Energy spectra of TGE electrons and gamma rays reveal the charge structure of thunderclouds

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November 24, 2022

Abstract

In this letter, we present for the first time simultaneously measured electron and gamma ray spectra of TGE. We also demonstrate how the measurement of the energy spectra of TGE particles can help to understand the charge structure of the thundercloud. We introduce two main scenarios that can support the initiation of the relativistic runaway avalanches (RREA) in the thundercloud. One of the scenarios includes the emergence of the lower positive charged layer (LPCR). The LPCR is a short-living charge structure sitting on hydrometeors, which exhibit accidental charge reversals depending on temperature changes. LPCR can sustain a positive (downwards directed) near-surface electric field for several minutes, before falling down with precipitation. Comparison of energy spectra of electrons and gamma rays makes it possible to scrutinize the LPCR emergence and estimate the height where the strong electric field that originates the RREA declines.

Measurement of TGE particle energy spectra: an insight in the cloud charge structure

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Abstract

In this letter, we present for the first time simultaneously measured electron and gamma ray spectra of TGE. We also demonstrate how the measurement of the energy spectra of TGE particles can help to understand the charge structure of the thundercloud. We introduce two main scenarios that can support the initiation of the relativistic runaway avalanches (RREA) in the thundercloud. One of the scenarios includes the emergence of the lower positive charged layer (LPCR). The LPCR is a short-living charge structure sitting on hydrometeors, which exhibit accidental charge reversals depending on temperature changes. LPCR can sustain a positive (downwards directed) near-surface electric field for several minutes, before falling down with precipitation. Recently, we launched on Aragats full-scale operation of large spectrometer, which is capable to measure the energy spectra of electrons and gamma rays in the energy range from 4 to 100 MeV. Comparison of energy spectra of electrons and gamma rays makes it possible to scrutinize the LPCR emergence and estimate the height where the strong electric field that originates the RREA declines.

Introduction

Observation of extended particle fluxes on high mountains and in regions of Japan with low charge centers in thunderclouds unambiguously established a new physical phenomenon—thunderstorm ground enhancement (TGE), increased fluxes of electrons, gamma rays, and neutrons detected by particle detectors located on the earth's surface ([1] and references therein). The energy spectra of TGE electrons and gamma rays are measured by the Aragats solar neutron telescope (ASNT [2]) designed for detection of neutrons coming directly from solar flares (solar protons are bending in the interplanetary magnetic field). ASNT is the largest spectrometer operating nowadays on mountain altitudes and is in operation last 13 years. It is intended for the measurement of intensity (count rate) and energy spectra of charged and neutral particles coming from different directions in the energy range 4-100 MeV. The spectrometer consists of 4 separate SEVAN-type detectors [3] each comprising 2 layers: the upper 5 cm thick plastic scintillator (veto scintillator) and 60 cm thick scintillator below it (spectrometer); area of both is 1 m^2, see Fig. 1. All possible coincidences of particle traversal through detector are counted with a sample interval of 2 s and the histograms of energy releases – with sample interval of 20 s. The detector is in operation for 20 years and allowed us to register more than 500 TGE events. Until now, ASNT is the only spectrometer that is capable to measure TGE electron energy spectrum. In 2010 we published the first energy release spectrum of an extraordinary strong TGE measured on 19 September 2009[4]; after tuning the electronics in May 2017 and lowering the energy threshold from 7 MeV down to 4 MeV we observed tens of large TGEs [5]. The full detector setup simulation made with GEANT4 [6] code makes it possible to obtain the electron and gamma ray spectra from one-and-the-same TGE event. A comparative analysis of relative intensities and maximum energy of both spectra reveals a new information on the cloud charge structure. The analysis of two selected TGEs observed in 2020 shows how the energy spectra relate to the cloud charge structure which supports the origination of a large TGE. Throughout this letter, we use the atmospheric electricity sign convention, according to which the downward directed electric field or field change vector is positive.

Operation of an electron accelerator in the thundercloud

Recently, we proposed main charge structures in the thundercloud,
which form a particle accelerator directing electrons downwards to the earth's surface [7].

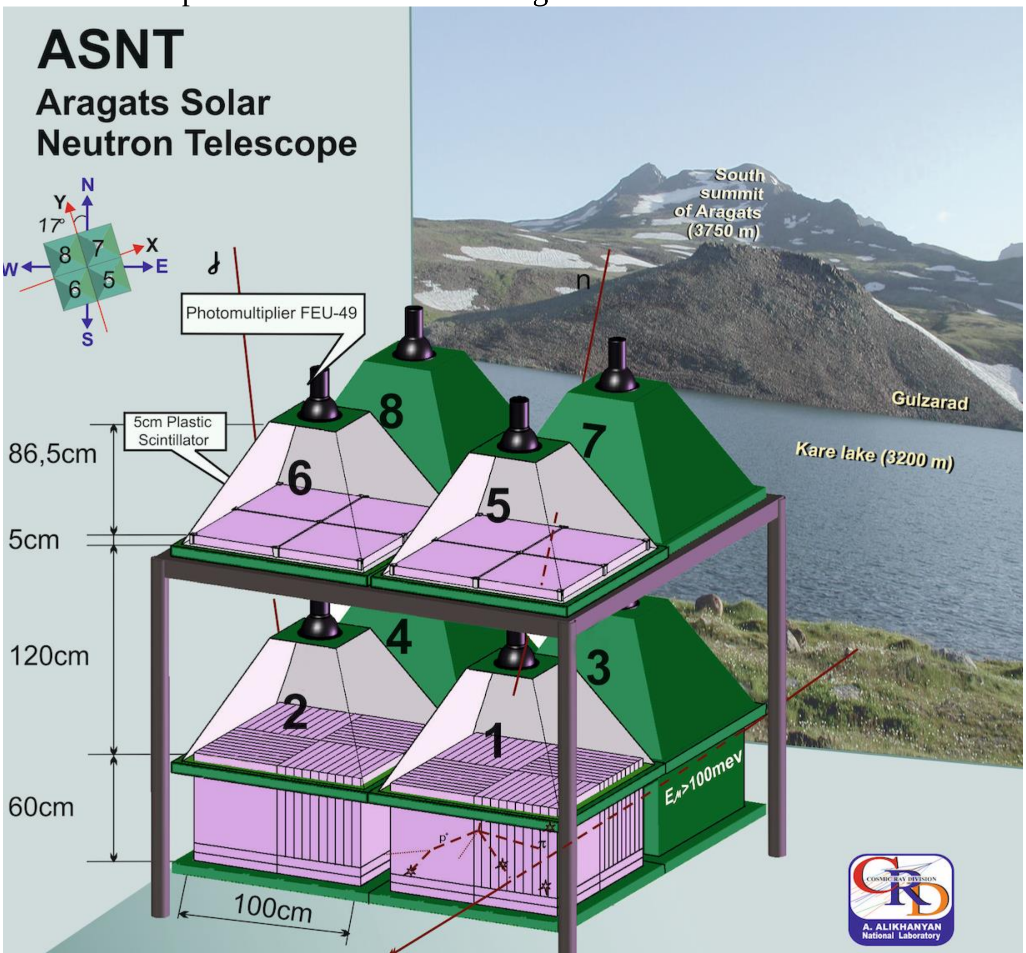

Figure 1. ASNT detector setup and its orientation relative to Aragats mountain

1. A dipole formed by main negative (MN) region in the center of the cloud and its mirror image at the ground (hereafter, MN-MIRR). If MN charge is large enough to induce strong electric field that exceeds the critical value, the relativistic runaway electron avalanches (RREA [8]) are unleashed and TGE will be intense, and particle energies up to 50 MeV will be observed. The near-surface (NS) electric field will be in a deep negative domain reaching -25 ÷ 30 kV/m for the largest TGEs. Regardless of the cloud base location, the electric field extends down almost to the earth's surface, and both electrons/positrons and gamma rays can be registered by particle detectors and spectrometers.

2. If an LPCR emerged, in the bottom of the cloud, additionally to the MN-MIRR, another dipole is formed by the MN-LPCR layers. Fields induced by the MN-mirror and MN-LPCR are identically directed and their sum can reach rather large values exceeding the threshold value to start RREA by 20-30%. Consequently, the RREA (and corresponding TGE) can be very intense in Spring and Autumn when LPCR is very close to the earth's surface (25-50 m, [9]). For a few minutes, when LPCR is mature and screens the detector site from the negative charge of MN, the near-surface field "uprises" to the positive domain. 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.

The expected pattern of the development of an RREA above Aragats we obtained from the CORSIKA simulations [10], performed with 1 MeV energy seed electrons (see details of simulation conditions in [11,12]). From figures 2a and 2b, we can see that for the large electric field strengths the maximum energy of RREA electrons can reach ≈70 MeV, and gamma rays – ≈50 MeV. However, after exiting from the accelerating electric field the maximum energy of electrons fast diminished due to ionization losses. After propagating in the thick air above detectors the energy of electrons reduces to ≈30 MeV and the energy of gamma ray still is ≈45 MeV, for the strength of the electric field in the cloud of 1.9-2.1 kV/cm. The maximum energy of the electron energy spectrum as compared with gamma ray one can be used for the estimation of the boundary of the strong intracloud electric field accelerated electrons downward. If the maximum energies of electrons and gamma rays are comparable, we can conclude that the electron accelerated electric field extends down almost to the earth's surface.

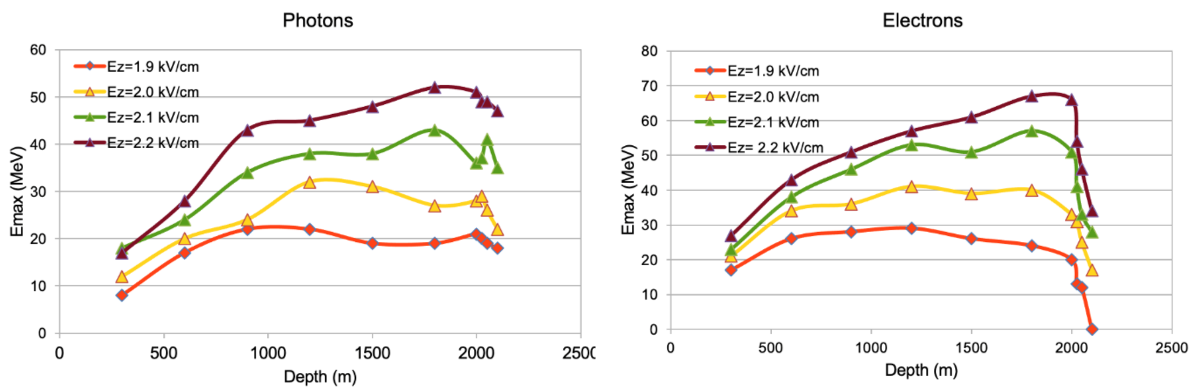

Figure 2. Development of the electromagnetic avalanche in the atmosphere; uniform electric field introduced from 5400 to 3400 m. Avalanche started at 5400 m, 2200 m above the Aragats station (depth equals 0). The maximum energy of avalanche particles is calculated each 300 m. After exiting from the electric field propagation of avalanche particles are followed additionally 200 m before reaching the station (depth 2200 m).

In Fig. 3 we show energy spectra of electrons and gamma rays measured on 22 April and 25 September 2020.

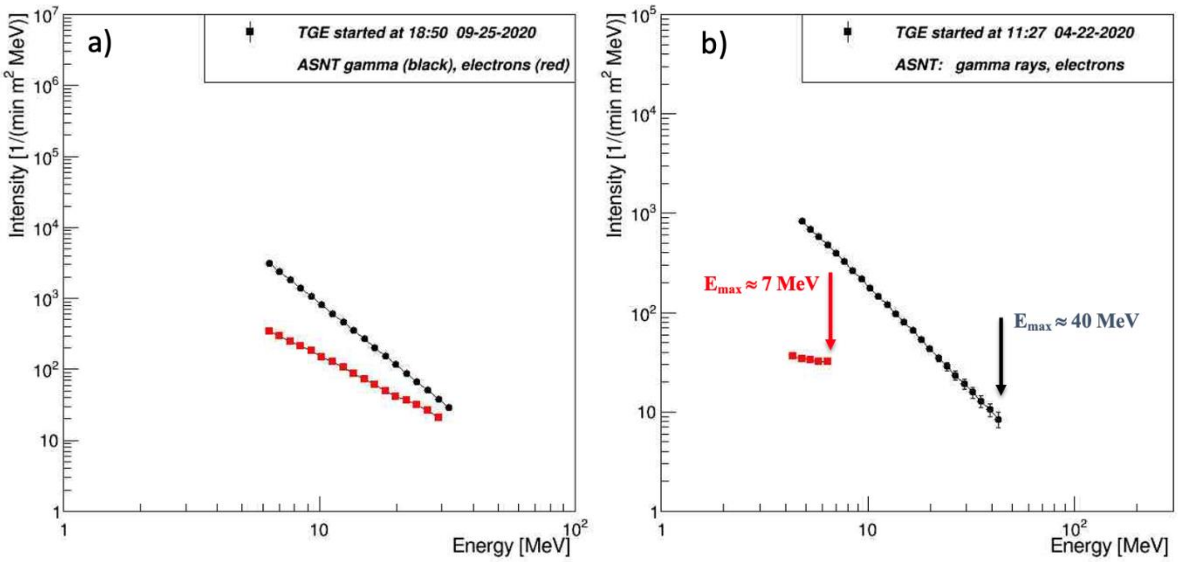

Figure 3. The differential energy spectra of two TGE events of 2020 measured by ASNT spectrometer. Black- gamma ray spectrum, red – electron spectrum.

As we see in Fig. 3 energy spectra of 2 TGE events drastically differ. On 22 April, electron flux is negligible and its maximum energy low, Fig 3b; while at 25 September electron energy spectrum is sizable, almost reaching the gamma ray intensity at high energies; maximum energies are approximately one-and-the-the-same, Fig. 3a. What is the reason for this drastic difference?

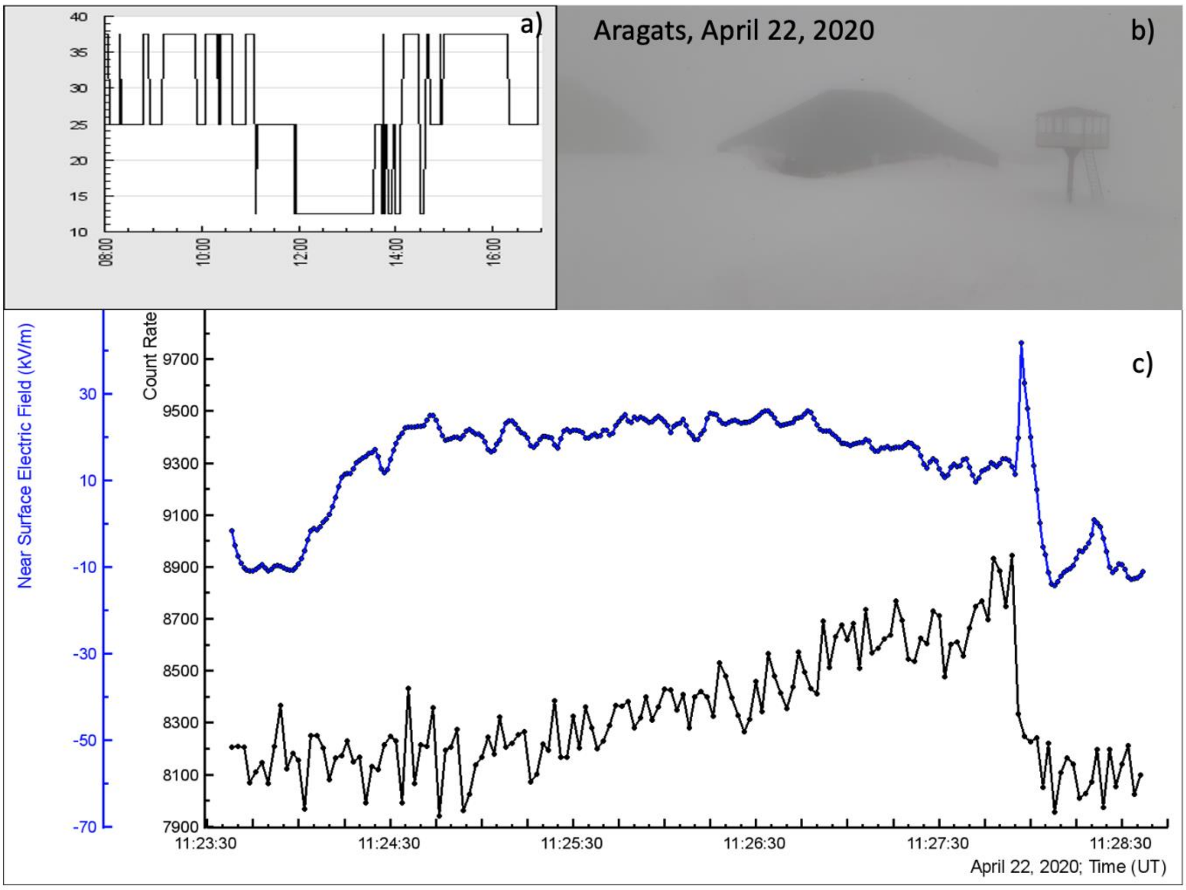

Figure 4. The cloud height a), a shot of SKL experimental hall demonstrating weather conditions on 22 April b), and TGE registered by the ASNT detector c). Blue and black curves in panel c show the disturbances of the near-surface electric field and count rate of the ASNT detector, respectively.

As we can see from the photography of the station in Fig.4b, and from an estimate of cloud height in Fig.4a the cloud was very low (25-50 m) above the station. A positive near-surface electric field lasting 4 minutes indicates the positive charge above, that forms a lower dipole with the main negatively charged region in the middle of the cloud.

Thus, if we assume that LPCR boundary coincides with the cloud bottom**,** we should expect that electron acceleration continues almost until earth's surface and we should expect sizable electron flux. However, it is absent, see Fig.3b. Consequently, we can conclude that LPCR boundary (the field "inversion height") is well above the cloud bottom. Obviously, we cannot characterize the field inversion by an exact number, sure, there are no unique "inversion height" but inversion region of a rather complicated shape. As the LPCR is a cloud of falling graupel, it is very difficult to have a line where the field inversion occurred, it should be some fast evaluating complex surface, it is one of reasons that method accuracy cannot be better than 50 m.
The algorithm to estimate the field inversion "height" looks as follows:

- Find maximum electron energy (7 MeV) and maximum gamma-ray energy (40 MeV) from the measured spectra.
- On the basis of simulations, assume that maximum initial energy of the electron at the exit from the region of the strong electric field is 20% higher than maximum energy of gamma-rays found from the spectra, that is □□50 MeV.

 Using the rate R of electron energy loss in the air (200 keV/m), estimate the height according to h 200 m.

Finally, we conclude that a rather large positively charged region was “screening” Aragats detectors for 4 minutes, and electrons were accelerated by the MN-LPCR dipole to very high energies. The large flux and high energies of gamma rays, that were not attenuated strongly in 200 m like electrons, see Fig 3a, are the arguments in support of the derived charge structure.

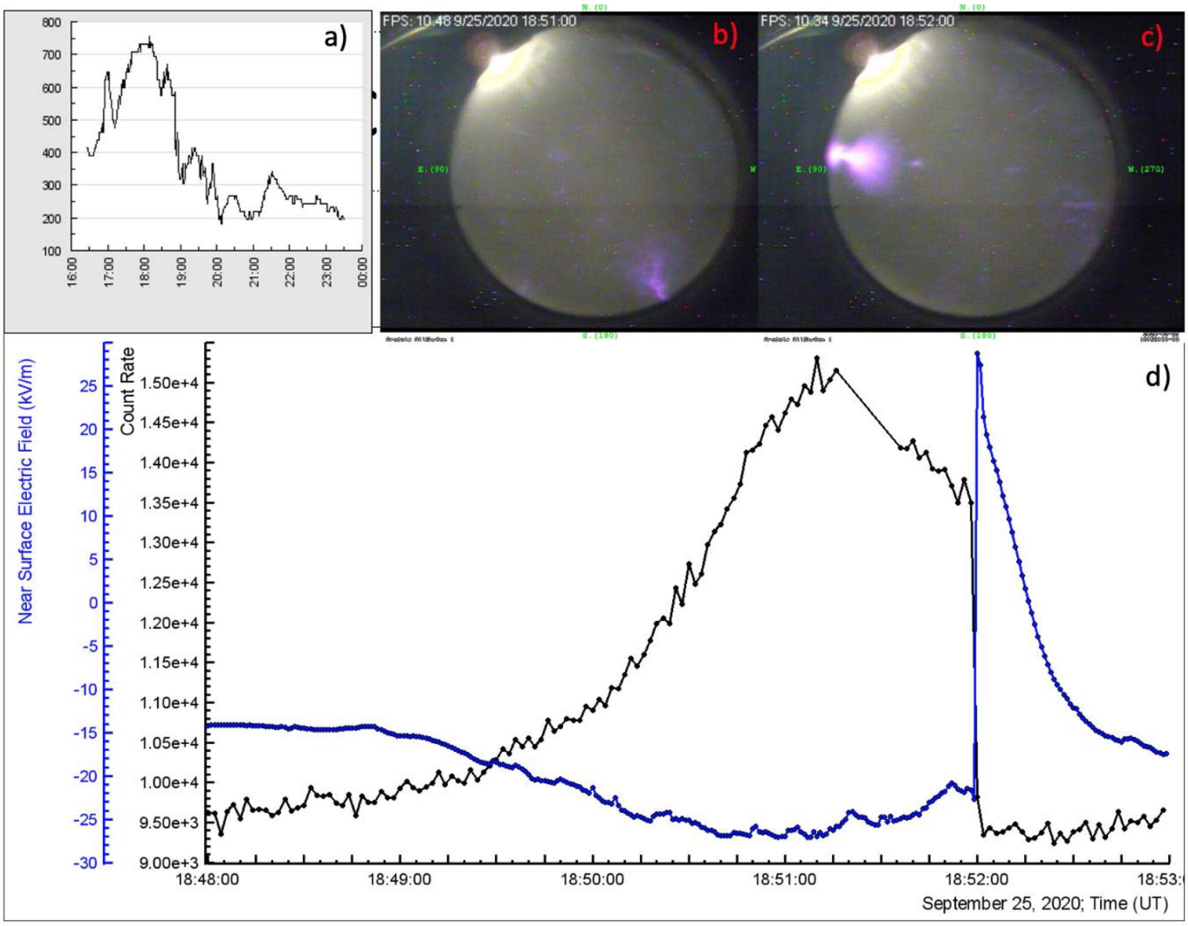

Figure 5. The cloud height a), shots of the sky above Aragats demonstrating “blue lights” – b) and c), and TGE registered by the ASNT detector c d). Blue and black curves in panel d show the disturbances of the near-surface electric field and count rate of the ASNT detector, respectively. Blue lights, shown in frames b) and c) are obtained from shots of panoramic camera that monitors skies above Aragats, see details in [9]).

On September 25, 2020, the near-surface electric field was in a deep negative domain during the development of the TGE, see Fig 5d. Thus, LPCR hasn’t emerged and the dipole that accelerates electrons downward was formed by MN-MIRR only. There is no field inversion point due to emerging LPCR like for TGE observed on 22 April. Absence of the LPCR is supported by high values of electron maximum energy (about 30 MeV) measured by ASNT, Fig. 3a.

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Conclusion

For the first time we present electron and gamma ray energy spectra measured by the large spectrometer on Aragats. Obtained energy spectra well coincide with CORSIKA simulations assuming the strength of electric field in the cloud to be 1.9-2.0 kV/cm. Gamma ray energy spectra measured by the ASNT scintillation spectrometer, also coincide with spectra measured by the NaI network operated on Aragats. Using difference between maximum energies of electrons and gamma rays we get insight in the cloud charge structure. The multiyear operation of the spectrometers which are capable to measure the energy spectra of gamma-rays and electrons demonstrates that they are very important device for monitoring emerging charge structures during thunderstorms. The 24/7 operation of ASNT on Aragats brings a rich harvest of the thunderstorms the charge structure of which is now clarified. On the basis of obtained results, two previously suggested scenarios of TGE origination are confirmed.

ACKNOWLEDGMENTS

We thank the staff of the Aragats Space Environmental Center for the operation of the NaI network on Mount Aragats. Special thanks to T.Karapetyan and B.Sargsyan for tuning and maintaining the ASNT spectrometer. The authors thank S. Soghomonyan for useful discussion and help in preparing the manuscript. The data for this article are available by accessing the multivariate visualization software ADEI in numerical and graphical type on the website of the Cosmic Ray Division of the Yerevan Physics Institute [13].

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