Simulations of the secondary cosmic ray propagation in the thunderstorm atmospheres resulting in the Thunderstorm ground enhancements (TGEs)

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Simulations of the secondary cosmic ray propagation in the thunderstorm atmospheres resulting in the Thunderstorm ground enhancements (TGEs)

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Abstract. GEANT4 simulations of the propagation of electrons in the thunderstorm atmospheres were performed to explain the Thunderstorm Ground Enhancements (TGEs), detected by the particle detectors of the Aragats Space Environmental Center (ASEC) operating at altitude 3200 m on slopes of Mt. Aragats in Armenia. The charged particle propagation and multiplication processes were simulated in the uniform electric fields of different strengths and elongation. The Gamma ray, electron and neutron energy spectra were obtained on the exit of the electrical field and beneath. Simulation results prove existence of 2 mechanisms of particle enhancements, first connected with electron – gamma ray avalanche process; and the second – with modification of energy spectra of particles in the strong electrical fields of the thunderclouds. The avalanche process can multiply number of electrons and gamma rays by several orders of magnitude well above the cosmic ray background in the energy range up to 40MeV; the energy spectra modifications lead to a few percent enhancements in the energy range up to 100MeV, as well as to depletion of the high-energy muon flux. Consequently the energy spectra at low energy are better fitted by exponential law; at high energies – by the power law.

1. Introduction:

Creation of a detailed model to explain the TGE events is hampered by unknown strength and structure of the electrical field in the thunderclouds. The location and time evolution of the charged layers in the thundercloud (sources of electrical field) is very poor studied domain due to missing of suitable and reliable experimental techniques. In these circumstances the experimentation with the computer models of the propagation of radiation through thunderstorm atmosphere is only available method for developing of the quantitative models of TGE events. The theoretical knowledge on the acceleration of electrons in the atmospheric electrical fields as well as interactions of electrons, gamma rays and neutrons with atmosphere nuclei and molecules are well established and simulated in the applied program packages [1]. The limits on possible values and elongations of electrical fields are known from registered soundings of balloons launched during thunderstorms [2] and from theoretical limits [3]. The density and energy spectra of populations of cosmic rays (CR) electrons at different altitudes in the atmosphere are also very well measured in last century. Therefore, by computer experiments, assuming plausible values of strength and structure of electrical field we get valuable

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information to be compared with experimental results. One of the first simulations [4] was performed to explain a rocket-triggered lightning experiment. From simulation experiments of Relativistic Runaway Electron Avalanche (RREA, [5], also referred as Runaway breakdown, RB – process [6]) were obtained RREA electron energy spectra approximated by the exponential function. To explain the measurements of hard gamma radiation from winter thunderstorms in Japan, (Torii et al. 2004), a tripol model of thundercloud electric field was used [7] and was obtain a significant flux of secondary bremsstrahlung gamma rays from the RREA process, some portion of which was capable to reach the ground. Another simulation code [8] estimates photon energy spectra, number of photons in the source, full bremsstrahlung energy, which in the best way fit the spectra of gamma ray flux published in [9]. The shift of the energy spectrum of the electrons/positrons and negative/positive muons entering large electrical field region in thunderclouds can lead to dips and peaks in time series of the count rates of surface particle detectors (see theory of meteorological effects in [10]. These effects were investigated in experimentally in [11] and [12].

2. Simulations of the particle propagation in the electrical fields

We used the following approximations in our simplified model of the electrical structure of the thundercloud:

Electric field within thundercloud is uniform (no "pockets" with enhanced field, and no different layers with opposite field directions). The electrical field strength of 1.8kV/cm which is greater than threshold value $E_t \approx 1.7$kV/cm was used. The length of electric fields equals to L = 1650m, from 5000m till 3350 above the detectors located at 3200m.

As seed particles secondary Cosmic Ray (CR) electrons in the energy range of 1-300 MeV and with fixed energy 1 MeV (simulating "pure" RREA process, ~1 MeV electrons commit minimal ionization losses in the atmosphere) were used. Incident electron spectrum was estimated by EXPACS WEB-calculator, which estimates secondary cosmic ray spectra at different altitudes and latitudes (Sato, 2009).

The following interactions were considered:

For electrons and positrons – ionization, bremsstrahlung, multiple scattering;

For positrons also –annihilation;

For gamma rays– Compton scattering, conversion, photoelectric effect, photonuclear reaction.

3.Electron and gamma ray energy spectra derived from simulations

To explain numnerous TGEs detected ar Aragats Space environmental center (ASEC, [13, 14, 15]) we implement simulations using described above simple model of the electric fields in the thundercloud. Results of the simulation are posted in Fig. 1, where we can apparently see 2 modes of particle generation. The RREA mode with maximal energy of electrons is 30-40 MeV and gamma rays - 20-30 MeV and MOS (modification of spectra) mode accelerating electrons up to 60-70 MeV; gamma ray spectrum prolonged up to 80-90 MeV. The electron and gamma ray energy spectra in the energy range 1-10 MeV demonstrate large multiplication of electrons in the RREA process and huge amplitudes of the TGEs. MOS regime is fast fading after 50 MeV and needs large surfaces of particle detectors to be measured above the background of ambient population of secondary cosmic rays.

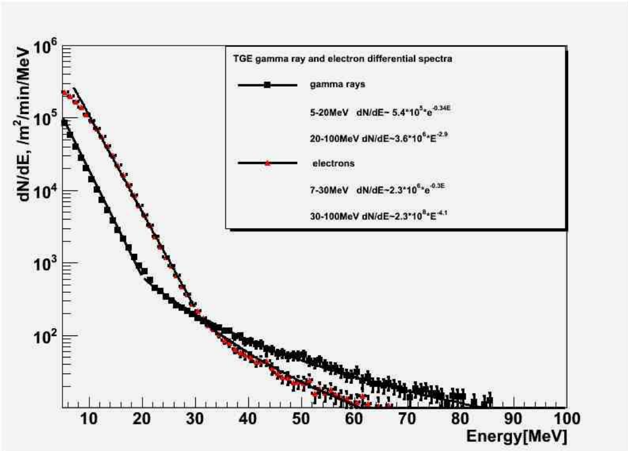

Figure 1. TGE electron and gamma ray spectra obtained from GEANT4 simulation of RREA process in electric field of 1.8 kV/cm with seed electrons 1-300 MeV.

The high-energy tail of the gamma ray spectrum is due to enhanced bremstrahlung radiation of the higher energy electrons traversing the electric field of the cloud. Because of highly enlarged radiation losses, high energy electrons cannot unleash the RREA, however, the additional flux of gamma rays radiated by these electrons can reach the mountain altitudes and be registered as small and modest enhancement over CR background.

To prove our hiphotesis on 2 component origin of TGE, we perform the same simulation with a fixed flux of 1 MeV seed electrons. The shape of electron and gamma ray spectra coincides with spectra obtained with 1-300 MeV electron seeds (exponential function – reflecting the particle multiplication in the avalanche process), however there are no high energy tails, see Figure 2. Thus, pure RREA process with chosen electrical field parameters cannot produce TGE electrons with energies above 30-40 MeV and gamma rays with energies above 20-30 MeV.

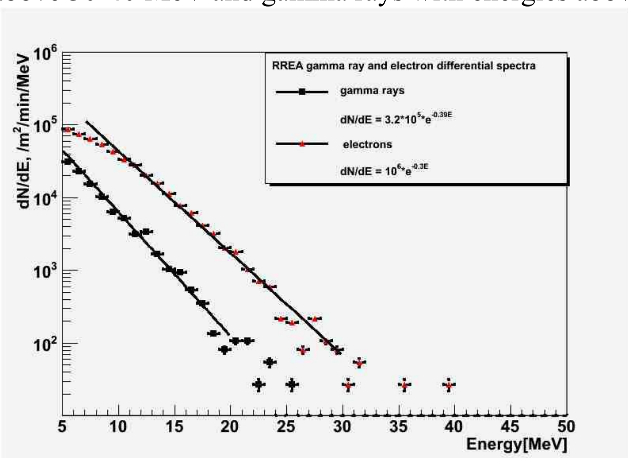

Figure 2. The electron and gamma energy spectra obtained in electric field of 1.8 kV/m prolonged from 5000 till 3400 m with 1 MeV electron as seeds.

To prove that MOS process can provide high-energy gamma rays we perform simulations of the electron propagation in the moderate electric field below RREA initiation threshold (1.5 kV/cm). In Figure 3 we see that only modification of the energy spectra of electrons can significantly enlarge the yield of the gamma rays reaching the earth surface. Electrons attenuate in the atmosphere after exiting from the cloud; however, as we can see from Figure 3, the gamma rays survive.

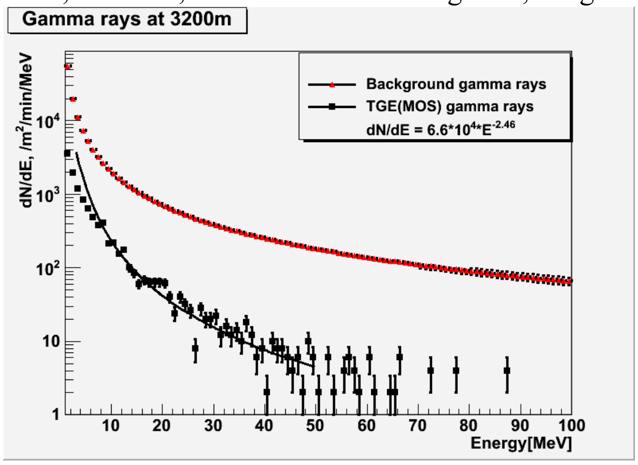

Figure3. Comparison of background gamma ray spectrum with the surplus gamma ray spectrum generated by electrons accelerated in the field of strength 1.5 kV/m below the critical field for the RREA initiation; the background cosmic ray gamma ray flux and TGE gamma ray flux are calculated at 3200 m altitude after exiting from the uniform electrical field at 3350 m altitude

Conclusion

Our simulations supports 2 component model of the TGE origin: the RRRE avalanches in energy domain up to 30-40 MeV and Modification Of energy Spectra (MOS) process operating on all energy scales and providing extension of TGE gamma ray energy spectra up to 100 MeV. The RREA process can multiply particle flux up to 10 times above ambient background of secondary cosmic rays; the MOS process can provide several percentage excess above cosmic rays, however for the much higher energies.

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