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Sinergy of extra-terrestrial particle accelerators and accelerators operated in the terrestrial atmosphere

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Sinergy of extra-terrestrial particle accelerators and accelerators operated in the terrestrial atmosphere

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Abstract We performed simulations of the EAS particle transport initiated by ultra-high-energy gamma rays entering the terrestrial atmosphere. During thunderstorms, the electric fields above the LHAASO array efficiently modulate EAS particles. Because of this modulation, the possible bias on the energy estimation for primary energies up to 100 TeV can be up to ten-fold. Moreover, for the higher primary energies (≈1 PeV), the electric field modulation enlarges "genuine" primary gamma ray energy 2.5-3 times. This result is very important because observation of PEVatrons by LHAASO is based on rather small statistics, and the highest energy events can occasionally coincide with thunderstorms. We also demonstrate the existence of a threshold effect on the intracloud E-field strength needed to trigger the startup of a runaway process that exponentially multiplies the free electrons entering a strong atmospheric electric field.

1. Introduction

Different kinds of particle accelerators are operating in the intergalactic plasmas filling the space with high-energy hadrons and gamma rays, which reach the earth's atmosphere and unleash extensive air showers (EASs) consisting of many millions of elementary particles covering several km^2 on the ground. During thunderstorms, emerging strong electric fields modulate the EAS particles significantly altering their energy spectra. When researching the operation of the electron accelerators in the thunderclouds the ambient population of the cosmic rays from the small and large EASs constitutes a more-or-less uniform background. The impulsive enhancement of the particle flux (so-called thunderstorm ground enhancements – TGEs, [1,2]) is revealed as a set of small or large peaks superimposed on this background. In particle detector count rates taken with time binning between 50 ms and a minute, we see peaks coinciding with large disturbances of the atmospheric electric field. Free electrons from small and large EASs are used as seeds by the atmospheric electron accelerators, an analog of "electron guns" in manmade accelerators. The cores of EASs occasionally hit the particle detectors to originate bursts of particles of 2-3 ms duration [3]. To detect significant peaks, we need precise particle detectors and spectrometers with a large count rate operated reliably for years.

In turn, if the experiment goal is to measure precisely shower size (number of electrons) and muon content of an EAS, 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. Thus, in spite of the lifetime of an EAS being a few microseconds, and TGE can be prolonged for minutes, they are interconnecting. Schematic views of various particle accelerators can be seen in cartoon Fig.1.

A core-collapse supernovae remnants (SNR) are the first candidate for the PeVatrons. With the advent of high-altitude EAS arrays HAWC [4] and LHAASO [5] 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.

As we can see in the right part of Fig.1, cosmic ray hadrons lose any directional information because they are deflected by galactic magnetic fields, while gamma rays represent a very small fraction of the total particles that impinged on Earth, keeping the initial direction pointed on their source. However, there is a controversy in determining the hadron or lepton origin of the detected gamma rays. Constraints on the energy of the relativistic electrons producing inverse Compton (IC) gamma rays at PeV energies can help to solve this controversy since ultra-high-energy electrons suffer strong energy loss in magnetic fields therefore their acceleration beyond PeV energies is questionable. Thus, PeV gamma ray emission can be attributed to a population of high-energy protons that would emit gamma rays through proton-proton interactions when traversing surrounding matter. Thus, PeVatron candidates observed by HAWC and LHAASO can reveal the hadronic dominance in SNR gamma emission.

Possible scenarios of electron acceleration in the atmospheric electric fields are shown on the left of the cartoon [6]:

a) The dipole formed by the main negative (MN) region in the middle of the thundercloud and its mirror image at the ground (MN-MIRR) that accelerates electrons downward. If the MN charge is very large inducing a very strong electric field that exceeds the critical value, the relativistic runaway electron avalanches (RREAs, [7-9]) can be unleashed and TGE will be large, and energies up to 50 MeV will be observed. The near-surface electric field will be in the deep negative domain − 30 kV/m for the largest TGEs. Thus, regardless of the cloud base location, electric field can extend almost to the earth's surface, and both gamma rays and electrons can be registered by particle detectors and spectrometers.
b) If a transient lower positively charged region (LPCR, [10]) emerges another dipole is formed by MN-LPCR. For a few minutes, when LPCR is mature and screens the detector site from the negative charge of MN, the near-surface field is in the positive domain. TGE can be very intense in Spring when LPCR can be very close to the earth's surface (25–50 m). Fields induced by the MN-MIRR and MN-LPCR are identically directed and their sum can reach rather large values exceeding the threshold value to start RREA by 20–30%. In Summer, the distance to the cloud base is larger (200–400 m) and usually, only gamma rays reach the earth's surface and are registered by the particle detectors. Electrons are attenuated in the dense atmosphere. TGE continues also after the returning of the near-surface electric field strength to the fair-weather value, due to tens of minutes long life-time of Radon progeny (^{214}Pb and ^{214}Bi). The rain brings back the Radon progeny from the atmosphere to the earth's surface and for several tens of minutes provides additional gamma ray radiation (the washout effect, see [11]).
c) In addition to these basic scenarios, the fast-changing charge structure of the cloud produces a more complicated configuration of the electric field. For instance, TGE can start with mature LPCR, but after its contraction, MN-MIRR sustains a strong electric field. Alternatively, in the middle stage of the first scenario, the LPCR is formed and for a few minutes, the near-surface electric field rises and reaches positive values, and then returns again to deep negative values when LPCR is depleted. The scenarios of the origination of the downward electron-accelerating electric field are numerous and the corresponding TGEs may vary in intensity and energy spectra; the corresponding near-surface electric field also can exhibit several reversals.

A major challenge of EAS experiments is the energy scale calibration. The shower size (Ne) is rather well correlated with the energy of the primary particle. However, the ambiguity in the particle type identification and large fluctuations of first interaction depth (shower age) smear the E-Ne relation. Additional difficulty poses possible biases due to emerging atmospheric electric fields. In the presented report, we will demonstrate how the emerging electric fields can introduce a bias in the energy estimation made by LHAASO. Due to the large surface of detectors and high location, LHAASO has a very low energy threshold (1 TeV) and excellent rejection of hadron-induced extensive air showers (reaching 10^{-5} at PeV energies). We select the LHAASO 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, whose vertical profile can extend to 1-2 km. As we show in the companion paper [12], the extension of the strong atmospheric electric field can reach 2 km vertically and 10 km horizontally. 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 [13-15]. Correspondingly, the EAS particle number with energies above the detector threshold is significantly enhanced. As a remedy for the shower size artificial enhancement, the shower size was reduced, resulting in changes in the detector trigger rate [15]. At Aragats was registered 400% enhancement of MAKET array trigger rate on 19 September 2019 [2,16]. Therefore, the RREAs can effectively mimic EASs successfully overgoing all checks.

To understand the influence of such a strong and prolonged electric field on the EAS size we perform simulations with CORSIKA code, analogically to our previous study for the primary protons transport above the Aragats research station [17].

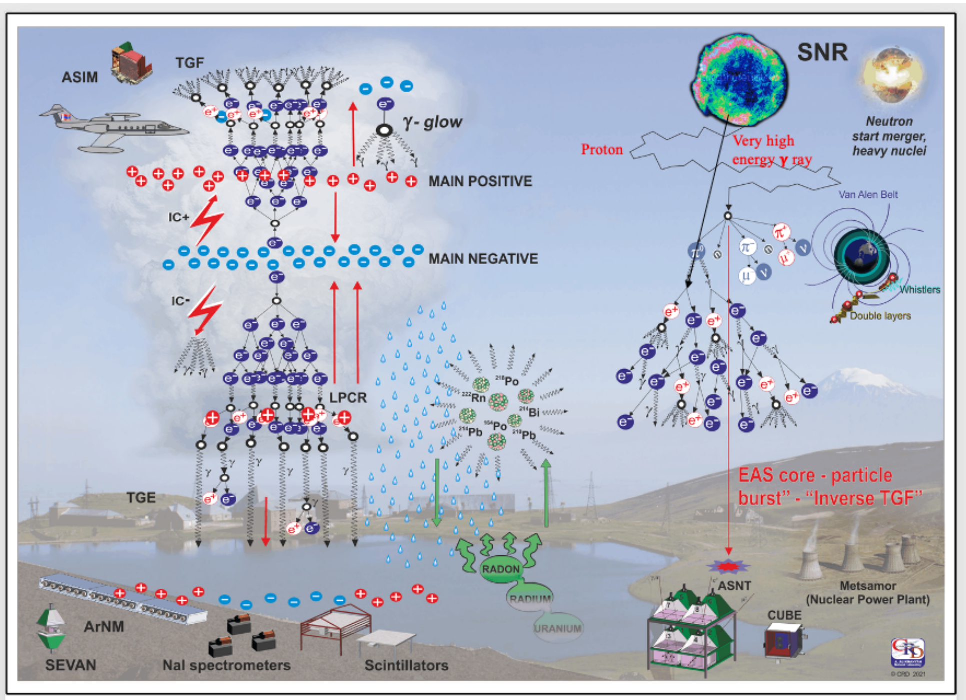

Figure 1. Intergalactic, galactic, and planetary accelerators, and radiation sources along with elementary particle detectors for their detection on the earth's surface

2. Simulation of air showers initiated by very high energy gamma rays traversing electric fields above LHAASO array

The code of CORSIKA 7.7400 [18], version 7.56 was used in these simulations. 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 respectively. 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 (TeV)	Ne			
	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 Figure 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 kV/cm the number of electrons exponentially grows for all energies of primary gamma rays.

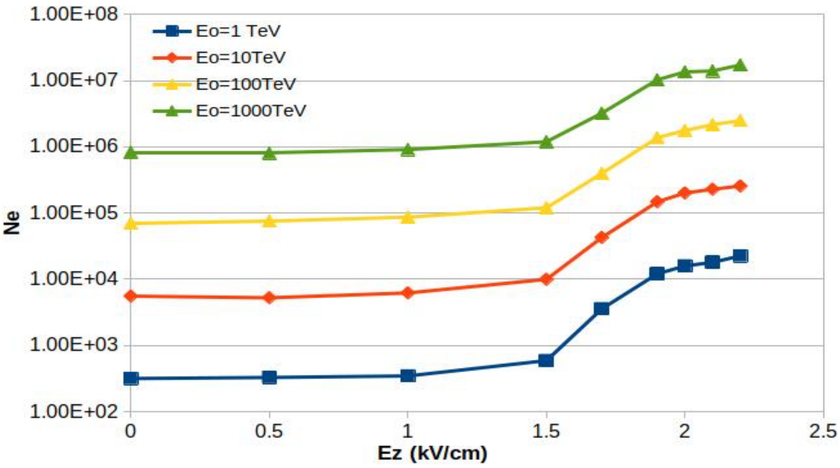

Figure 2. The number of electrons registered on the earth's surface after crossing the atmospheric electric field of different strengths. The primary gamma ray enters the electric field at a height of 6460 m.

In Figure 3 we show the correlation of the primary energy with shower size, leading to a simple energy estimator, shown in the body of the Figure. The obtained approximation was used for the estimation of the primary gamma ray energy after crossing the electric field. The number of EAS electrons was significantly enhanced, see Table 2.

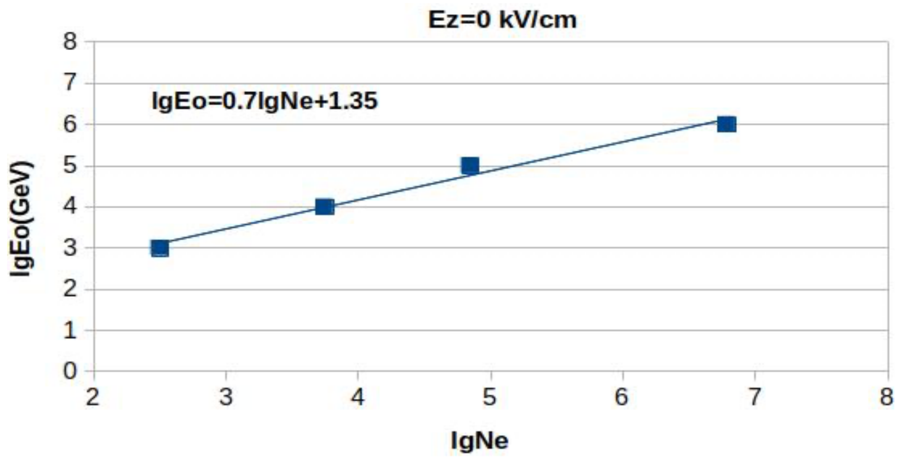

Figure 3. The dependence of primary gamma ray energy on the number of electrons (shower size) reaching 4460 m (the height of LHAASO experiment)

In Table 2 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

We perform simulations of gamma ray transport in the thunderous atmosphere above the LHAASO array to research possible biases in the energy estimation (we use a very simple estimator based on shower size Ne only). For the low primary energies (1 TeV) the bias was ten-fold and more, for the higher primary energies (1 PeV) 2.5-3 times. As the highest energy gamma rays observed by LHAASO are rather scarce, it is important to check if they were detected in fair weather and if electrons were not multiplied in the strong electric fields above the detector. We demonstrate as well the threshold effect of intracloud electric field for starting a runaway process, that exponentially multiplied the free electrons entering a strong atmospheric electric field.

Acknowledgement

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