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The synergy between High-energy Physics in Atmosphere and Cosmic Ray Physics

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Abstract

The high-energy physics in the atmosphere (HEPA) undergoes a profound transformation in the last decade. Correlated measurements of particle fluxes modulated by strong atmospheric electric fields, of wideband waveforms originating from atmospheric discharges, optical emission in the lower atmosphere, along with registration of a variety of meteorological parameters on the earth's surface (including near-surface electric field and geomagnetic field), is rewarded by a better understanding of very complicated processes in the thunderous atmosphere. The synergy of the Cosmic Ray and Atmospheric physics lead to the development of models of the origin of particle bursts registered on the earth's surface, the vertical profile of the strong electric field in the lower atmosphere, muon stopping effect, interrelations of particle fluxes and lightning flashes, circulation of Radon progenies, and others.
The successes of the multivariate measurements of the last decade put the HEPA the priority science areas in both the Cosmic Ray and the Atmospheric physics communities. The HEPA research intensifies the development of new methods of testing models and theories on atmospheric electricity, particularly in conditions that are related to the most important processes that influence earth's environments.

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1. Introduction

Different kinds of particle accelerators are operating in the intergalactic plasmas filling the space with high-energy particles; some of them reach the earth's atmosphere and unleash extensive air showers (EASs) covering several km^2 on the ground. Many species of elementary particles are born in the terrestrial atmosphere by high-energy protons and fully-stripped nuclei accelerated at the galactic and extragalactic sources and on the Sun. During thunderstorms, emerging strong electric fields modulate the particle showers significantly altering secondary particle energy spectra and initiating short and extended particle bursts. The impulsive enhancements of the particle fluxes (so-called thunderstorm ground enhancements – TGEs, [1,2]) are disclosed as peaks in the time series of count rates of particle detectors coinciding with the strong atmospheric electric field, which accelerates and multiplies free electrons of cosmic rays. Only a multisensory approach joining particle and atmospheric physics instrumentation will allow the revealing of the physics of particle burst phenomena, usually connected both to the EAS phenomenon and complicated atmospheric processes, now referred to as high-energy physics in the atmosphere (HEPA).

Multiyear observations made at Aragats cosmic ray observatory give a vast amount of data on particle bursts. When researching the operation of the electron accelerators in the thunderclouds the ambient population of the secondary cosmic rays constitutes a more-or-less uniform background. Free electrons abundant at every height in the atmosphere are used as seeds by the atmospheric electron accelerators, an analog of "electron guns" in manmade accelerators. The cores of EASs when occasionally hitting the particle detectors originate short bursts of relativistic particles of ≈1 ms duration [3]. To detect significant peaks of both types, we need networks of precise particle detectors and spectrometers providing a large count rate, which operates reliably for years long [4-6].

The comparison of electron and gamma ray energy spectra measured on Aragats, allows us to identify the emerging electrical structures in the atmosphere which makes it possible to accelerate seed electrons from the ambient population of cosmic rays up to ≈50 MeV [7,8]. Muons do not multiply in the electric field as electrons; however, electric fields lead to the modernization of their energy spectra and induce an interesting muon stopping effect, used for the estimation of the maximum energy of atmospheric electric fields [9]. Huge fluxes of electrons and gamma rays, measured on mountain peaks, can exceed the background up to 100 times and pose yet not estimated influence on the climate. More than 2,000 thunderstorms are active throughout the world at a given moment, sending $\approx 10^{18}$ electrons and gamma rays with energies above 100 keV to the earth's surface each second. The long-term effects of this radiation on climate should be carefully estimated.

In turn, if the experiment goal is to measure precisely shower size (number of electrons) and muon content of the EASs, we have to consider the possible influence of the atmospheric electric field, which can artificially enlarge the number of the shower particles and introduce a bias in the primary particle energy estimate. The existence of such a strong electric field above EAS arrays can be proved by recovering TGE electron and gamma ray energy spectra and by the abrupt enhancement of the EAS array triggers [10-12]. 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 [13].

EAS and TGE physics 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. In this paper, we will present results demonstrating the synergy of atmospheric cosmic ray physics that will provide opportunities for the further development of HEPA opening new areas of research and connecting different branches of science for understanding the physics of geospace.

1. EAS cores or a very special lightning discharges are generated "downward TGFs"?

High Altitude Water Cherenkov Array (HAWC, [14]) consists of 300 water Cherenkov detectors of 4 meters high and 7.3 meters 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. For each trigger, BIMAP captures 15 milliseconds of data with 5 milliseconds 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 Tab. 1 of [15]. CORSIKA 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.

Another large surface detector of the TA (TASD, [16]) is composed of 507 scintillator detectors on a 1.2-km square grid occupying a total 700-km^2 area. TASD provides shower footprint information including core location, lateral density profile, and timing, which are used for recovering shower axes and energy. Each measuring unit consists of upper and lower scintillators 1 cm thick and a 3 m^2 area. The bursts of consecutive TASD triggers were recorded in 1-millisecond 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). There are typically about 750 NLDN-recorded flashes (IC and cloud to ground) per year over the 700-km^2 TASD array. In 8 years of TA operation, there were identified only 20 bursts correlated with lightning activity [17]. Thus, fewer than 0.7% of NLDN flashes recorded over the TASD were accompanied by identifiable gamma bursts. The burst durations were within several hundred microseconds and the altitude of the source - was 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) [18].

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. Possibly, the TA burst events are also initiated by EAS cores hitting the array, without any relation to the lightning activity. The difficulty of detecting EAS cores by particle detectors consists of the very short time of their propagation through the detector (a few tens of ns). Usually, the window for particle registration is set to ≈ 1 microsecond, and all EAS core particles will be registered as one very large pulse.

The Aragats neutron monitor (ArNM) has a unique option to register thermal neutrons.

Yuri Stenkin et al., for the first time, described the detection of neutron bursts in the NM related to the occasional hitting of the detector by a core of a high-energy EAS [19]. 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 [20]). The primary particle energies corresponding to these events are exceeding 10 PeV. In Fig. 1 we show pulses from a neutron burst with a multiplicity of 107, which was registered at 4:08:05 on November 26, 2016. The sequence of the amplitudes of pulses from one of ArNM proportional counters recorded by a Picoscope 5244B is shown in Fig. 1(a-c). The signal of the ArNM was also relayed to the NI MyRIO board, 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 microseconds.

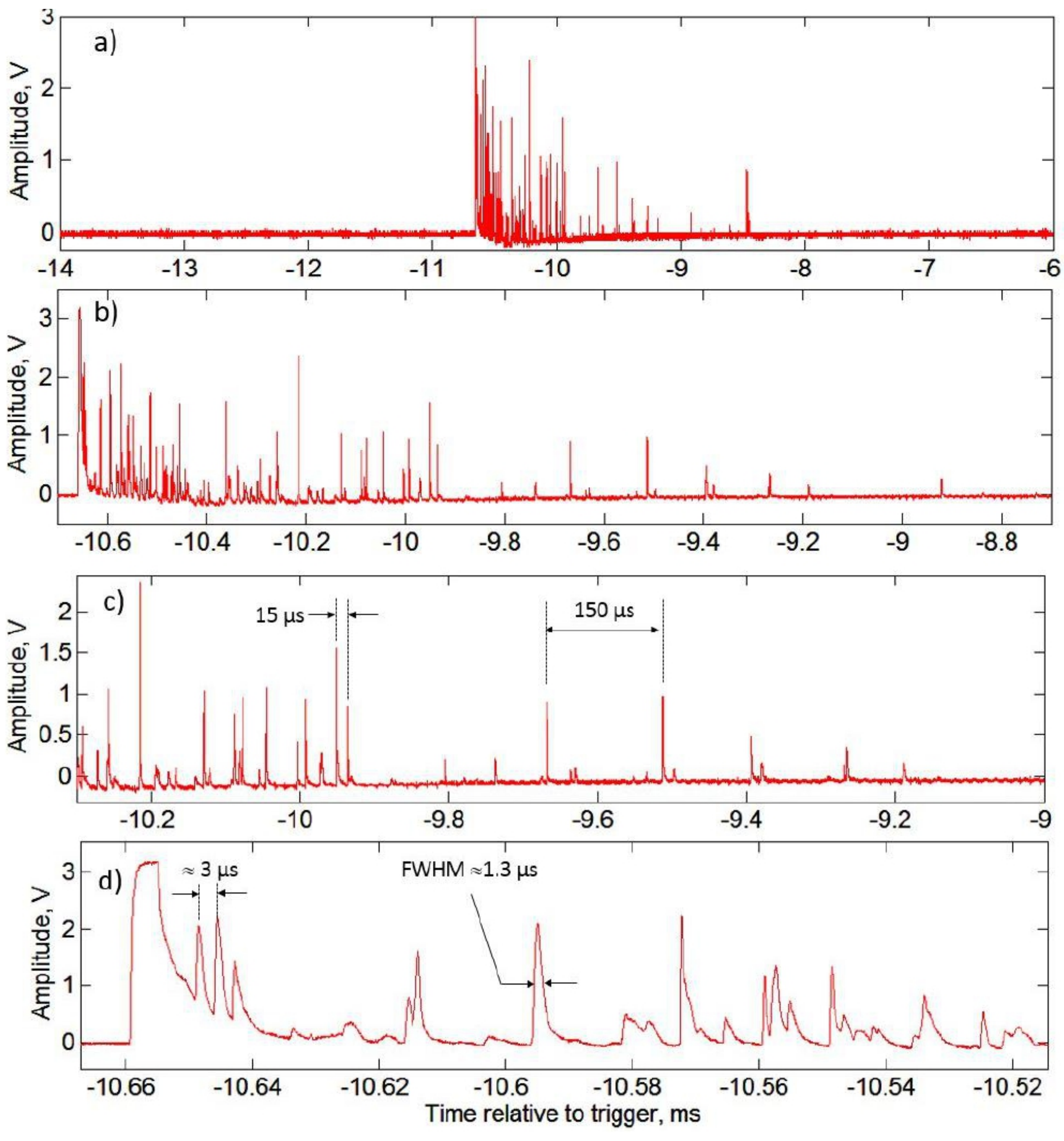

Figure 1. Oscilloscope records of neutron burst that occurred at 4:08:05 on November 26, 2016. The burst duration is ≈ 2.2 milliseconds and the multiplicity is 107 per m^2. The four panels (a-c) show the records of the burst on different time scales.

Exhausting information on EAS core hitting ArNM can be found in the dataset of 50 high-multiplicity events published in the Mendeley repository [21]. Thus, the neutron monitor is enlarging the very short EAS time profile (20 – 30 ns) by ≈ 5 orders of magnitude (2-3 milliseconds) making it possible to use rather a slow device (neutron monitor) for the registration of particle bursts. Hence, using multiyear monitoring results, we explain "downward TGFs" by very common cosmic ray physics phenomena – EAS cores hitting the detector.

2. Possible overestimation of the PeV gamma ray energy by high-altitude EAS arrays during thunderstorms

With establishing high-altitude EAS arrays HAWC [22] and LHASSO [23] with excellent possibilities of gamma/hadron separation, finally a century-long problem of the cosmic ray origin is near to being solved. For the first time, it was possible to reliably verify that galactic gamma-ray spectra measured from the direction of several well-known SNRs extend beyond 1 PeV. Due to the large surface of detectors and high location, LHASSO has a very low energy threshold (1 TeV) and excellent rejection of hadron-induced extensive air showers. We select the LHASSO array not only because recently they identified 12 PeVatron candidates, which have been previously observed by imaging atmospheric Cherenkov telescopes. LHAASO site locates at Haizi Mountain, Daocheng County, Sichuan Province, which is at the edge of the Tibetan Plateau with an altitude up to 4410 m. The Tibetan plateau is also known as a place of frequent thunderstorms and very large intracloud electric fields, that vertical profile can extend to 1-2 km. The strength of the atmospheric electric field depends on the air density (altitude) and can reach 1.5-2 kV/cm at altitudes 3-6 km. Several EAS arrays, including those located in Tibet, already report the 20-30% enhancement of the trigger rate during thunderstorms [24-26]. At Aragats was registered 400% enhancement of MAKET array trigger rate on 19 September 2019 [2,27]. Therefore, the RREAs can effectively mimic EASs successfully overgoing all checks.
To understand the influence of such a strong electric field on the EAS size we perform simulations with CORSIKA code. The electric field was introduced at heights of 4460-6460m. The threshold energies of secondary particles (hadrons, muons, electrons, gamma rays) were 0.3, 0.3, 0.03, 0.03 GeV consequently. In Table 1 we show the simulated number of electrons in fair weather, and how a number of EAS electrons abruptly enlarged after crossing the large-scale electric field.

Table 1. Enhancement of the number of electrons initiated by a primary gamma ray with energies from 1-1000 TeV in the electric field of different strengths

Eo	Ne			
(TeV)	Ez=0 kV/cm	Ez=1.9 kV/cm	Ez=2.0 kV/cm	Ez=2.1 kV/cm
1	316	12103	15904	18044
10	5560	148088	201096	229163
100	69996	1374853	1775837	2169369
1000	827547	10346388	13605357	14066929

In Fig. 2 we show the abrupt enhancement of electron number, after an increase of the electric field strength above the critical value. Starting from 1.7 keV/cm the number of electrons exponentially grows for all energies of primary gamma rays.

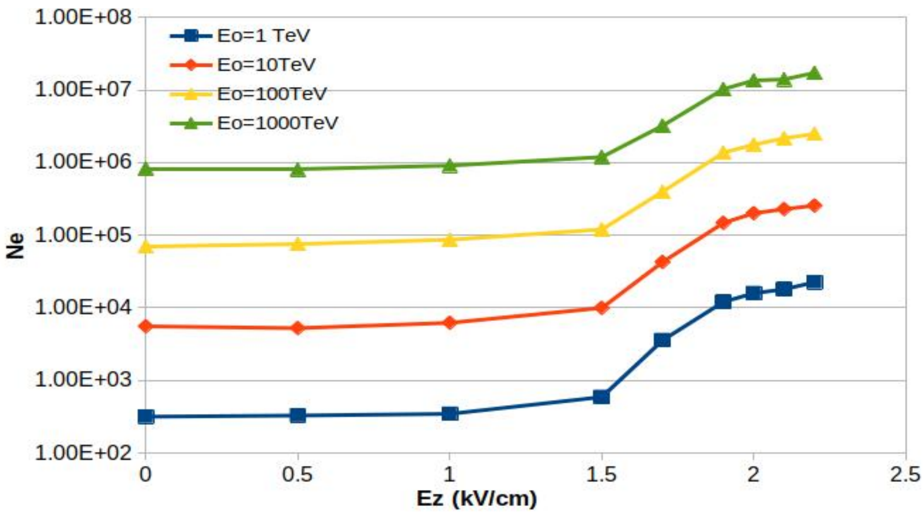

Figure 2. The number of electrons registered on the earth's surface after crossing the atmospheric electric field of different strengths. The primary gamma ray enters the electric field at a height of 6460 m.

In Table 3 we show the energy of a primary gamma ray used in the simulation and calculated by the "biased" shower size (number of electrons after crossing the electric field) energy. As we can see in the Table the estimated energy of the primary gamma ray significantly differs from the "genuine" value.

Table 2. Genuine and estimated energies of primary gamma rays after transport through the electric field of 2.1 kV/cm strength.

Eo (GeV)	Eest (GeV)
1.00E+03	2.23E+04
1.00E+04	1.34E+05
1.00E+05	6.50E+05
1.00E+06	2.42E+06

3. Conclusions

TGE measurements prove that a strong electric field covers huge volumes in the thunderous atmosphere. The largest TGEs registered by SEVAN network [28] units at Mt. Musala (Bulgaria) and Mt. Lomnicky Stit (Slovakia [29]), as well as the results obtained by the Japanese group [30], prove that TGE isn't only a specific Aragats feature, but – a universal characteristic of thunderstorms. The measured energy spectra allow us to get insight into the charge structure of the thundercloud and clarify the role of the lower positively charged region (LPCR) in the development of the TGE.

RREAS are accelerated to large energies by atmospheric electric fields and end up as TGEs, which allocate to the earth's surface sizable doses of radiation. This additional radiation should be introduced to the models of weather forecasting and global change. Our measurements show that a strong electric field covered a huge area in the thunderous atmosphere, modulating and largely enhancing the cosmic ray flux at areas of many tens of km^2. Such strong electric fields just above the arrays of particle detectors located at high altitudes can significantly change the EAS electron and gamma ray content leading to a large overestimating of the energy of primary particles during thunderstorms

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Particle bursts observed by HAWC and Aragats experiments can be explained by 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 confirm that the neutron bursts originated from EAS cores without any relation to lightning occurrences.

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