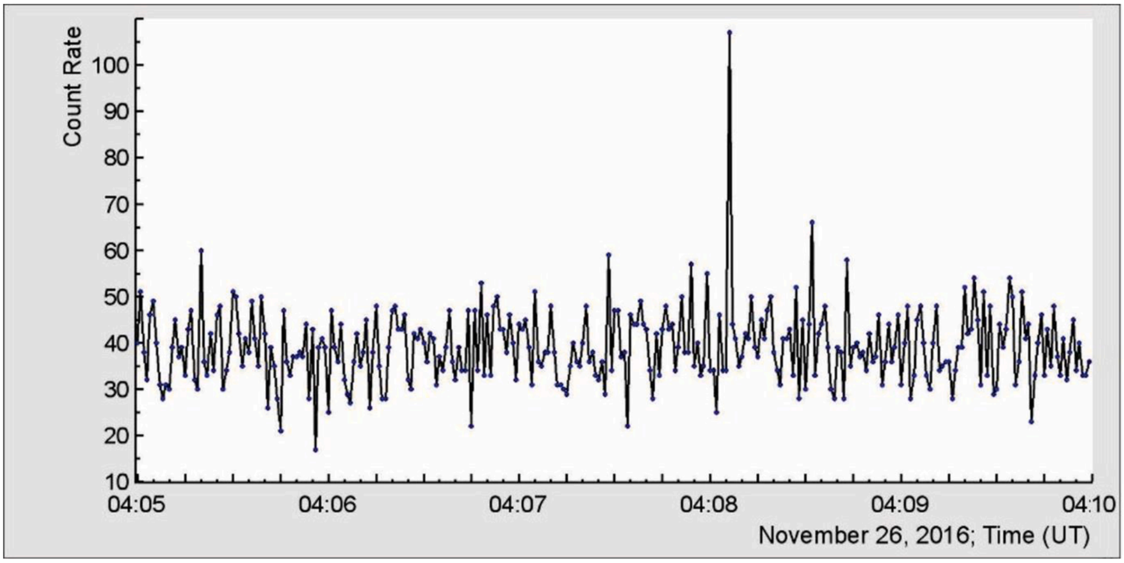

Fig. 1. The 1-sec time series of the count rate of the Aragats Neutron Monitor (the proportional chamber N2). A neutron burst with multiplicity of 107 is registered at 4:08:05 on November 26, 2016.

Registration of the neutron multiplicity was used, as well, at the scientific and educational center NEVOD (MEPhI). The mean time of the neutron "bursts" measured by the URAN array (see Fig. 3 in Izhbulyakova et al., 2020) well coincides with the measured by the ArNM (Fig. 4a). The neutron multiplicity method also is used for the investigation of hadrons in the cores of high-energy EAS at the Tien Shan high-altitude cosmic ray station (Chubenko et al., 2016). The observation of particle bursts recently published by the HAWC collaboration (Abeysekara et al., 2012) is very important as an independent observation obtained by implying different experimental techniques.

In addition, by measuring neutron multiplicity, it is possible to investigate the EAS cores in much more details than previously. An abundant number of the EAS particles that concentrated near the shower core highly saturate the nearby (at distances smaller than 5 m) detectors (usually plastic scintillators), making it impossible to research the hadron distribution in the EAS cores. Therefore, by registering neutron multiplicities by several proportional counters of NM the distribution of the parent hadrons at the EAS core also can be studied.

3. Possible scenarios of DTGF origination

High Altitude Water Cherenkov Array (HAWC, Abeysekara et al., 2012) consists of 300 water Cherenkov detectors of 4 m high and 7.3 m in diameter. A small, fast scintillator detector (7.62 × 7.62 cm LaBr3) located nearby huge water-Cherenkov detectors of HAWC, occasionally observed large particle bursts. The small detector output was attached to the Broadband Interferometric Mapping and Polarization (BIMAP) sensor's electronics (Shao et al., 2018). For each trigger, BIMAP captures 15 ms of data with 5 ms of pre-trigger data. All bursts observed at HAWC between September 2017 and September 2019 occurred during fair-weather days, meaning that there were no nearby lightning flashes, see Table 1 of Bowers et al. (2021). CORSIKA (Heck et al., 1998) simulations confirm that particle bursts originated from EAS core particles captured in nuclei of soil which produced high-energy gamma-rays through (n, γ) reactions. Observed by HAWC particle bursts were not related to atmospheric discharges; the observed bursts are initiated by particles belonging to EASs cores hitting the HAWC array.

Another large detector, the surface detector of the TA (TASD, Abu-Zayyad et al., 2013) is composed of 507 scintillator detectors on a 1.2 km square grid occupying totally 700 km^2 area. TASD provides shower footprint information including core location, lateral density profile, and timing, which are used for recovering of shower axes and energy. Each measuring unit consists of upper and lower scintillators 1 cm thick and 3 m^2 area. The upper and lower planes are separated by a 1 mm-thick steel plate and are read out by photomultiplier tubes that are coupled to the scintillator via an array of wavelength-shifting fibers. The output signals from the photomultipliers are digitized by a 12-bit ADC with a 50 MHz sampling rate. An event trigger (frequency 0.01 Hz) is recorded when three adjacent units observe a signal larger than three vertical equivalent muons (VEMs) within 8 us. (= 2 MeV per 1 cm of scintillator). When a trigger occurs, the signals from all units within ±32 us, which detect an integrated amplitude greater than 0.3 VEM are also recorded. The efficiency of registering high-energy photons on average is proportional to the thickness of the scintillator in cm (1-2% for the 1 cm thick scintillator).

The bursts of consecutive TASD triggers were recorded in 1 ms time intervals in correlation with lightning flashes above the telescope array (TA) detector, observed by the lightning mapping array (LMA) and the Vaisala National Lightning Detector Network (NLDN). The Lightning flashes that produce trigger bursts were very rare. There are typically about 750 NLDN-recorded flashes (IC and cloud to ground) per year over the 700 km2 TASD array. In 8 years of TA operation, there were identified only 20 bursts correlated with lightning activity (Abbasi et al., 2018). Thus, fewer than 0.5% of NLDN flashes recorded over the TASD were accompanied by identifiable gamma bursts. The burst durations were found to be within several hundred microseconds, and the altitude of the source was typical of a few km above ground level. The authors do not relate these showers to EASs, as in the HAWC and Aragats experiments, but to a downward negative leader, which ends up in a negative cloud-to-ground discharge (-CG) (Abbasi et al., 2019). In the recent publication (Belz et al., 2020) they introduce a lightning-related scenario of the "downward TGF" origination: "The results show that the TGFs occur during strong initial breakdown pulses (IBPs) in the first few milliseconds of -CG and low-altitude intracloud flashes, and that the IBPs are produced by a newly-identified streamer-based discharge process called fast negative breakdown."

Thus, to explain HAWC and Aragats bursts authors use well-known EAS physics, and for the explanation of the analogical bursts observed in the TA experiment – a streamer to leader transition including IBPs and their enigmatic sub-pulses. In the HAWC and Aragats experiments, the particle bursts and lightning activity are completely separated. No relation to lightning activity was assumed and observed. Maybe the TA burst events are a subsample of the EASs triggers that occasionally coincide with lightning activity? It will be very interesting if TA

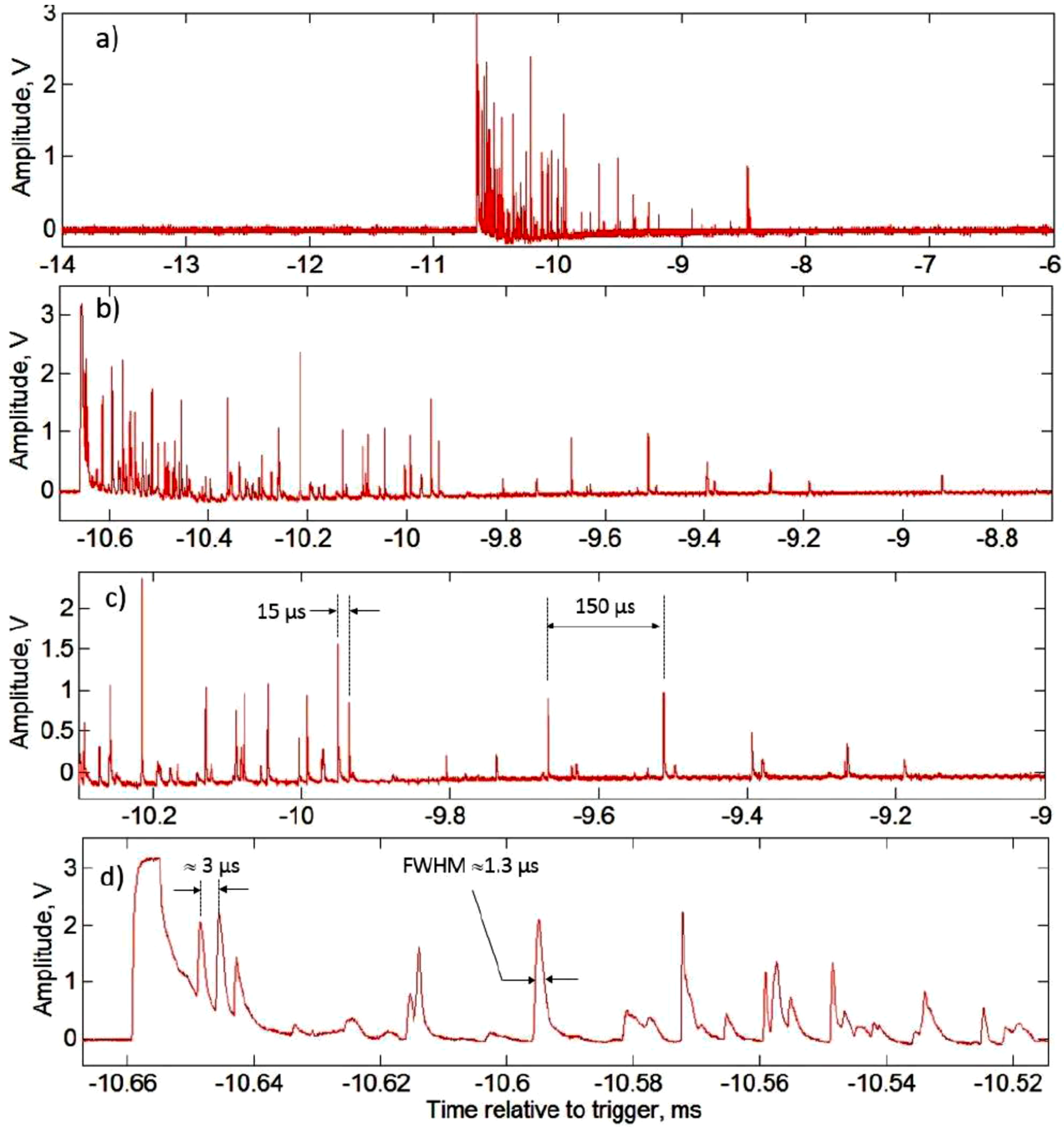

Fig. 2. Oscilloscope records of neutron burst that occurred at 4:08:05 on November 26, 2016. The burst duration is ≈ 2.2 ms and the multiplicity is 107 per m^2. The four panels (a-c) show the records of the burst on different time scales.

collaboration published similar bursts at fair weather that should hit TA array as frequently as HAWC and Aragats.

Recently another scenario of the origination of intense bursts based on corona discharges was suggested in Stolzenburg and Marshall (2021). The point corona discharges usually occurred beneath thunderstorms very near to the tips of the grounded sharp conductors when electric fields at the ground reach threshold values of ~3 to 5 kV/m. In a small discharge region, the strength of the electric field can reach 2 MV/m, and EAS-originated electrons will run away and make electron-photon avalanches producing an intense burst of particles on the earth's surface. However, because of the stochastic nature of the corona discharges, these small local regions will emerge spontaneously and not coherently. Thus, the TGEs observed by the remote detectors (and detectors inside the buildings) cannot demonstrate the coherent and smooth enhancement and decay of particle flux.

Another exotic hypothesis to explain the particle flux enhancements during thunderstorms is the ball lightnings origination in the skies with consequent intense radiation of gamma rays (Shmatov, 2020). This hypothesis identifies multiple light spots observed during TGEs in the skies above Aragats (Chilingarian et al., 2019) with a swarm of ball lightning emerging in the electrified atmosphere. Though, as for the previous hypothesis, the emergence of the stable gamma ray flux registered by detectors covering many thousands of m2 should be explained.

4. Conclusions

Enhanced particle fluxes emerging in space and on the earth's surface during thunderstorms are produced in the atmospheric electric field by the runaway process when free electrons from small and large EASs enter an electric field, which strength is larger than the critical value. Particle bursts observed by HAWC and Aragats experiments can be

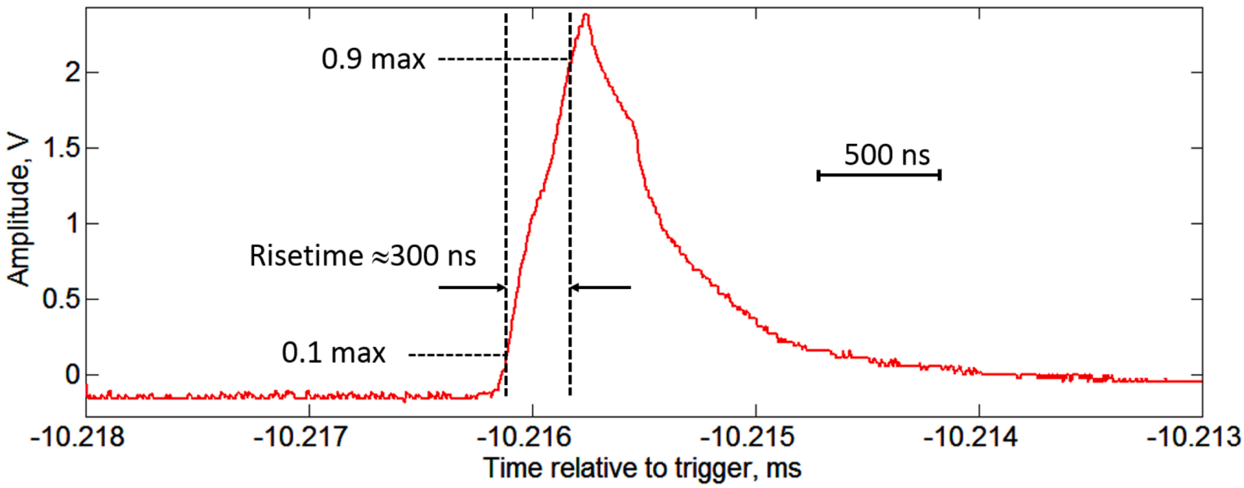

Fig. 3. A 5 μs fragment of the oscilloscope record shows a typical pulse shape of the neutron monitor, the risetime (0.1–0.9) is ≈300 ns.

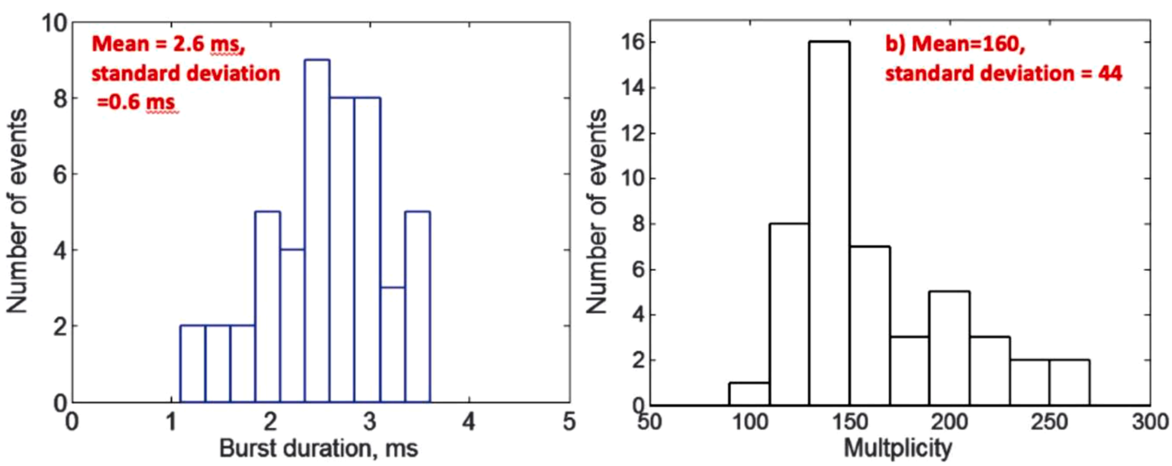

Fig. 4. Histogram of the neutron burst duration (a) and corresponding multiplicity histogram (b).

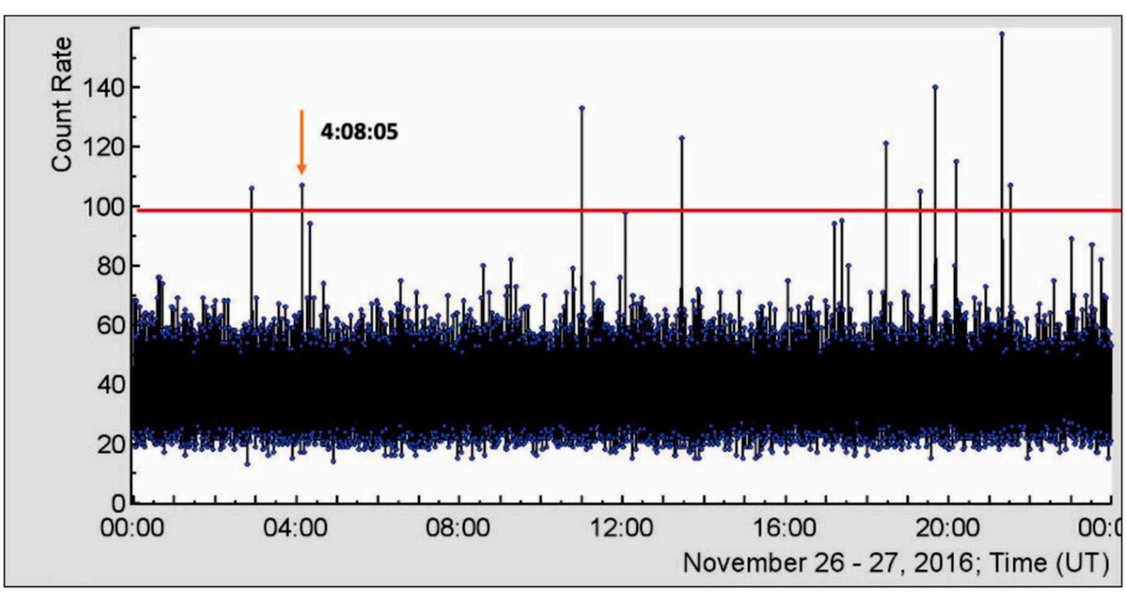

Fig. 5. 1-s time series of ArNM multiplicities (proportional counter N2). By the red line the multiplicities above 100 are outlined, by the red arrow – the neutron burst shown in Figs. 1 and 2.

explained by the conventional EAS physics. Thus, EAS physics and HEPA are synergistically connected and need to exchange results for the explanation of particle bursts and for revealing the influence of atmospheric electric fields on the EAS shape and size.

The largest cosmic ray experiments (Abeysekara et al., 2012; Izhbulyakova et al., 2020; Chubenko et al., 2016; Bartoli et al., 2016; Li et al., 2017) confirm the neutron bursts from EAS cores without any relation to lightning occurrences. To explore the lightning nature of the bursts observed by TA collaboration, which they correlated with lightning activity (streamer-based discharge process called fast negative breakdown), it will be very interesting to collect bursts in fair weather and compare them to the burst data collected during thunderstorms. And, sure, the long waiting physical mechanism of the MeV particle acceleration during the atmospheric discharges should be explained. To prove the corona discharge and ball lightning scenarios authors should demonstrate that the corona discharge at multiple not connected metallic structures and emitting by randomly emerged ball lightning system in the skies can produce a uniform electric field above the ground on tens of thousands of square meters area, and that continuous discharges can sustain such a uniform field for minutes.

The network of near 50 Neutron monitors operate at different altitudes, latitudes, and longitudes for more than 60 years (Mishev and Usoskin, 2020). Maintenance of such a detector is very cheap and they are providing data for many years with minimal intervention of personnel. The data stream is collected in the databases with open access and a user-friendly interface (Mavromichalaki et al., 2011). By using the neutron monitor database (NMDB) after a simple modernization of NM electronics, and after making simulations of the detector response for all included in the network neutron monitors, it will be possible to recover the energy spectra of galactic cosmic rays all around the globe.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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