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Statistical analysis of the Thunderstorm Ground Enhancements (TGEs) detected on Mt. Aragats

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Abstract

Starting from 2008 experimental facilities of the Aragats Space Environmental Center (ASEC) routinely measure time series of secondary cosmic ray fluxes. At these years of the minimum of solar activity we analyze the new high-energy phenomena in the terrestrial atmosphere. Namely, Thunderstorm Ground Enhancements (TGEs) and Extensive Cloud Showers (ECSs). Several new particle detectors were designed and fabricated having lower energy threshold to detect particle fluxes from the thunderclouds; some of them have possibility to distinguish charged and neutral fluxes. During 2008–2012 years ASEC detectors located at Aragats, Nor Amberd and Yerevan were detected ~300 TGE enhancements. Amplitude of majority of them is less than 5%; however, 13 TGEs have amplitude exceeding 20%. The maximal value of observed enhancement was 271% (September 19, 2009). The paper summarizes five-years study of the TGEs on Aragats. The statistical analysis revealing the month and day-of-time distributions of TGE events, as well as the amplitude and event duration diagrams are presented.

Keywords: Cosmic rays; Thunderstorm activity; TGE

1. Introduction

Sudden boost of the secondary cosmic ray flux correlated with thunderstorm activity, so called Thunderstorm Ground Enhancements (TGEs, Chilingarian et al., 2010, 2011) is the manifestation of the high-energy processes in the terrestrial atmosphere (Dwyer et al., 2012a) Origin of TGE is strong electrical field in the thundercloud, giving rise to rather complicated physical phenomenon, including several physical processes:

1. Relativistic Runaway Electron Avalanches (RREA, Wilson, 1925; Gurevich et al., 1992; Babich et al., 1998; Dwyer, 2003; Khaerdinov et al., 2005);
2. Modification of the Secondary cosmic ray (electrons, muons, protons and charged mesons) energy spectra (MOS, Dorman and Dorman, 2005; Muraki et al., 2004);
3. Photonuclear reactions of the RREA gamma rays (Chilingarian et al., 2012a,b; Tsuchiya et al., 2012; Babich et al., 2013);
4. Roentgen and gamma radiation from the lightning (Dwyer et al., 2012b);

Surface detections of the TGE process, although have long history, are discrepant and rare. The first attempts to observe the runaway electrons on the earth surface were carried out by Wilson's co-workers Schonland, Viljoen and Halliday in South Africa with cloud chambers. However, due to low sensitivity of cloud chambers to low energy gamma rays (the majority of particles reaching the earth surface from the electron–photon avalanches unleashed by runaway electrons in the thunderclouds are few MeV gamma rays) the results of these experiments were

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discouraging. Looking for the electrons with energies up to 5 GeV subsequently returning to the earth surface following the force lines of geomagnetic field (at the great distance from the thundercloud which had produced them) surely could not give positive outcome (see Halliday, 1941). However, the observation of the runaway electron phenomena and distinguishing it from the modification of energy spectra turns to be rather difficult. "In summary and as introduction to the present set of experiments, after 70 years of repeated theoretical and experimental investigations, it is still not clear whether or not the runaway electron acceleration mechanisms operates in a significant manner in either thunderstorms or lightning" (Suszcynsky et al., 1996). In last 2 decades there were significant progress in detection of the particles (mostly gamma rays) from thunderclouds (Aglietta et al., 1989; Eack et al., 2000; Brunetti et al., 2000; Alexeenko et al., 2002; Torii et al., 2002, 2011; Lidvansky, 2003; Tsuchiya et al., 2007, 2011). Detailed historical reviews of TGE detection are presented in Chilingarian et al. (2010), Dwyer et al. (2012a,b). The idea of C.T.R. Wilson that accelerated in the thunderclouds electrons can reach the atmosphere found its proof after the launch of the orbiting gamma ray observatories. Numerous Terrestrial Gamma Flashes (TGFs) are routinely observed at 500 km above the Earth in correlation with strong equatorial thunderstorms (Fishman et al., 1994; Smith et al., 2005; Bucik et al., 2006). The origin of TGFs is believed to be the runaway electrons accelerated by the upper dipole as Wilson suggested in 1925.

Starting from 2008 experimental facilities of the Aragats Space Environmental Center (ASEC) (Chilingarian et al., 2003, 2005a,b) routinely measure time series of secondary cosmic ray fluxes. During these years several new particle detectors were designed and fabricated having lower energy threshold and possibility to distinguish charged and neutral fluxes (Arakelyan et al., 2013; Chilingarian et al., 2013). Variety of ASEC particle detectors allows for the first time detect RREA process in the atmosphere (Chilingarian et al., 2011), recover both the electron and gamma ray energy spectra of largest TGEs (the sum of multiple RREA) and develop the model of the TGE phenomena (Chilingarian, Mailyan et al., 2012).

16 by 1 m^2 area scintillators previously belonging to the stopped in 2007 MAKET surface array (Chilingarian et al., 2007), registering Extensive Air Showers (EAS) were distributed on the surface of $\sim$1000 m^2. If signals from the first 8 scintillators covering $\sim$ 400 m^2 area coincide within the trigger time of 400 nanoseconds the amplitudes of all photomultiplier pulses (proportional to the number of particles hitting each scintillator) are stored. At fair weather the surface array registered EAS events initiated mostly by the primary protons with energies above $\sim$50 TeV (25 EAS per minute, 8-fold coincidences) and 100 TeV (8 EAS per minute, 16-fold coincidences).

At 19 September 2009 the ASEC detectors measure the largest TGE ever measured at Aragats. The significance of detection at energies of 10 MeV exceeds 200σ. Measuring electron flux with different thresholds allows recovering for the first time the electron integral energy and estimate the height of thundercloud above detectors. The time series of the surface array triggers also demonstrate huge enhancement. During 7 min of the TGE $\sim$200 additional triggers were registered; the count rate at 22:47, 19 September 2009 was enhanced $\sim$8 times for the 16-fold coincidences and 5 times for the 8-fold coincidences. The statistical analysis of detected showers reveals their systematic difference from the EAS events (see for details Chilingarian et al., 2011): the density was much lower and spatial spread of the electrons was much more uniform (EAS spatial distribution have characteristic bell-like form). Therefore, the particle showers from the thunderclouds constitute different from EAS physical phenomena and were named – Cloud Extensive Showers (CESs). A CES phenomenon is very rare: only 3 largest TGEs from 300 were accompanied by CES observation. CESs originated from individual runaway electrons accelerated in the cloud just above the detector. Like multiple EASs from the primary cosmic rays are sustaining stable flux of secondary cosmic rays, multiple CESs are sustaining transient enhancement of the TGEs lasting minutes. Due to global character of primary cosmic ray flux the secondary cosmic ray flux did not change significantly; CES phenomenon is very local and depends on the height of cloud above detector and on the strength of electric field in it. Both parameters are fast changing and only during several minutes cascades from runaway electrons can be developed enough to cover several thousand square meters of surface. Only very suitable location and large sizes of the scintillators allows detect CES on Aragats and for the first time prove existence of RREA phenomena.

During 2008–2012 ASEC detectors at Aragats (3200 m above sea level, geographical coordinates 40°28′N, 44°10′E) were operated 24 h, 12 months uninterruptedly, gathering rich harvest of TGE events (totally 277 TGE events in 5 years, see Tables 1–5). Much less TGE events (20, see Table 6) were detected in the same period at Nor Amberd station, on the slopes of Aragats (2000 m above sea level, geographical coordinates 40°22′N, 44°15′E). And only one TGE by 3.8% amplitude was detected in Yerevan (1000 m above sea level, geographical coordinates 40°20′N, 44°49′E), (see Table 7, measurements in Yerevan started in 2011).

34 of 277 TGE events were registered in 2008, 46 TGEs in 2009, 88 TGEs in 2010, 67 TGEs in 2011 and 42 TGEs in 2012 years. 190 TGEs from 277 have amplitude less than 5%, 55 TGEs have amplitude between 5% and 10% and 32 TGEs have amplitude greater than 10%. Only 13 TGEs have amplitude exceeding 20%. The maximal value of observed enhancements was 271% (September 19, 2009) and the minimal registered −0.8%. In the observed years the most productive months were: May and June in 2008, May–July in 2009. The maximum number of TGE events was detected in October 2010.