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Thunderstorm ground enhancements—Model and relation to lightning flashes

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ABSTRACT

In the beginning of last century C.T.R. Wilson proposed that strong electric field of the thunderclouds might accelerate electrons to very high energies. However, this and many other electromagnetic processes in our atmosphere are poorly understood till now; the key questions about the thundercloud electrification and lightning initiation remain unanswered. During recent decades several observations of gamma ray, electron and neutron fluxes correlated with thunderstorms were reported. Nonetheless, the origin of these fluxes is under debate till now. The direct registration of the particle showers initiated by the runaway electrons (the most popular theory) was missing. We present the experimental evidence of the microsecond duration electron bursts originated from runaway electrons accelerated in thunderclouds. The electron acceleration downward becomes possible after creation of the Lower Positive Charged Region below the main negative charged layer in the middle of the thundercloud. Our analysis is based on the vast thunderstorm data from the Aragats Mountain in Armenia, 3200 m above sea level. Varieties of particle detectors located at Aragats Space Environmental Center are registering neutral and charged particle fluxes correlated with thunderstorms, so-called Thunderstorm Ground Enhancements. Simultaneously the electric mills and lightning detectors are monitoring the near-surface electric field and lightning flashes. In the paper we present the model of TGE initiation. We demonstrate the necessity of the Lower positive charge region development for the lower dipole operation and TGE initiation. Our observations establish direct relationship of the negative electric field strength and rain rate with TGE.

1. Introduction

One of the first particle physicists and researchers of the atmospheric electricity Nobel award winner sir C.T.R. Wilson in the beginning of last century recognized that “the occurrence of exceptional electron encounters has no important effect in preventing the acquisition of large kinetic energy by particles in a strong accelerating field” (Wilson, 1925a). It was the first publication introducing an enigmatic physical phenomenon of electron acceleration by the strong electric fields in thunderclouds called “runaway” electrons by the astronomer Eddington (1926).

Of course, in 1925 the particle cascade theory was not yet established, the measurements of the electric field in thunderclouds were not done and C.T.R. Wilson overestimated the scale of electron acceleration. He thought that electrons could gain unlimited energy from the electric field: “The general effect of an accelerating field is that a beta-particle, instead of dying as it were a natural death by gradual loss of energy, is continually acquiring more and more energy and increasing its chance of surviving all accidents other than direct encounters with the nuclei of atoms” (Wilson, 1925a) and “A particle may thus acquire energy corresponding to the greater part of the whole potential difference between the poles of the thundercloud, which may be of the order of 10^9 V” (Wilson, 1925b). However, that is not possible, due to abundant radiation losses of electrons with energies greater than 50 MeV traversing the atmosphere. The first measured runaway electron spectrum in thunderstorm ground enhancements faded around 50 MeV (Chilingarian et al., 2010). The potential difference as large as 10^9 V also seems to be not feasible according to direct measurements of the intracloud electric fields with the balloon experiments (Stolzenburg and Marshall, 2008).

The first model of the structure of the electric field in thunderclouds anticipates a dipole between negative charged layer in the middle of the thundercloud and positive layer on the top. This, so called, main negative dipole[1] accelerated electrons upward. Wilson wrote: “In the central dipole region, where the downward-directed electric field is greatest, the electrons are accelerated upward to the positive layer but once above the positive layer, their motions are retarded by the electrostatic field

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[1] We adopt the “atmospheric electricity” sign convention: the positive field (E kV/m) accelerates electrons downward in the direction of the Earth; the negative field (−E kV/m) vice-versa accelerates electrons upward in the direction of space.

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and their trajectories bend downward again (Wilsons notebooks, cited by Williams (2009)) and "Fast beta rays can then reach the atmosphere or be bent around by magnetic field to reach Earth at varying distances according to energy and initial directions" (letter to B.F.J. Schonland, cited by Williams (2009)).

The more realistic tripole structure of the thundercloud electric field introducing the short leaving Lower positive charged region (LPCR) below the main negative was established only recently and till now its origin is not fully understood. The LPCR on the base of cloud with middle negatively charged layer constitute lower negatively charged dipole, which accelerates electrons downwards. Electrons accelerated by the lower dipole produce, so-called, thunderstorm ground enhancements—TGEs, intense fluxes of electrons, gamma radiation and secondary neutrons (Chilingarian et al., 2011). The idea of Wilson that accelerated electrons can reach the atmosphere find proof after launching of the orbiting gamma ray observatories. Numerous terrestrial gamma flashes (TGFs) are routinely observed at $\sim$500 km above Earth in correlation with strong equatorial thunderstorms (Fishman et al., 1994). The origin of TGFs is believed to be the electrons accelerated by the upper dipole as Wilson suggested in 1925.

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 the 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 gamma rays) the results of these experiments were discouraging. Looking for the electrons with energies up to 5 GeV incident to the earth surface following the force lines of geomagnetic field surely could not give a positive outcome (see Halliday, 1941). The observation of the runaway electron phenomena 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 was significant progress in detection of the particles (mostly gamma rays) from thunderclouds (Parks et al., 1981; McCarthy and Parks, 1985; Aglietta et al., 1989; Eack et al., 2000; Brunetti et al., 2000; Alexeenko et al., 2002; Torii et al., 2002; Tsuchiya et al., 2007). However, till now there are numerous unsolved problems concern complicated TGE phenomena. Some of these problems, i.e., the model of TGE; the nature of emerging LPCR; TGE relation to atmospheric discharges will be presented and discussed in the paper.

2. Research made on Aragats Space Environmental Center (ASEC)

Cosmic Ray Division (CRD) of the A. Alikhanyan National lab (Yerevan Physics Institute) during recent 20 years commissioned and operated on the research station Aragats and Nor Amberd numerous particle detectors uninterruptedly registering fluxes of charged and neutral cosmic rays. The main topic of research was physics of the high-energy cosmic rays accelerated in our Galaxy and beyond. Surface arrays consisting of hundreds of plastic scintillator were measuring Extensive air showers (EASs), the cascades of particles born in interactions of primary high-energy proton or fully stripped nuclei with atoms of terrestrial atmosphere. Aragats physicists investigate the, so-called, knee region, where energy spectrum of protons and nuclei suddenly change the spectral index from -2.7 to -3. A new developed method of distinguishing between showers initiated by primary particles lead to possibility of measuring partial spectra and the exploration of the particle acceleration mechanism by the shock waves in vicinity of exploding super-novae stars. MAKET-ANI experiment proves very sharp knee in light nuclei energy spectrum at energies of 2–3 PeV and absence of knee in heavy nuclei energy spectrum up to 20 PeV (Chilingarian et al., 2004). This finding of charge dependent position of the knee was later confirmed by the KASCADE experiment (Antoni et al., 2005).

After finishing EAS experiments on Aragats was started a new excited topic—Solar physics and Space Weather. The neutron monitors located at 3200 and 2000 m and numerous new particle detectors measuring charged and neutral components of secondary cosmic rays making Aragats one of the largest centers for researching of solar-terrestrial connections. During 23-rd solar activity cycle were measured many important Solar energetic events, including largest series of GLEs (Ground level enhancements) and Forbush decreases in November 2003 (so-called Halloween events) and discovery of the highest energy solar protons at 20 January 2005 (Chilingarian, 2009). Culmination of the solar physics research was creation of the SEVAN (Space Environmental Viewing and Analysis Network) a network of particle detectors located at middle and low latitudes, which aims to improve fundamental research of space weather conditions and to provide short and long-term forecasts of dangerous consequences of space storms (Chilingarian and Reymers, 2008). The SEVAN network consists of hybrid detectors registering charged and neutral components of secondary cosmic rays. The network detects changing fluxes of different species of secondary cosmic rays at different altitudes, longitudes and latitudes, thus turning into a powerful integrated device used to explore solar modulation effects.

Starting from 2008 during very quiet 24-th solar activity cycle the CRD turns to investigations of the high-energy phenomena in the atmosphere. Existing and new designed particle detectors and unique geographical location of Aragats station allow to observe in 5 years more than 300 particle bursts, which were called TGEs—thunderstorm ground enhancements. TGEs observed on Aragats are not only gamma rays, but also sizable enhancements of electrons (Chilingarian et al., 2013b) and rarely also neutrons, usually lasting 10 min or more. Aragats physicists enlarge the possibilities for TGE research by coherent detection of the electrical and geomagnetic fields, rain rate, temperature, relative humidity and other meteorological parameters, as well as by detection of the lightning. Adopted multivariate approach of investigations allows connecting different fluxes, fields and lightning occurrences and finally establishing comprehensive model of the TGE.

The same approach allows unambiguously proving the existence of the neutron fluxes linked to the TGEs and well correlated with the gamma ray fluxes. The mechanism of the neutron generation by the photonuclear reaction of the gamma rays born in thunderclouds was suggested in Babich and Roussel-Dupré (2007) and observed at Aragats during the strongest TGEs (Chilingarian et al., 2012a). A new realistic simulation of the RREA process in the thunderstorm atmosphere helps to clarify contribution of the direct gamma ray production in a lead absorber to the Neutron monitor counts (NM, Tsuchiya et al., 2012). At any offset of the "emitting region" relative to the detector location the "direct neutron production" quickly diminished and the "atmospheric" neutron contribution enlarged (Chilingarian et al., 2012b). Therefore, both photonuclear processes in the air and in the lead absorber of NM should be considered to explain the neutron fluxes correlated with thunderstorms.

3. Extensive cloud showers—Experimental proof of the runaway process

Gurevich et al. (1992) developed a theory of the runaway process. They showed that when Møller scattering (electron–electron elastic scattering) is included, the runaway electrons described by Wilson will undergo avalanche multiplication, resulting in a large number of