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On the origin of the particle fluxes from the thunderclouds: Energy spectra analysis

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Abstract – Simultaneous measurements of the gamma ray differential energy spectra, electric field disturbances, and meteorological conditions provided by experimental facilities located at Mt. Aragats in Armenia allows to establish the model of particle acceleration and propagation in thunderstorm atmosphere. We present comparisons of measured and modeled thunderstorm ground enhancements (TGEs). The origin of the majority of TGEs is the MOS process —the modification of energy spectra of cosmic ray electrons in the atmospheric electric fields. The gamma ray differential energy spectra are well described by the power law function with indexes in the range $-1.5 \div -2.5$ for the electric field strengths 0.8–1.5 kV/cm at altitudes of 3400–5000 m a.s.l. The good agreement of the characteristics of experimental and simulated TGEs gives hope to estimate the intracloud electric field by the observed parameters of TGE gamma ray energy spectra.

Introduction. – Recent reports on intense fluxes of high-energy electrons, gamma rays and neutrons associated with thunderstorms illustrate that new interesting physics is still being discovered in our atmosphere [1,2]. Measuring as much as possible parameters of particle fluxes, electric field disturbances and meteorological environments allows for the first time to simultaneously detect and describe electron, gamma ray and neutron fluxes from the thunderclouds [3], observe relativistic runaway electron avalanches (RREA) [4] and finally develop a comprehensive model of the thunderstorm ground enhancement (TGE[1]) [5].

Due to difficulties of observation of the structure of the intracloud electric field, research of high-energy phenomena in atmosphere heavily used computer simulation. Here we report experimental observations of intense gamma ray fluxes by the network of the surface particle detectors located at mountain altitudes supported by the modeling of particle propagation in the thunderstorm atmosphere. The parameters estimated both from simulations and observations allow direct comparisons and unambiguous physical inference on the nature of the TGE. TGE originated from the lower dipole between the main negatively charged layer in the middle of the thundercloud and the transient lower positive charge region (LPCR) [6] in the bottom of the thundercloud. The lower dipole accelerates electrons from the ambient population of secondary cosmic rays (CR) downward. The electric field effectively transfers energy to the electrons modifying their energy spectra (MOS process) [7,8]. As thunderclouds at mountain altitudes usually are very close to the Earth's surface, the electron and gamma ray fluxes escaping from the thundercloud do not completely attenuate in the atmosphere and reach the Earth's surface enhancing a rather stable CR "background" flux in the energy range 1–100 MeV. If the electric field strength exceeds the critical value, the relativistic runaway avalanches (RREA) [9–11] may be unleashed, enlarging the electron and gamma ray fluxes several times. RREA, called also extensive cloud showers (ECS) [4], are systematically different from the extensive air showers (EASs) originating from the galaxy or from the high-energy solar cosmic rays incident on the Earth's atmosphere.

Most of the enhancements embedded in the time series of the particle count rates are rather small —only

[1]The name was introduced in [4]. Another name has been given to "thunderstorm" particles in [2], *i.e.* "gamma-ray glows". However, we will continue to refer to this emission as TGE, since it reflects the observed physical phenomenon and is directly linked to the analogical phenomena of terrestrial gamma flashes (TGFs) and ground level enhancements (GLEs).

a few percent above the cosmic ray background (see the statistical analysis of TGE events in [12]). The simulations of secondary cosmic ray electron propagation in weak electric fields (with the strengths smaller than the threshold value E_{th}, necessary for starting the RREA process) were performed with the GEANT4 code. Electric fields provide additional energy to CR electrons by modifying their spectra; consequently the electron lifetime increases, and additional path lengths in the atmosphere enlarge the probability of the gamma ray production. As a result, we obtain additional gamma rays at the observation level. Terrestrial gamma flashes (TGFs) [13] and thunderstorm ground enhancements (TGEs) are usually explained by invoking a runaway process, requiring very strong electric fields emerging in clouds. For instance, the authors of ref. [14] stated: "Any intense burst of gamma-rays in our atmosphere with energies exceeding 7 MeV, almost certainly is produced by runaway electrons experiencing RREA multiplication". However, in contrast to TGFs the MOS process is dominating in the TGE generation, especially in the energy range above 40 MeV. The MOS process can only provide sufficient number of gamma rays with energies larger 40 MeV; the RREA process generates gamma rays with energies below 40 MeV although with a much larger intensity.

Minute-to-minute differential energy spectra of gamma rays measured by the NaI spectrometers located at an altitude of 3200 m (see details in [15]) were used to compare the power law indexes and intensities of gamma ray differential spectra with simulations in order to relate the characteristics of the measured TGE spectra to electric field strength in thunderclouds.

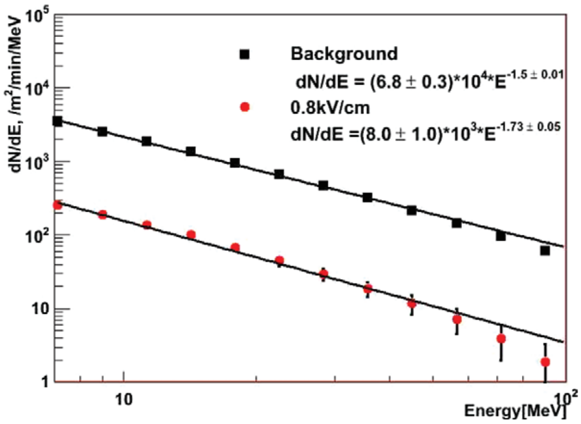

Fig. 1: (Colour on-line) Comparison of the energy spectrum of the secondary CR gamma rays (background) with the MOS gamma ray spectrum at 3200 m altitude; the electric field of 0.8 kV/cm strength is prolonged 1600 m.

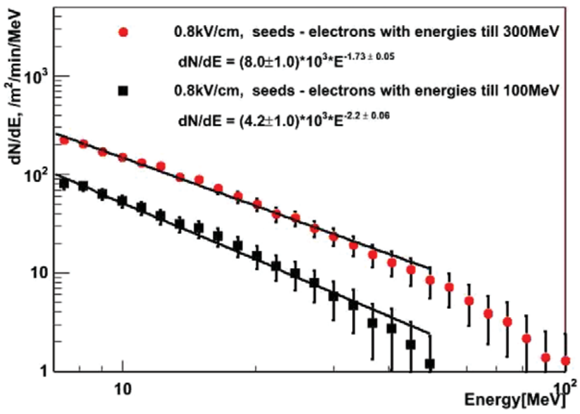

Fig. 2: (Colour on-line) Comparison of gamma ray energy spectra originated from electrons with energies from intervals 1–300 and 1–100 MeV; the electric field of 0.8 kV/cm strength is prolonged 1600 m.

Simulation of the MOS process. – The secondary cosmic ray electrons with energies up to 300 MeV were generated with the PARMA code [16]. Particle propagation and multiplication were simulated by the GEANT4 code in the thunderstorm atmosphere's uniform electric field prolonged from 5000 m till 3400 m and then an extra 200 m till the particle detector location at 3200 m. An additional "thunderstorm" gamma ray energy spectrum is compared with the ambient CR spectrum in figs. 1, 2; the spectrum of surplus gamma rays is prolonged up to 100 MeV. The MOS/CR ratio is ~10% up to energies of ~20 MeV. Then the ratio is quickly decreased, demonstrating that the MOS process provides a minor enhancement of gamma rays above energies of ~40 MeV; nonetheless large-area particle detectors located at Aragats can reliably register these small enhancements. To consider the influence of high-energy electrons the energy spectrum of gamma rays originated from electrons with energies in the range 1–100 MeV is compared with the energy spectrum obtained from electrons with energies in the range 1–300 MeV. As we can see in fig. 2 if the electric field strength is low (0.8 kV/cm, well below the RREA threshold) the number of gamma rays originated from electrons with energies 1–100 MeV is much smaller than the number of gamma rays originated from electrons with energies 1–300 MeV, although the number of seed electrons with energies 1–100 MeV is 10 times more than the number of electrons with energies 100–300 MeV. Thus, the RREA process accelerated electrons up to ~40 MeV [8] and enhancing the electron and gamma ray fluxes more than an order of magnitude cannot be responsible for the majority of TGEs registered at Aragats. The MOS process enhances electron and gamma ray fluxes for a few percent, however, for much larger energies than RREA, is the major player responsible for TGE process.

In fig. 3 the dependence of the MOS gamma ray spectra on the electric field strength is demonstrated. We can see that not only the number of gamma rays increased with the electric field strength, but also the absolute value of the spectral indexes increased by more than 1 unit. For the field with strength 0.8 kV/cm the energy spectra is described by the power law $\mathrm{d}N/\mathrm{d}E \sim E^{-1.73}$; for strong electric fields "touching" and exceeding the RREA threshold (1.7 and 1.8 kV/cm) the absolute value of the

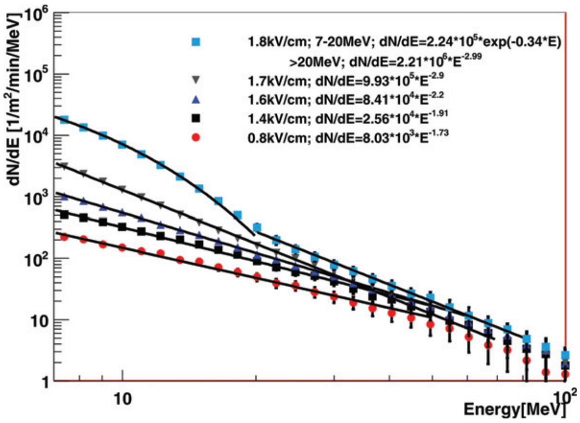

Fig. 3: (Colour on-line) Differential energy spectra of TGE gamma rays generated by secondary cosmic ray electrons in the atmosphere accelerated by electric fields of different strength. Uniform electric field prolonged from 5000 to 2400 m; observation level: 3200 m; energy range 7–100 MeV. To avoid statistical fluctuation due to the scarce population of high-energy bins the power law fit was done in the intensity range above 10 particles per min per m.

gamma ray spectral index is larger —approaching −3. The exponential shape of the gamma ray energy spectrum in the energy range 7–20 MeV for the strength of the electric field 1.8 kV/m reveals an avalanche process in the atmosphere.

TGE flux temporal evolution and its connection with changing the intracloud electric field. – A network of NaI spectrometers located at an altitude of 3200 m allows to measure the differential energy spectra of gamma rays on the one-minute scale in the energy range 7–100 MeV [15]. Five large NaI crystals provide enough statistics for the reliable approximation of the detected energy releases with the power law fit. For instance, the minute-to-minute surplus of the count rate registered on 19 June from 7:28 to 7:45 is rather large (3000–7000 additional particles); the total number of registered additional gamma quanta were ∼80000. In fig. 4 we show the scatter plot of the power fit parameters (absolute value of power index *vs.* coefficient of power law extrapolated to 1 MeV) of minute gamma ray energy spectra measured on May 12, May 15 and June 19, 2013 along with simulation results from fig. 3. For the comparison purposes we plot as well 2 "super-TGEs" (detected on 19 September 2009 and 4 October 2010) with measured individual RRE avalanches [3,4].

Emphasized in fig. 4 is the relation between experimentally observed and modeled gamma ray energy spectra parameters which allows to at least roughly estimate the electric field in the thundercloud responsible for the TGE. "Super-TGEs" located in the upper-right corner of fig. 4 are linked to the RREA process that exponentially increased the intensity. Correspondingly, the absolute values of the power index of the extrapolate energy spectra rise up to ∼3.5.

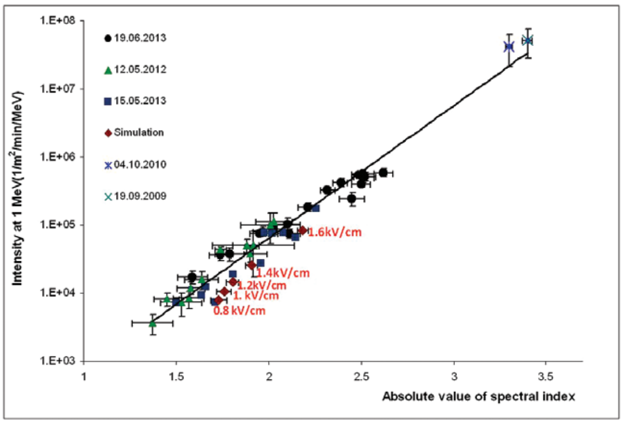

Fig. 4: (Colour on-line) Correlation between observed intensity and absolute value of the power index of the TGE gamma ray energy spectra; the electric field strength is written near the symbols representing simulations of the TGE process.

Discussion and conclusions. – We demonstrate that modest electric fields not reaching the RREA threshold initiate the majority of TGEs in the thunderstorm atmospheres. The power law shape of the gamma ray differential energy spectra tends to soften with increasing electric field strength. When the intracloud electric field reaches the RREA initiation threshold the TGE intensity exponentially grows and an exponential fit, as we see in fig. 3, is suitable for the spectra interpolation at energies 7–20 MeV; at higher energies the power law fit describes the spectrum rather well. The absolute value of the spectral index approaching 3.5 for the largest TGEs is connected with the RREA process with direct observation of individual runaway avalanches [3,4].

The comparison of the experimentally measured gamma ray energy spectra parameters with simulations of the TGE process for different strengths of the intracloud electric field provides calibration data for the approximate estimation of the electric field during TGE. We recognize that for the reliable recovering of the electric field in the thundercloud we will need a more precise direct method of remote measuring of the electric field. A lidar-based method aiming at an accurate estimation of the strength of the electric field in the thunderclouds is now developing in our institute [17].

Terrestrial gamma flashes (TGFs) [13] are believed to originate from electrons accelerated in the upper dipole between the main negative and main positive layer in the upper part of the thundercloud. Gamma rays emitted by accelerated upward electrons propagate in space (generating electron-positron pairs) and reach gamma ray spectrometers in an orbit several hundred kilometers above the Earth's surface. The space-based gamma ray observatories are intended primarily to detect gamma bursts and other energetic processes in the Universe. Modified triggers of gamma ray events allow a copious detection of the TGFs mostly from equatorial thunderstorms. However, the distant locations of the fast moving particle detectors on the Earth's orbit lead to several difficulties in the verification of the TGF models. The millions of gamma ray photons detected from copious TGEs detected at Aragats allow a detailed analysis of the energy spectra evolution in time and can serve as well for the confirmation of the TGF models.

High-energy processes in the magnetosphere and atmosphere like TGEs, TGFs, TLEs (transient luminous events) and the recently discovered relativistic electron acceleration in the Earth's outer radiation belt [18] trigger various dynamic processes in the Earth's environments and have broad astrophysical relevance. Investigation of the "accelerated" structures in the geospace plasmas can shed light on the particle acceleration to a much higher energy by the similar structures of space plasmas in the most distant objects in the Universe. As it was mentioned in [19] the Earth's broad environment is a real laboratory for high-energy astrophysics.

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