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Recovering of the energy spectra of electrons and gamma rays coming from the thunderclouds

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ABSTRACT

Strong electric fields inside thunderclouds give rise to enhanced fluxes of high-energy electrons and, consequently, gamma rays and neutrons. During thunderstorms at Mount Aragats, hundreds of Thunderstorm Ground Enhancements (TGEs) comprising millions of energetic electrons and gamma rays, as well as neutrons, were detected at Aragats Space Environmental Center (ASEC) on 3200 m altitude. Observed large TGE events allow for the first time to measure the energy spectra of electrons and gamma rays well above the cosmic ray background. The energy spectra of the electrons have an exponential shape and extend up to 30–40 MeV. Recovered energy spectra of the gamma rays are also exponential in energy range 5–10 MeV, then turns to power law and extends up to 100 MeV.

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1. Introduction: Thunderstorm ground enhancements (TGEs)

The attempts to discover high-energy phenomena in the atmosphere, so called, Thunderstorm Ground Enhancement (TGE), in spite of a long history since prediction of C.R.T. Wilson in 1924 (Wilson, 1925), were discrepant and rare. Early measurements (Schonland, 1930; Schonland and Viljoen, 1933) reported the existence of electron flux simultaneously, or earlier, than lightning located 30 km apart. Atop Mount Lemmon (altitude 2800 m) at the lightning research facility of the University of Arizona, the simultaneous detection of cosmic ray flux (by the 10-cm diameter and 10-cm length plastic scintillator) and electric field (by an electric field mill) demonstrates ~10% enhancement of the 1-minute count (Shaw, 1967). The average excess duration was ~10 min; the threshold energy of the particle detector was ~100 keV. The Italian EAS-TOP surface array (Aglietta et al., 1989) measures significant excesses in the air shower count rate lasting 10–20 min. The enhancements with maximum amplitude of 10%–15% were attributed mostly to the highest energy Extensive Air Showers (EAS; large shower sizes, $>10^6$ electrons), and to zenith angles of incidence smaller than 20°; "thickness" (time interval of the EAS particles arrival) of shower was slightly larger than in normal conditions (Vernetto et al., 2001).

A radiation monitoring post in a nuclear power plant in Japan reports on a comprehensive observation of a gamma ray burst emission lasting less than 1 min—correlated with snow and lightning activity. Enhancements were detected only during wintertime, when thunderclouds are as low as several hundred meters (Torii et al., 2002). The same group observed a summer thunderstorm at the top of Mount Fuji (3776 m high). The flux of high-energy gamma rays had continuous energy spectrum up to 10 MeV, prolonged up to 20 min. The authors of Torii et al. (2009) claim that the bremsstrahlung photons generated by the energetic electrons were produced continuously due to an intense electric field in the thundercloud rather than having originated in the process of lightning discharge.

A Japanese group on another Japanese power plant also detected short (less than 1 min) gamma ray bursts during winter thunderstorms (Tsuchiya et al., 2007). The same authors reported a simultaneous detection of gamma rays and electrons at a mountain observatory Norikura located 2770 m above sea level (Tsuchiya et al., 2009). Two emissions, lasting 90 s, were associated with thunderclouds. At the same research station at Norikura in the Japanese Alps a large multilayered particle

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detector operates, primarily intended to register solar neutron events. In August 2000 on account of thunderstorms, particle flux enhancement was detected in 3 layers of a 64 m^2 area detecting system (Muraki et al., 2004).

In experiments at the Baksan Neutrino Observatory of the Institute for Nuclear Research, the time series of hard and soft components of secondary cosmic rays are continuously measured along with measurements of the electric field and monitoring of thunderstorms. Intensity changes of the soft cosmic rays (below 30 MeV) and hard component (>100 MeV) were studied (Lidvansky and Khaerdinov, 2009). It was shown that the critical field and particle energy for this process are ~300 kV/m and ~10 MeV respectively (Khaerdinov et al., 2005).

A network of the NaI detectors along with EAS triggering system is located at Tien-Shan Cosmic Ray station of the Lebedev Physics Institute, at altitude of 3340 m. The goal of the research is to detect runaway breakdown initiated by EAS with energy above 1000 TeV—so-called RB-EAS discharge. Based on short gamma flashes (less that 200 μs) detected by the network of gamma ray detectors, the authors of Gurevich et al. (2009) claim that RB-EAS discharge is a rather rare event — occurring in only ~1% of all EAS registered during thunderstorms, requiring coincidence of several conditions. The most important of them being that the strong electric field should be located not higher than 400–500 m above the detector.

Recently Japanese groups perform new measurements of gamma ray emission and detect the source of the radiation in thundercloud moving across locations of several nuclear power plants (Torii et al., 2011; Tsuchiya et al., 2011).

Facilities of the Aragats Space Environment Center (ASEC) (Chilingarian et al., 2003, 2005) observe charged and neutral fluxes of secondary cosmic rays by the variety of particle detectors located in Yerevan and on slopes of Mount Aragats at altitudes 1000, 2000 and 3200 m. ASEC detectors measure particle fluxes with different energy thresholds as well as EAS initiated by primary proton or stripped nuclei with energies greater than 50–100 TeV (Chilingarian et al., 2010). Abrupt enhancements of particle detector count rates correlated with thunderstorm activity, so called Thunderstorm Ground Enhancements (TGEs) detected during 2008–2011 bring vast amounts (243 TGE events) of small and very few large TGEs (only 6 TGE events with amplitude exceeding 20%) allowing the detailed analyses and taxonomy of the new high-energy phenomena in the atmosphere.[1] The flux enhancement is presented in percent relative to rather stable background of the ambient population of secondary cosmic rays. As we can see in the left corner of the histogram (Fig. 1), majority of TGE events have amplitude less than 10%. These small TGEs and analogical TGEs reported by other groups can be explained by the modification of the energy spectra of charged particles in the electric field of thunderclouds. Due to asymmetry of positive-to-negative flux of secondary cosmic rays in the terrestrial atmosphere, peaks and dips can arise in time series of count rates of surface particle detectors. These effects have been theoretically analyzed in Dorman and Dorman (2005) and detected on Mount Norikura (Muraki et al., 2004) and in Baksan, Russia (Alexeenko et al., 2002). Measurements at ASEC and simulations with GEANT4 package (Agnsotelli et al., 2003) confirm additional flux of gamma rays up to 1000% in the energy range of 2–20 MeV and up to 10% in the energy range up to 100 MeV. Simultaneously dips in the muon flux at energies above 200 MeV were obtained by GEANT4 simulations and detected by ASEC detectors.

Few very large enhancements seen in the right corner of Fig. 1 can be explained only by invoking the Runaway Breakdown (RB) process (Gurevich et al., 1992), also referred as Relativistic Runaway Electron avalanche (RREA, Dwyer, 2003, 2007; Carlson et al., 2008). Ambient population of secondary cosmic ray electrons in the electric fields with strength greater than the critical value[2] unleashes the electron-gamma ray avalanches and total number of particles on the exit from cloud can be multiplied by several orders of magnitude. Proceeding from the measurements of the charged and neutral fluxes as well as from the energy deposit of particles in thick scintillators, we recover the energy spectra of TGE electrons and gamma rays for the 2 largest TGE events of September 19, 2009 and October 4, 2010. Installation of Aragats field meters (Boltek firm electric mill EFM100, http://www.boltek.com/efm100.html) and lightning detectors (LD250 powered by the software from Astrogenic systems, http://www.boltek.com/ld250.html) allows correlating the measured particle fluxes with near-surface electric field disturbances and with occurrences of lightning of different types.

In Fig. 1, we present the histogram of the 243 TGE amplitudes (relative enhancements above cosmic ray background) measured by the MAKET detector in 2008–2011; the dates of 4 largest TGE events are displayed as boxed text. Lightning occurrences, as well as sketch of the RREA process in upper and lower dipoles also are depicted. The indispensible condition of TGE initiation is the creation of the lower dipole accelerating electrons downward. The temporarily emerging lower positive charge region (LPCR, Qie et al., 2009) is smaller than the mid-level negative and upper positive layers of the main upper thundercloud dipole (Williams, 1989). Therefore TGE phenomena are local and its duration coincides with the duration of the LCPR, which is usually ~10 min.

The critical electric field strength for the conventional discharge in thunderclouds is very large (~10 times more than RREA critical field) and was never measured in thunderclouds. Therefore, electron-gamma ray avalanches could initiate lightning by creating the initial conductive channel (Gurevich et al., 1999; Dwyer, 2005). Lightning in turn can provide the RREA process with additional seed electrons from the current pulses along developing lightning leader channels (Carlson et al., 2009; Lu et al., 2010, 2011; Cummer et al., 2011).

For the Terrestrial Gamma-ray Flashes (TGFs, Fishman et al., 1994) the physical model is symmetric. The electrons are accelerated upward by the negative field between main negative layer in the middle of the cloud and main positive layer near the top of the cloud. The additional seed electrons are provided by the positive intracloud lightning occurrences usually accompanying the detection of TGFs by the orbiting

[1] Time series of changing particle fluxes registered from ASEC monitors, as well as magnetometer and electrical mill measurements are available from http://adei.crd.yerphi.am/adei/.

[2] The critical electric field E_t = 1.534; 1.625, and 1.742 kV/cm at 4500, 4000 and 3400 m respectively. E_t dependence on altitude follows the air density dependence on altitude.

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