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Observation of Thunderstorm Ground Enhancements with intense fluxes of high-energy electrons

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ABSTRACT

The high altitude (~3200 m above sea level) of Aragats Space Environmental Center (ASEC) and low elevation of the thunderclouds provides a good opportunity to detect Thunderstorm Ground Enhancements (TGEs), particles of which rapidly attenuate in the atmosphere. In 2012, we have estimated the energy spectra of several TGEs and revealed significant electron fluxes extended till 30–40 MeV. Measured in the one and the same event gamma ray and electron fluxes allow to estimate the height of the thundercloud above the detector. Proceeding from the energy spectra and the height of the cloud we estimate the electron spectra on the exit from the electric field of the thundercloud, the number of excess electrons in the cloud and avalanche multiplication rate.

1. Introduction

Thunderstorm Ground Enhancements (TGEs) are direct proof of the high-energy phenomena in the terrestrial atmosphere; see review by Dwyer et al. [15] and references therein.

The origin of a TGE is a strong electrical field in a thundercloud, giving rise to rather complicated physical processes, including the following phenomena:

- Relativistic Runaway Electron Avalanches (RREA, [25,17,3,14, 18];
- Modification of the Secondary cosmic ray (electrons, muons, protons and charged mesons) energy spectra (MOS, [13,20];
- Photonuclear reactions of the RREA gamma rays [10,11,24,4];
- Roentgen and gamma radiation from the lightning [16].

The direct measurement of the RREA by extended surface array of plastic scintillators was performed at Aragats in 2009 [8]. Largest TGEs consist of multiple individual electron/gamma ray avalanches. However, the electron fluxes are very difficult to study due to fast attenuation in the lower atmosphere, till now only for one TGE event it was possible to estimate the electron energy spectrum and calculate avalanche multiplication rate [7,9].

On October 7, 2012 a TGE consisting of two peaks at 14:11 and 15:08 was detected at Aragats Space Environmental Center (ASEC; [5,19]. Different types of the detector assembly operating on Aragats, quipped with sophisticated coincidences techniques, allowed performing electron/gamma ray separation and proving the existence of the large fraction of the high-energy electron flux at 15:08. At 14:11 TGE mainly consists of enhanced gamma ray flux, as the most of TGEs detected at ASEC and worldwide. Because of very fast attenuation of electrons in the atmosphere, usually TGE gamma ray flux significantly exceeds the electron flux; only for very low thunderclouds it is possible to detect electron flux. Thus, even for very low efficiencies of gamma ray registration the gamma ray contamination can be sizable in the overall TGE. To overcome this difficulty, we use in our analysis data from numerous ASEC particle detectors. Among these detectors are STAND3 layered detector and hybrid[1] ASNT (Aragats Solar Neutron Telescope, [6] and Cube detectors [2]. First we will analyze the STAND3 data, for distinguishing the high-energy electrons. Thereafter, we double check for the presence of significant electron fluxes using ASNT data. ASNT data also allows estimating the gamma ray flux. Based on these measurements and assumed spectral shape of the gamma ray flux we decide if the high-energy electrons were detected or only large fluxes of TGE gamma rays are responsible for the detector count rate enhancement. Finally, the estimated flux will be checked with Cube detector data, which allows selecting the neutral component of TGE flux. If the results from these 3 different detectors are consistent, we apply procedures of energy spectra recovery (see details in [9] and get gamma ray and electron energy spectra.

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[1] Hybrid detectors consist from thick and thin plastic scintillators and due to sophisticated DAQ electronics are sensitive to both charged and neutral fluxes.

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2. Experimental data of the October 7, 2012 TGE

The new generation of ASEC detectors comprises from 1 and 3 cm thick molded plastic scintillators arranged in stacks (STAND1 and STAND3 detectors) and in cubical structures surrounding thick scintillators and NaI crystals for purification of detected neutral flux (Cube1 and Cube3 detectors). Light from the scintillators is reradiated by optical spectrum-shifter fibers to the long-wavelength region and passed to the FEU-115 M type photomultiplier (PM). Maximum of luminescence is on about 420 nm wavelength and luminescence time is about 2.3 ns [27]. The tuning of STAND detectors consists in selections of PM high voltage and signal discrimination threshold. The threshold is chosen to guarantee both high efficiency of signal detection and maximal suppression of the electronics noise. Tuning of STAND was made by means of the 8-channel signal analyzer developed at ASEC for online data processing [1]. Proper tuning of the detector provides 98–99% signal detection efficiency simultaneously suppressing electronic noise down to 1–2%. The data acquisition (DAQ) electronics measures and stores all coincidences of the signal appearance in the detector channels. Coincidence "1 0 0 0" corresponds to signal registration only from upper scintillator, "1 1 0 0" – from the first two upper scintillators, and so on. GEANT4 simulations demonstrate that STAND3 detector (see Fig. 1), can measure count rate of incident electrons with energy thresholds 5, 15, 25, 35 MeV (combinations "1 0 0 0", "1 1 0 0", "1 1 1 0" and "1 1 1 1"). The 5 MeV electrons can give signal above the discrimination level only in the upper scintillator, to be absorbed then in the scintillator body, or in the metallic tilts of scintillator housing; the 15 MeV electrons can penetrate and be registered also in the second scintillator, and so on. In this way, measuring the enhancements of count rates of above mentioned 4 combinations of detector layer operation we can recover the integral energy spectra of TGE electrons, of course, after subtracting the gamma ray contamination. The peaks of October 7, 2012 TGE measured by the layers of STAND3 detector are shown in the Fig. 2. The increases of the maximal minute count rate corresponding to various coincidences of STAND3 are shown in Table 1 in standard deviations of the measurements (number of σ).

As we can see in Table 1, at 15:08 October 7 2012, STAND3 detector registered high-energy electron TGE. Electrons with energies above 35 MeV can reach and be registered by the 1 1 1 1 combination of STAND3 with efficiency dependent on energy. The efficiencies for electron detection by STAND3 detector are shown in Fig. 3. The electronics signal threshold[2] is $\sim$3 MeV, thus, all 4 STAND3 layers can detect gamma rays with energies greater than $\sim$3 MeV, although with much smaller registration efficiencies comparing with electron detection efficiencies. In Fig. 4, the gamma ray detection efficiencies by coincidences of STAND3 detector layers are shown. Gamma rays should have high enough energy to create high-energy charged particles, which can reach bottom layer (the gamma ray energy should be above 40 MeV to generate signal in all 4 layers with probability 1%).

Electrons with energies greater than 35 MeV will contribute to "1 1 1 1" combination. In contrast, only a small fraction of high-energy gamma rays will be detected as "1 1 1 1" combination. Therefore, we conclude that STAND3 data of "1 1 1 1" combination proves the existence of the high-energy particles above 25 MeV at 15:08. Using GEANT 4 simulations and data from ASNT and Cube detectors we will find if there is a sizeable contamination from gamma rays.

In Fig. 5, ASNT detector consisting of upper 5 cm and lower 60 cm thick scintillator layers is depicted. Each layer consists of 4 scintillators and each scintillator has an area of 1 m^2. In Fig. 6,

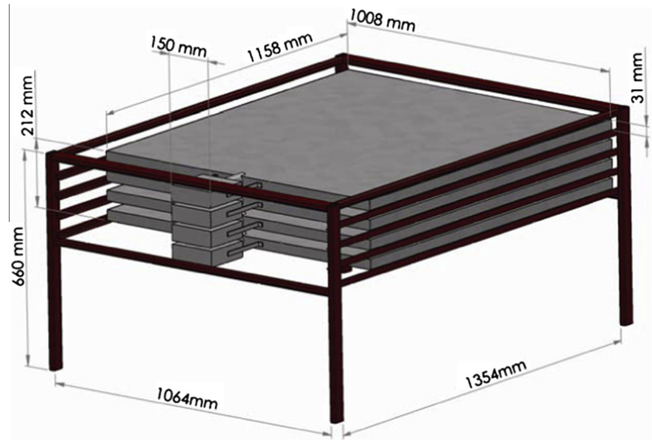

Fig. 1. STAND3 detector; each of 4 stacked horizontally plastic scintillators is 3 cm thick and 1 m^2 area.

the gamma ray detection efficiencies of 5 cm and 60 cm scintillators are presented. Thicker is the scintillator more is the probability of gamma rays to interact and create charged particles, which will deposit their energy in the scintillator.

During October 7, 2012 TGE at 15:08, the increase detected by 5 cm scintillators of the ASNT detector was twice larger than that of 60 cm scintillators (see Table 2). However, the neutral particle detection efficiency of the thick scintillator is much higher; especially for the gamma rays with energies above 30 MeV (see Fig. 6). Taking into account energy loses in the material of the roof and the electronics threshold, the minimal energy of electrons should be $\sim$15 MeV to be measured by the 5 cm detector. Only electrons having energies above $\sim$30 MeV can pass through the roof and the upper 5 cm scintillator layer and be detected also by 60 cm scintillator ("11" coincidence).

Detected at 15:08 small increase was measured by ASNT vertical "11" coincidence - a simultaneous signal in both scintillators (see Table 2), the probability of gamma ray detection by this coincidence is vanishingly small (the efficiency of gamma ray detection is near zero at energies <20 MeV). The increase observed by ASNT vertical coincidence confirms the "electron" nature of TGE of 15:08.

In [9], we discussed and analyzed two largest TGEs of September 19, 2009 and October 4, 2010. The September 19, 2009 TGE has the largest ever detected electron intensity. The October 4, 2010 TGE has the largest ever detected gamma ray intensity, with small electron contamination. The ratio of the enhancements in 5 cm and 60 cm thick scintillators of ASNT on September 19 was $\sim$4 and on October 4 $\sim$2; i.e. the largest "electron" TGE has 2 times larger ratio of thin/thick scintillator counts comparing with largest "gamma-ray" TGE. In this concern, it is worth mentioning that for the first peak detected at 14:11 October 7, 2012 the ratio of thin/thick is $\sim$1.21, see Table 2; two times less than at 15:08. Therefore, greater is the ratio, larger is the fraction of electrons reaching the Earth's surface.

Recovered electron/gamma ray ratios above the roof of the laboratory building for the energies above 10 MeV were estimated to be 0.6 and 0.007 for September 19, 2009 and October 4, 2010 TGEs respectively (see details in [9].

The Cube assembly (Fig. 7) consists of two 20 cm thick scintillation detectors of 0.25 m^2 area each surrounded by 1 cm thick 1 m^2 area scintillators. This design ensures that no particle can hit the inside 20 cm detectors without passing through one of 1 cm scintillators. Both 20 cm thick plastic scintillators are overviewed by the PM FEU- 49 with large cathode, operating in low-noise mode.

[2] The threshold of the shaper-discriminator feed by the PM output.