

Mount Aragats as a stable electron accelerator for atmospheric High-energy physics research

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Abstract. The observation of the numerous Thunderstorm ground Enhancements (TGEs), i.e. enhanced fluxes of electrons, gamma rays and neutrons detected by particle detectors located on the Earth's surface and related to the strong thunderstorms above it helped to establish a new scientific topic - high-energy physics in the atmosphere. The Relativistic Runaway Electron Avalanches (RREAs) are believed to be a central engine initiated high-energy processes in the thunderstorm atmospheres.

RREAs observed on Aragats Mt. in Armenia during strongest thunderstorms and simultaneous measurements of TGE electron and gamma ray energy spectra proved that RREA is a robust and realistic mechanism for electron acceleration. TGE research facilitates investigations of the long-standing lightning initiation problem.

For the last 5 years we were experimenting with the "beams" of "electron accelerators" operated in the thunderclouds above the Aragats research station. Thunderstorms are very frequent above Aragats, peaking at May-June and almost all of them are accompanied with enhanced particle fluxes. The station is located on a plateau at altitude 3200 asl near a large lake. Numerous particle detectors and field meters are located in three experimental halls as well as outdoors; the facilities are operated all year round.

The key method employed is that all the relevant information is being gathered, including the data on the particle fluxes, fields, lightning occurrences, and meteorological conditions. By the example of the huge thunderstorm that took place at Mt. Aragats on the 28th of August 2015, we show that simultaneous detection of all the relevant data allowed us to reveal the temporal pattern of the storm development and to investigate the atmospheric discharges and particle fluxes

1. INTRODUCTION

The theoretical investigation of the high-energy processes in the atmosphere started 90 years ago by the Nobel Prize winner and creator of one of the first particle detectors C.T.R.Wilson (1924). Numerous papers published in recent decades by A.Gurevich, J.Dwyer, L.Babich, A.Lidvansky and co-authors (see citations to original publications in Dwyer, Smith, and Cummer, 2012) introduce the Runway Breakdown (RB), otherwise cited as Relative Runaway Electron Avalanches (RREA) as a central engine of the high-energy processes in the thunderstorm atmospheres. Measurements of particle fluxes on high mountains and in regions of Japan with low charge centers in thunderclouds prove the existence of particle fluxes that last up to a few tens of minutes correlated with thunderstorm activity (see details and references to original publications in review of Dwyer and Uman, 2014). The first detection of huge fluxes of electrons, gamma rays and neutrons on Aragats in 2009 (Chilingarian et al., 2010) has unambiguously established a new physical phenomenon - Thunderstorm ground Enhancement - TGE, increased fluxes of electrons, gamma rays and neutrons detected by particle detectors located on the Earth's surface. The in situ observation of RREAs during strongest thunderstorms on Aragats (Chilingarian et al., 2011) and simultaneous measurements of TGE electrons and gamma ray energy spectra (Chilingarian, Mailyan and Vanyan, 2012) proved that RREA is a realistic and robust mechanism for electron acceleration in the atmosphere. In these publications, it was emphasized that lightnings, and TGFs are alternative mechanisms for the discharging of the atmospheric "electric engine"; there was also introduced the origin of the highest energy gamma photons - Modification of the Cosmic ray (CR) electron energy Spectrum (MOS) in the strong electric field of the thundercloud. Chilingarian and Mkrtchyan, 2012, emphasized the role of the transient Lower Positive Charge Region (LPCR) in electron-gamma

ray avalanche unleashing. Detailed measurements of the gamma ray energy spectra by large NaI spectrometers on Aragats (Chilingarian, Hovsepyan, Kozliner, 2013) allow to reliably extend the energy range of the "thunderstorm" gamma rays up to 100 MeV. All these results were obtained at the Aragats research station in Armenia during the last 5 years with "beams of electron accelerator" operated in thunderclouds above the research station. Aragats Space Environmental center (ASEC, Chilingarian et al., 2005) is located at an altitude of 3200 m on the plateau nearby a large lake and clouds usually are formed just above it (see Fig. 1).

Numerous particle detectors and field meters are located in three experimental halls as well as outdoors; the facilities are operated all year round. After understanding the TGE physics, we plan to apply this new evidence, i.e. fluxes of particles from the thundercloud, to approach the long-standing problems of lightning initiation and lightning leader propagation.

The key method employed is that all the relevant information is being gathered, including the data on the particle fluxes, fields, lightning occurrences, and meteorological conditions. By the example of the huge thunderstorm that took place at Mt. Aragats on the 28th of August 2015, we show that simultaneous detection of all the relevant data allowed us to reveal the temporal pattern of the storm development and to investigate the atmospheric discharges and particle fluxes. The paper is comprised of the following sections: instrumentation; chain of positive lightnings; chain of negative lightnings; small size TGE; and large size TGE. Thunderstorms are very frequent above Aragats, the peak activity being in at May-June and September-October. Almost all of them are accompanied with enhanced particle fluxes. In Fig. 1 we see an artistic view of multiple electron-gamma ray avalanches directed to the earth's surface and to the open space. The first ones originated TGEs regis-

tered by the ground based particle detectors; the second ones – originated Terrestrial gamma flashes (TGFs, Fishman et al., 1994) observed by the orbiting gamma ray observatories.

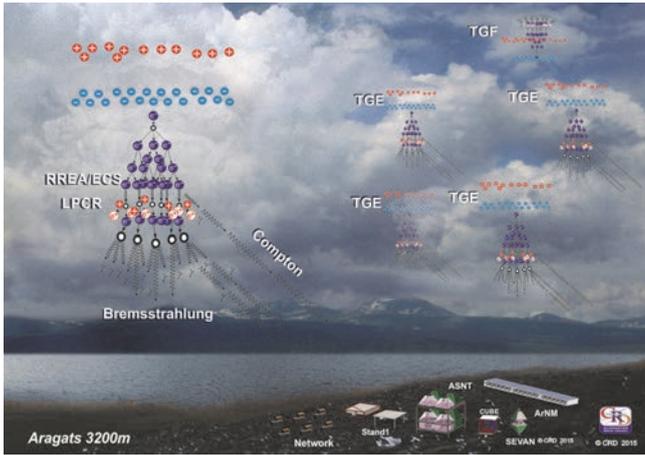


Figure 1. Artistic view of the multiple RREA cascades in the thunderstorm atmosphere directed to earth's surface (TGEs) and - to the space (TGF)

By analyzing a particular stormy day at Aragats, namely 28 August 2015, we will demonstrate the operation of the electron “accelerator” in the vicinity of the station and present the stages of our physical inference on the discovery of the new phenomenon of “Long TGEs” – lasting for several hours enhancements of low-energy gamma ray fluxes (0.4 - 2 MeV).

2. INSTRUMENTATION

The particle detectors of the Aragats Space Environmental Center (ASEC, Chilingarian et al., 2005) can measure the fluxes of the species of secondary cosmic rays (electrons, gamma rays, muons and neutrons), which have different energy thresholds. Numerous thunderstorm-correlated events, detected by the ASEC facilities, constitute a rich experimental set for the investigation of the high-energy phenomena in the thunderstorm atmosphere. The new generation of ASEC detectors consist of 1 and 3 cm thick molded plastic scintillators arranged in stacks and cubic structures (Chilingarian, Chilingaryan and G.Hovsepian, 2015). The “STAND1” detector is comprised of three layers of 1-cm-thick, 1-m² sensitive area molded plastic scintillators fabricated by the High Energy Physics Institute, Serpukhov, Russian Federation see Fig. 2. The light from the scintillator through optical spectrum-shifter fibers is reradiated to the long- wavelength region and passed to the photomultiplier FEU-115M. The maximum of luminescence is emitted at the 420-nm wavelength, the luminescence time being about 2.3 ns. The STAND1 detector is tuned by changing the high voltage applied to PM and setting the thresholds for the discriminator-shaper. The threshold should be chosen to guarantee both high efficiency of signal detection and maximal suppression of photomultiplier noise. Proper tuning of the detector provides ~99% efficiency of charged particle detection. The data acquisition (DAQ) system counts and stores all coincidences of the detector channels. Coincidence “100” means that a signal has been registered in the upper detector only. This combination registered low- energy electrons with an efficiency of ~99%; the threshold energy of ~1 MeV is one of the lowest among all ASEC detectors.

The gamma ray detecting efficiency of this combination is about 2%. For the coincidence 010, the gamma ray

detection efficiency is increased to ~3% due to creation of the additional electron-positron pairs in the substance of the upper scintillator. Coincidence “111” means that all three layers register particles; the minimal energy of charged particles giving a signal in all three layers is ~10 MeV. With the same DAQ electronics are registered the time-series of a similar (but 3 cm thick) particle detector stand aside near the stacked structure.



Figure 2. STAND detector consisting of three layers of 1 cm thick scintillators.

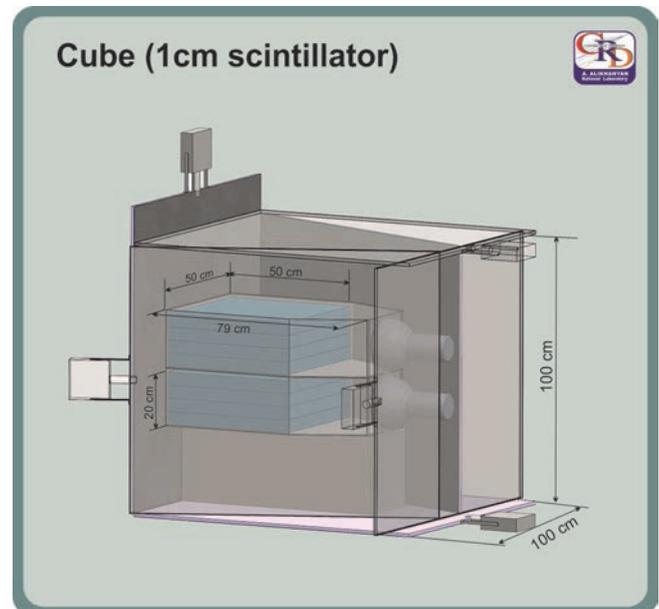


Figure 3. Cube detector; thick scintillators located inside are measuring neutral flux with purity ~98%.

Special experimental facilities were designed and installed at Aragats in order to separate electron and gamma ray fluxes. Two 20 cm thick plastic scintillators are surrounded by 1 cm thick molded plastic scintillators (see Fig. 3). Thick scintillators detect charged flux with a very high efficiency (~99%); they can also detect neutral flux with an efficiency of ~20%. Thin scintillators also detect charged flux with very high efficiency (~99%), though the efficiency of detecting neutral flux is highly suppressed and equals 1%–2%. Thus, using the coincidences technique, it is possible to purify the neutral flux detected by inside scintillators, rejecting the charged flux by the veto signals from surrounding thin scintillators. The calibration of the cube detector proves that the veto system (preventing the counting signal in the thick scintillator if there is a signal in at least one of the six surrounding thin scintillators) can reject 98% of the charged flux (see details in Chilingarian, Mailyan and Vanyan, 2012).

The histograms of the energy deposits in the two inner thick scintillators are stored every minute. The one-minute count rates of the surrounding 6 scintillators are measured and stored as well.

The detector network measuring particle energy consists of four NaI crystal scintillators packed in a sealed 3-mm-thick aluminum housing. The NaI crystal is coated by 0.5 cm of magnesium (MgO) by all sides (because the crystal is hygroscopic) with a transparent window directed to the photocathode of a FEU-49 photomultiplier (PM), see Fig. 4.

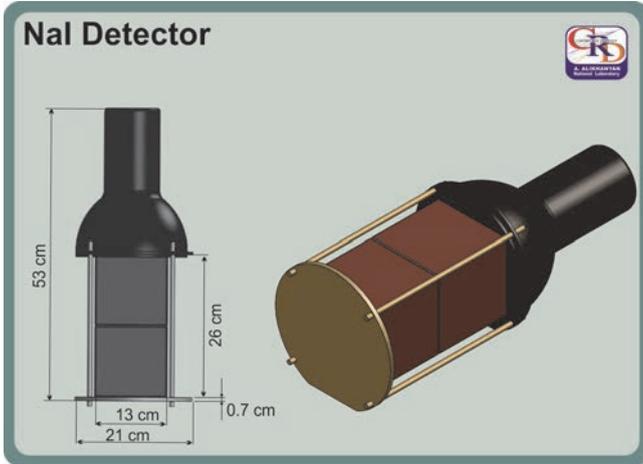


Figure 4. NaI(Tl) crystal assembly.

The large cathode of FEU-49 (15-cm diameter) provides a good light collection. The spectral sensitivity range of FEU-49 is 300–850 nm, which covers the spectrum of the light emitted by NaI(Tl). The sensitive area of each NaI crystal is $\sim 0.0348 \text{ m}^2$; the total area of the four crystals is $\sim 0.14 \text{ m}^2$; the gamma ray detection efficiency is $\sim 80\%$. A logarithmic analog-digit-converter (LADC) is used for the coding of PM signals. Calibration of LADC and code-energy conversion was made by detecting the peak from exposed ^{137}Cs isotope emitting 662 keV gamma rays and by high-energy muon peak (55 MeV) in the histogram of energy releases in the NaI crystal. The PM high-voltage was tuned to contain both structures (peaks) in the histogram of LADC output signals (codes) and to ensure linearity of LADC in the energy region of 0.4 - 60 MeV. The detailed description of other ASEC detectors including charts with all sizes is available from the WEB site of the Cosmic Ray Division of Yerevan Physics Institute: <http://crd.yerphi.am/ADEI> in the WIKI section of the multivariate visualization platform and from (Chilingarian et al., 2010, Chilingarian, Chilingaryan, and Reymers, 2015).

The count rate of a particle detector depends on the chosen energy threshold of the shaper-discriminator, size of the detector and on the amount of matter above it. The inherent discrepancy of the parameters of PMs also can add $\sim 15\%$ difference to the particle detector count rates. Significant amount of substance above the sensitive volume of NaI crystals (0.7 mm of roof tilt, 3 mm of Aluminum and 5 mm of MgO) prevents electrons with energy lower than $\sim 3\text{-}4 \text{ MeV}$ to enter the sensitive volume of the detector. Thus, the network of NaI spectrometers below 4 MeV can detect gamma rays only.

The small sizes of the NaI crystals and short duration of TGE pose a limitation on the lowest gamma ray flux that can be reliably observed. The usual requirement on the minimal amount of particles in a histogram bin is >5 ; therefore, the minimal flux that can be reliably detected by the NaI network should be above 200 per minute per m^2 (the

area of 4 crystals is 0.14 m^2 and required number of particles in 4 crystals above 20). For smaller fluxes fluctuations overwhelm the signal.

The significance of detecting peaks in the time series of the particle count rates is determined by the p-values of the peak significance test, i.e. by the value of the peak divided by the standard deviation of count rate (number of standard deviations contained in the peak, $N\sigma$). The p-value is the most comprehensive measure of the reliability of detecting peaks in a time series. Large p-value corresponds to small chance probabilities that the observed peak is a background fluctuation and not a genuine signal. Therefore, we can safely reject the null hypothesis (background fluctuation) and confirm the TGE. Very large p-values not only prove the unambiguous existence of a particle flux from the cloud, but also serve as a comparative measure of the TGE observations using different detectors.

The deep negative near-surface electric field is a necessary condition for the TGE origination. Moreover, the observed changes of the electric field, along with detected particle fluxes encompass information on the dynamics of the cloud electrification, which is very difficult to acquire by in-situ measurements. A network of three electric mills continuously monitors the disturbances of electric field on Mt. Aragats. Electrical mill EFM 100 produced by Boltek Company operates with 20 Hz frequency performing 20 measurements of the near-surface electric field per second. Comparisons of electric field strengths obtained by the three identical EFM-100 electrical mills prove reliability and high accuracy (discrepancy of device readings do not exceed 10%) of electric field measurements.

3. SERIES OF POSITIVE LIGHTNINGS AT $\sim 12:00 - 13:00$

On 28 August, almost all day long, the thunderstorms at Aragats were accompanied with numerous nearby lightnings and several episodes of the enhanced particle fluxes registered by the detectors located at ASEC.

The network of NaI spectrometers had detected an enhanced flux of low energy gamma rays with several episodes of abrupt bursts, as it is shown in Fig. 5. In spite of the fact that the NaI crystals are much smaller than the plastic scintillators, due to the low energy threshold (0.4 MeV) and higher efficiency to register gamma rays the count rate of each of the four spectrometers are higher than the counts of larger plastic scintillators. The $\sim 15\%$ discrepancy of the count rates of the four spectrometers are explained by the differences in PM parameters. This discrepancy does not influence the amplitude of TGE (peak value of the count subtracted by background value), which is the same for all 4 spectrometers.

The matter above the sensitive volume of NaI spectrometer absorbs electrons with energies below 3 MeV. Thus, registration of gamma rays below 0.4 MeV is only feasible; sure the detection of electrons of the higher energy is possible. In Fig. 5 we can see that the time series of CU-BE detector (a 20-cm thick detector located inside the veto housing; energy threshold $\sim 4 \text{ MeV}$) demonstrate enhancement only around 23:20 when, as we will see later the gamma ray flux exceeded 4 MeV due to presence of the bremsstrahlung gamma rays from the runaway electrons. The STAND1 detector (energy threshold $\sim 1 \text{ MeV}$) showing a flux enhancement coherent to NaI at a smaller scale had also demonstrated a pronounced peak around 23:20.

For recovering electron and gamma ray intensity in the TGE flux at energies above 4 MeV we use data from CUBE detector vetoing the charge flux.

Due to the small sensitive area of NaI spectrometers, we can recover differential energy spectra at energies above $\sim 10^3/\text{m}^2\text{min}$, equivalent to 5-10 registered particles in an energy bin. Histograms of the energy releases in NaI crystals are collected and stored each minute; therefore we can recover 1440 energy spectra daily. To achieve better statistical accuracy, we use the data from all 4 spectrometers and combine several minutes around the peak values of the count rate. The energy spectra were recovered, according to the methodology described in (Chilingarian et al., 2007) for 4 TGE episodes at 14:49 -14:52; 16:37-16:44; 23:18-23:21 and 23:29-23:31. The relative enhancement was calculated by subtracting from the peak value of the count rates the background measured just before the enhancement started. Only the relative enhancement in measurements with NaI crystals has physical meaning in the described series of measurements. The NaI spectrometers were located just below the iron tilts of the roof. In August at Aragats, the sun is extremely strong and the temperature under the iron roof reached 50-60 C°. The high temperature influenced DAQ electronics and, respectively, the detector count rate increases at peak temperatures up to 10% as compared with nighttime count rate when the temperature drops down to 5-10 C°. Therefore, though the maximal absolute count rate was achieved at $\sim 15:00$, the TGE at 23:20 has larger amplitude and was much more significant; it could be explained by the bremsstrahlung gamma rays emitted by the runaway electrons in the thundercloud just above the detectors.

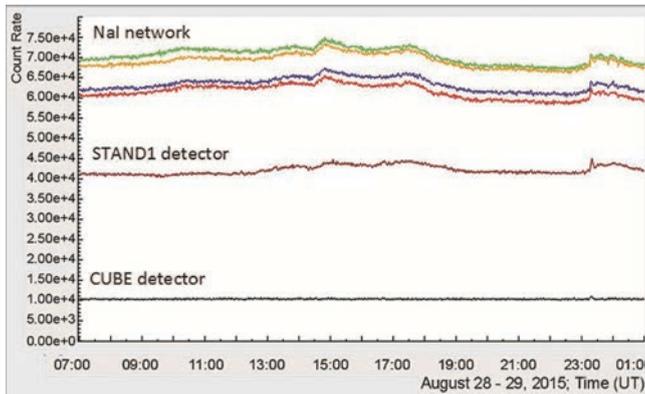


Figure 5. One-minute count rates of the network of 4 NaI spectrometers. TGE at 23:18-23:21 contain high energy gamma rays detected by all ASEC particle detectors.

The electric field disturbances at 28 August 2015 were prolonged and deep reaching -35 kV/m; lightning activity was strong and some of the lightnings were within 5 km from the station. Numerous positive lightnings that started at $\sim 8:00$ stipulate small disturbances of the near-surface electric field. The network of three EFM-100 electric mills measured the near-surface electric field. The devices operated according to the “atmospheric electricity” sign convention (a positive electric field at ground is produced by positive charge overhead and negative electric field on the ground is produced by negative charge overhead). Thus, the recorded positive field change corresponds to negative lightning, which decreases the negative charge overhead and negative field change corresponds to positive lightning, which decreases the positive charge overhead. The heavy-duty storm that started at $\sim 12:00$ was followed by copious positive lightnings lasting until $\sim 13:00$ (Fig. 6). In Fig. 6 we show the electric field disturbances measured by the elec-

tric mill located on the roof of MAKET building, the corresponding distance to the lightning and one-second time series of 1 m² plastic scintillator. The spikes in the particle count rates are due to the showers hitting the scintillator. In one-minute time series they are smoothed by integration over 60 seconds, but in 1-second time series spikes are visible.

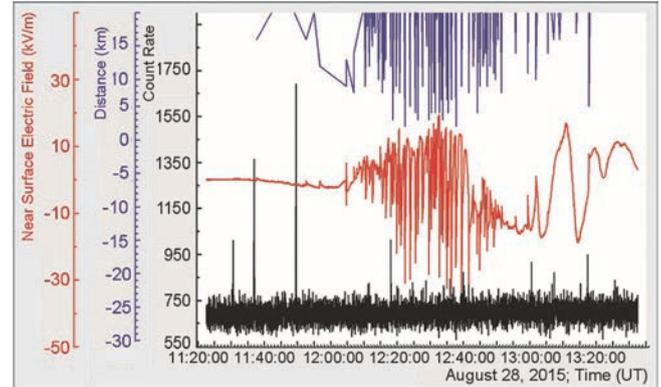


Figure 6. Positive lightnings series observed at 28 August 2015, 12:00 - 13:00; the top lines - distance to lightning, the middle curve - disturbances of near surface electric field; in the bottom - 1-second time series of count rates of 3 cm thick and 1 m² area plastic scintillator.

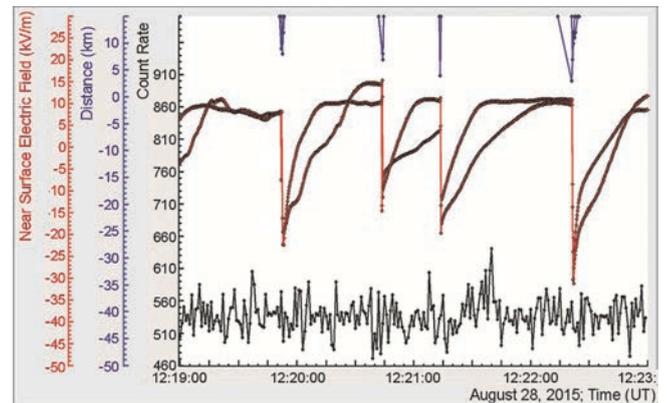


Figure 7. One episode of positive lightning series observed on 28 August 2015 at 12:00 - 13:00; the top lines - distance to lightning, the middle 2 curves - disturbances of near surface electric field measured by electric mills located at a distance of 300 m from each other; in the bottom - 1-second time series of count rates of 3 cm thick and 1 m² area plastic scintillator.

In Fig. 7 we show four minutes of stormy weather matched with 4 positive lightnings (zoomed from Fig. 6).

The pattern of rapid decrease of the electric field was approximately the same for both electric mills located at a distance ~ 300 m from each other. The abrupt decrease of the near-surface electric field followed by relatively slow recovery indicates the neutralization of a positive charge in the thundercloud. However, the operation of the charging engine permanently recovers the positive charge region in the thundercloud. In Tab. 1 we post the characteristic of 4 positive (+CG) lightnings from ~ 100 that occurred on 28 August 2015; in the end of an hour-long series of positive lightnings they changed to the negative ones.

From Tab. 1, where we present the main characteristics of the lightnings shown in the previous Figure we can outline typical features of the positive cloud-to-ground lightning that occurred on Aragats on 28 August 2015:

1. Mean electric field before the start of the lightning $\sim 8-15$ kV/m;
2. Typical values of the drop of electric field $\sim -30 - -40$ kV/m.

3. After reaching its minimum, the near-surface electric field slowly returned to the pre-lightning values due to continuous charge separation processes in the cloud in 21-31 seconds;

4. Time from the start of electric field sharp decrease till its minimum was ~ 0.1 – 0.65 sec;

5. Distance to lightning was ~ 3-8 km.

Rather large amplitude of the positive lightning field changes (-30 - -40 kV/m) achieved in time less than 1 sec and large recovery time of electric field (tens of seconds) indicates strong discharge processes at nearby distances (10 km). Several high masts are located near the station, from their tops the electron streamers can propagate to the positive charge regions in the thunderclouds above. As usual during a series of positive lightnings no enhancements of particle flux were registered.

The strong rain that started at 13:22 stopped at 14:00. The temperature started to rise from 4 C° at 13:00 till 6 C° at 14:30 and then abruptly dropped till 3.4 C° at 14:50 UT. The relative humidity decreases from 95% at 13:00 till 75% at 14:30.

Electric field was in negative domain - 8 till - 24 kV/m; few lightnings were detected. At 14:30 the gamma ray flux started to rise, reaching maximum at 14:50. The differential energy spectrum of the gamma ray flux is shown in Fig. 8. We fit the energy spectrum with 2 power law dependences; the point where interpolating dependence is changed usually is named the “knee”. Knee position is located at ~1 MeV

and is rather smooth. The energy spectrum extends to ~ 2 MeV and then fast decays.

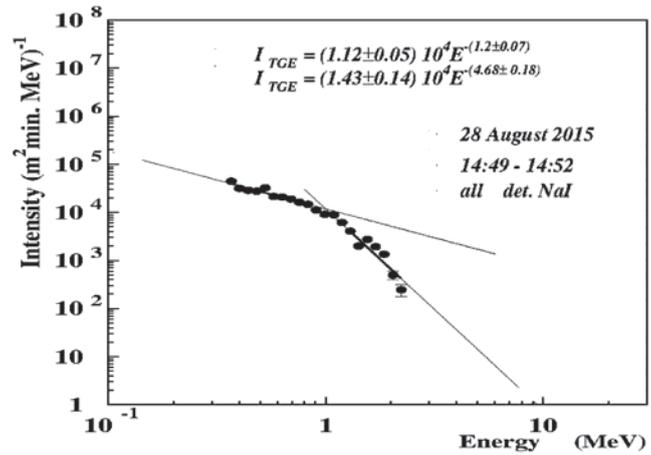


Figure 8. The differential energy spectrum of sum of 4 NaI spectrometers; the background was measured just before the TGE started. Flux intensity - $0.18 \times 10^5 / \text{m}^2 \text{min}$; knee position 0.9 MeV; intensity after knee $0.50 \times 10^7 / \text{m}^2 \text{min}$.

Next hour the lightning activity became stronger, see Fig. 9; however, the atmospheric discharges were far from the Aragats station and, therefore, the amplitudes of the near surface electric field disturbances were small, as it is seen in Tab. 2. The relative humidity (RE) successively increased from 75% at 14:30 to 92% at 15:45 when the rain resumed. At the same time, the wind speed decreased from 2 m/sec to 0.2 – 0.6 m/sec and the temperature decreased from 3.4C° till 2.9 C°.

Table 1. Main characteristics of a sample of lightning occurrences at 12:19 – 12:23 28 in August 2015

Start of Lightning (UT) and el. field value (kV/m)	Time of el. field minimum (UT) and field minimal value (kV/m)	Duration (sec)	Recovering (sec)	Drop of el. field	Dist. (km)	WWLLN time	WWLLN dist.
12:19:52.1 8	12:19:52.75 -23	0.65	21	-31	8		
12:20:43.7 15	12:20:43.8 -18	0.1	29	-33	7		
12:21:13.8 10	12:21:14.0 -20	0.2	23	-30	4		
12:22:21.3 10	12:22:21.8 -30	0.5	31	-40	3		
12:51:31.15 -14	12:51:31.55 -8	0.4	29	6	8	12:51:31.23 - 12:51:31.47	5-9

4. SERIES OF NEGATIVE LIGHTNINGS AT ~ 15:00 – 16:00

After 15:00, as we can see from Fig. 9 and the Tab. 2, the pattern of disturbances of electric field drastically changed as compared with the ones registered 2 hours before (Figs 6 and 7). The lightning locations were 10-20 km from the station (confirmed by WWLLN, see last column of Tab. 2). Therefore, the amplitude of disturbances of the near surface field was small – 3-7 KV/m. Lightnings were mostly negative, i.e. the large amount of negative charge overhead was decreased.

No TGEs were detected. The spike in 1-sec time series of plastic scintillator was due to the particle shower that hit the detector at 15:07:23.

The illustration of the 3 seconds of time series of near-surface electric field, revealing the pattern of an unusual lightning that occurred at 15:59:54.4 - 15:59:55 is given in Fig.10. In 0.6 seconds the negative discharge (abrupt enhancement of the electric field) with amplitude 3 kV/m suddenly turned to a positive one (abrupt decrease of the electric field) with amplitude -7 kV/m (see also Tab. 2).

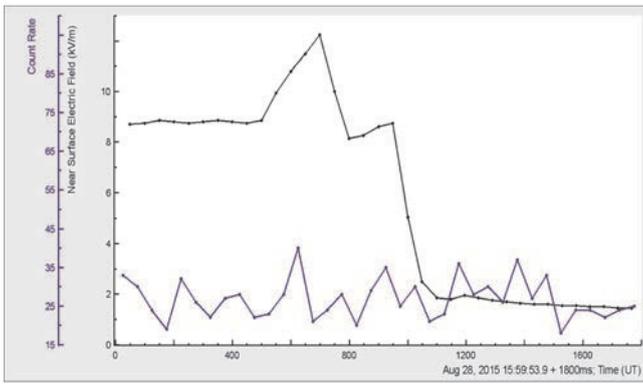


Figure 9. Multiple negative lightnings detected at 14:45 – 16:30; the top lines – distance to lightning, the middle curve – disturbances of near surface electric field; in the bottom – 1-second time series of count rates of count rates of 3 cm thick and 1 m² area plastic scintillator.

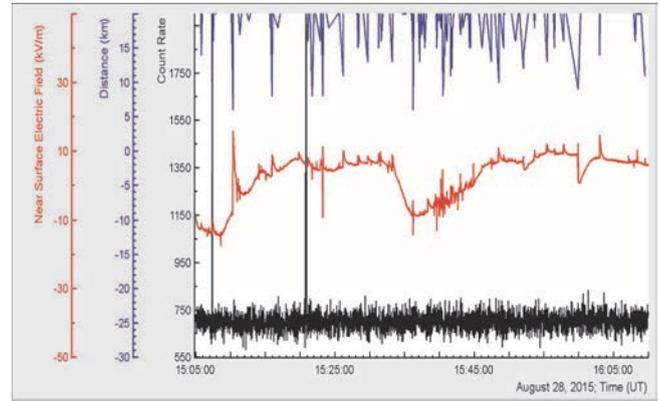


Figure 10. Disturbance of near surface electric field demonstrate starting negative discharge suddenly turned to positive one; in the bottom – 50 msec time series of 3 cm thick 1 m² area outdoor plastic scintillators.

Table 2. Main characteristics of a sample of lightning occurrences at 15:38 – 16:03 28 in August 2015

Start of Lightning (UT) and el. field value (kV/m)	Time of maximum (UT) and maximum value (kV/m)	Duration (sec)	Recovering (sec)	Drop of el. field	Dist. (km)	WWLLN time	WWLLN dist.
15:38:21.8 -7	15:38:22.7 -4	0.9	32	3	14	15:38:22.41	21
15:53:39.4 7	15:53:40.3 (15:53:39.9) 10	0.9	41	3	18	15:53:39.5	14
15:59:54.4 9	15:59:54.6 12	0.2	0.1	3	9	15:59:54.32	14
15:59:54.85 9	15:59:55.0 2	0.15	-	-7	20	15:59:54.34	8
16:03:01.05 8	16:03:01.55 15	0.5	27	7	13,15	16:03:01.0 – 16:03:01.86	11-21

5. SMALL SIZE TGE WITH MAXIMUM AT ~ 16:40

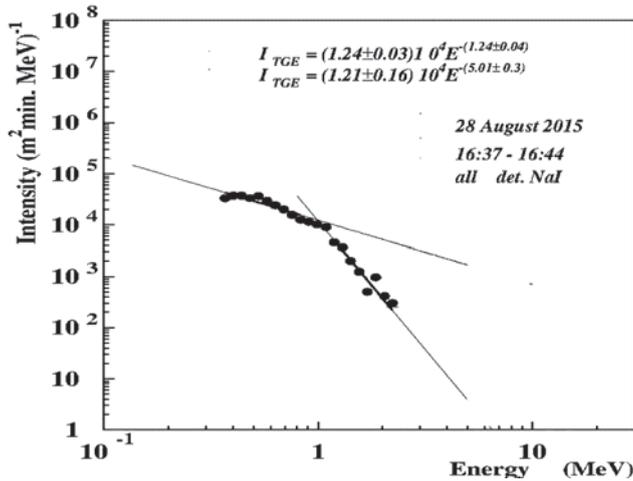


Figure 11. Differential energy spectrum of the “small size” TGE. Flux intensity - $0.95 \times 10^4 / \text{m}^2 \text{min}$; knee position - 0.9 MeV; intensity after knee - $0.25 \times 10^4 / \text{m}^2 \text{min}$.

At 16:20 electric field moved to negative domain and at 16:43 dropped to -23 kV/m. Between 16:36 and 16:43 at the large negative electric field there appeared several small “bumps” with an amplitude of less than 5 kV/m. During that “bumpy” time (16:37-16:44) several ASEC particle detectors registered TGE. The intensity of the event was 2 times less than previous TGE see Fig. 11. The “knee” position is analogous to the previous spectrum and the change of interpolating power law function is smooth too. Energy spectrum is continuing till ~ 2 MeV.

The relative humidity (RE) was 92-95% during TGE (high RE is another necessary condition to unleash large TGE) and wind speed was ~1 m/sec. The temperature started to fall at 16:26 from 3.5 C° down to 2.9 C° during TGE. Wind direction was 180° N. It stopped raining at 16:27 and resumed at 17:00. Consequently, there was no rain during TGE.

6. LARGE TGE OCCURRED AT ~ 23:18-23:21

Disturbances of electric field and lightnings prolongs till 17:30, rain till 22:00. After rain stopped electric field start to decrease at 23:00 reaching -28 kV/m at 23:21. The relative humidity (RE) rose from 89% at 23:14 till 92% at 23:17 and remain constant till 23:23. Wind speed abruptly increased from 0 at 23:13 till 7.5 at 23:19, and then increased down to 1 m/sec at 23:23. The temperature started to decrease at 23:13 from 3.9 C° reaching 0.8 C° at 23:23. Wind direction was 200N. The TGE flux reaches maximum at 23:19; energy spectra of TGE extends till 6 MeV, see Figure 12. TGE event duration is ~ 10 minutes; intensity and maximal energy – largest on 28 August. Knee position shifted to 1.12 MeV and knee is sharper than in previous TGEs considered on 28 August 2015.

The veto system of the CUBE detector rejected most of the charged particles by six 1 m² area and 1 cm. thick plastic scintillators shaped in a cubic structure. The located inside two 0.25 m² area and 20 cm thick scintillators with the veto system switched on, registered neutral particles. The CUBE detector with two inner 20 cm thick plastic scintillators with energy threshold ~4 MeV had also demonstrated pronounced peaks (Fig 13). Fig. 13 does not show the time

series of the count rates itself, but the time series of the p-values of the peak significance test. The large p-values of peaks observed by 2 inner 20 cm thick scintillators of CUBE detector allows to estimate charged and neutral fluxes of TGE above ~ 4 MeV (NaI spectrometers allow to measure pure gamma ray flux below 3-4 MeV and mixed flux above 3-4 MeV).

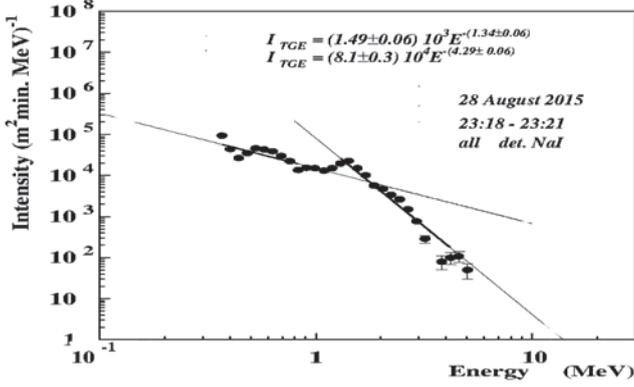


Figure 12. Differential energy spectrum of TGE obtained by 4 NaI spectrometers; Flux intensity - $0.34 \times 10^5 / \text{m}^2 \text{min}$; knee position - 1.2 MeV; intensity after knee - $0.17 \times 10^5 / \text{m}^2 \text{min}$.

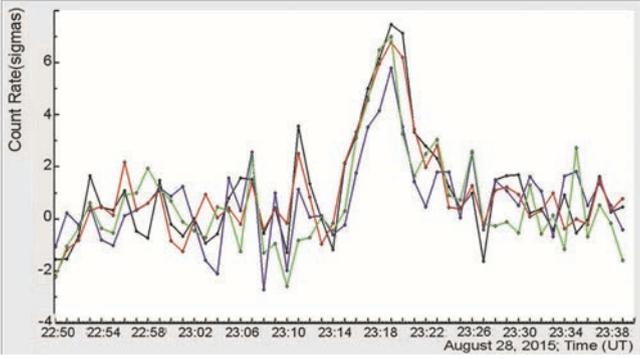


Figure 13. TGE observed by the CUBE detector's two stacked 20 cm thick plastic scintillators with and without veto system switched on.

From the Tab. 3 we can see that at 23:19 the CUBE scintillators registered maximal count rate; for that minute we calculate the electron and gamma ray intensities incident on the CUBE detector.

Due to non-zero probability of electrons to miss registration in the 1-cm thick plastic scintillator of the veto system, and due to non-zero probability for the detection of the gamma ray by the same scintillator, we have made corrections to recover intensities (see details in Chilingarian, Mailyan and Vanyan, 2012). However, these corrections are below $\sim 2\%$ as compared with calculation of the gamma ray intensity directly from the amplitude of the peak observed by the thick scintillator with the veto switched on (538 counts). The intensity of gamma rays above ~ 4 MeV

is $\sim 10^4 / \text{m}^2 \text{min}$; and the intensity of electron flux - $8 \times 10^2 / \text{m}^2 \text{min}$. Thus, the fraction of electrons at energies above 4 MeV does not exceed $\sim 7\%$.

Table 3 Count rate of 20 cm thick plastic scintillator with and without veto (minutes after 23:00 UT)

28 August (UT)				
23:16	10548	8614	4526	3577
23:17	10736	8749	4633	3647
23:18	10853	8797	4735	3739
23:19	10990	8923	4802	3764
23:20	10954	8750	4755	3585
23:21	10564	8589	4534	3507
23:22	10508	8516	4418	3548
23:23	10459	8617	4484	3575

In Tab. 4 we show the mean values of count rate, the peak value, amplitudes of the peaks (also in the number of standard deviations); and calculated intensities (integral spectra) of gamma ray and electron flux above ~ 4 MeV. We assume the efficiency of gamma ray detection by 20 cm thick scintillator to be equal 20% and detection of electrons 99%.

The efficiency of detecting gamma rays by the "veto" 1-cm thick scintillators is 2% and electrons - 99%. Particles to be registered in the bottom thick scintillator (see Fig. 3) should traverse through the upper one therefore due to attenuation of the particle flux intensities measured by the bottom scintillator are significantly lower.

After the decline of TGE at 23:23 the low energy particle flux measured by NaI spectrometers remained high. However, the conditions required for unleashing large TGE did not last and energy spectrum measured at 23:39 - 23:41 contained only low energy particle (see Fig.14).

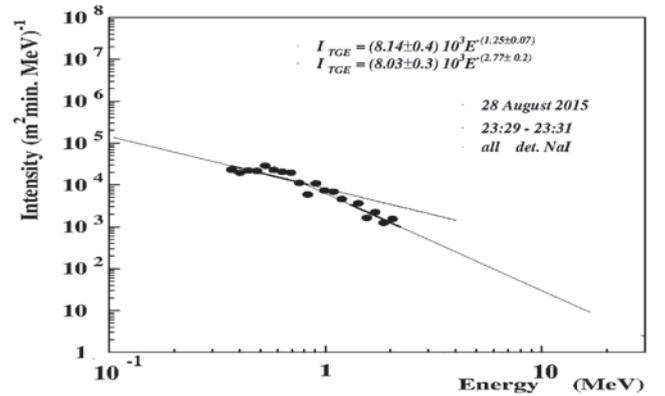


Figure 14. The differential energy spectrum of sum of 4 NaI spectrometers measured after large TGE. Entire intensity $0.21 \times 10^5 / \text{m}^2 \text{min}$; knee position - 1.2 MeV; intensity after knee $0.4 \times 10^4 / \text{m}^2 \text{min}$.

Table 4. Calculated intensities of TGE electron and gamma ray fraction; threshold 4 MeV

Name	Mean	σ	23:19 peak	TGE - ΔN (N σ)	e intensity ($1/\text{m}^2 \text{min}$)	γ intensity ($1/\text{m}^2 \text{min}$)	e/ γ
Cube 7	10258	108	10990	742 (6.9)	800	10920	7.3%
Cube 8	8494	81	8923	429 (5.3)	368	6768	5.4%
7 with veto	4294	79	4802	538 (6.8)	-	-	-
8 with veto	3431	47	3764	333 (7.1)	-	-	-

7. DISCUSSION AND CONCLUSIONS

The model of TGEs can be formulated briefly as follows (Chilingarian, 2014): electrons from the ambient population of the cosmic rays (CR) are accelerated downward (towards the Earth) by the positive dipole formed by the main negatively charged layer in the middle of the cloud and a transient lower positive charge region in the bottom of the cloud. In very strong electric fields the energy gained from the field surpasses the electron energy losses in the atmosphere and the intensive process of the electron multiplication and acceleration initiate large particle avalanches reaching and being registered on the earth's surface (TGE). If the strength of electric field is not enough to discharge RREA, nonetheless the energy of an electric field is transferred to the electrons changing their energy spectrum and enhancing the probability of bremsstrahlung (MOS process). Both MOS and RREA processes have been experimentally observed at Aragats high-mountain research station in good agreement with simulations (Chilingarian, Mailyan and Vanyan, 2012). Recently as well intense fluxes of gamma rays were measured by the airborne detector near the end of a downward RREA, consistent with another positive dipole - occurring between the upper positive charge layer and the negative screening layer above it (authors name it "gamma glows" Kelly et al., 2015).

However, in our previous publications we consider TGE events, mostly large ones, when the RREA was unleashed just above the detector site during several minutes. In this paper, we consider data collected on a whole day of 28 August 2015. The day was stormy, electric field disturbances continuous, lightnings enormous and the electron accelerator above provided evidence on several long, low

According to the model of TGE initiation (Chilingarian, 2014) the intense RREA process in the cloud originates bremsstrahlung photons that follow the passage of electrons. The electrons from the ambient population of secondary cosmic rays were accelerated up to energies 30-40 MeV. The size of LPCR does not extend more than 1 km therefore high-energy bremsstrahlung photons illuminate the earth's surface only locally under the thundercloud. The Compton scattered photons of lower energy due to much broader angular distribution can illuminate much larger surface under a cloud. Only on a few occasions when the emitting region is above the detector site we register large TGE with maximal energies above 3-4 MeV. These episodes are usually short because the wind moves the cloud relative to particle detector location. The Compton scatter photons can reach the detector site from several RRE avalanches periodically emerging in the large thundercloud for the much longer time, see Fig. 1. The position of the knee at ~ 1.1 - 1.2 MeV supported our assumption. Intensity of gamma rays with energies above pair production threshold (1.022 MeV) should be abruptly decreased due to catastrophic energy losses of the electrons and positrons in the atmosphere.

In this event, the flux of >10 MeV gamma rays was the highest energy part of the bremsstrahlung photons that are emitted by electrons accelerated to a few tens of MeV. As known from the bremsstrahlung cross-section, such photons, with energies close to that of primary electrons, are projected forward in a narrow cone. In addition, such high-energy photons undergo less Compton scatterings than lower energy photons that tend to be spread over a wide area. Therefore, it is likely that the extent of the >10 MeV gam-

energy TGEs and intensive and energetic enhancements. For the first time we describe and analyze not only isolated TGE events, but also the whole temporal history of the long duration thunderstorm, including high and low energy TGEs, periods of positive and negative lightnings, meteorological conditions, disturbances of the near-surface electric field. Our recent measurements reveal a meaningful relation between TGEs and lightnings (Chilingarian et al., 2015). Scrutinizing a particular stormy day at Aragats we demonstrate operation of the "moving electron accelerator" generated high-energy (up to 6 MeV) bremsstrahlung gamma photons when RREA was above the station and low energy (0.4- 2 MeV) Compton scattered gamma rays when a strong electric field moved from the station.

NaI spectrometers registered totally additional (compared to the fair weather day) ~ 1.8 million gamma rays. TGE differential energy spectra were estimated by the network of the NaI spectrometers for 4 TGE episodes. Three of them contain only low energy gamma rays with energies below 4 MeV, large TGE with maximal flux at 23:19 contain also gamma rays with energies up to 6 MeV. The spectrometer data is confirmed by the count rate measurements of other ASEC detectors. The 1-minute time series of CUBE detector with energy threshold above ~ 4 MeV does not demonstrate any enhancements for the low energy TGEs. The same time series demonstrates pronounced peaks with very high statistical significance for the high-energy TGE. The energy spectra are of a broken power law type. Due to the very large number of the registered gamma rays we estimate spectra for each of TGE events. We fit our spectra with 2 power law dependences that allow physical inference on the possible origin of 2 gamma ray populations.

ma rays observed in this event almost equals that of the whole acceleration region.

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REFERENCES

- Chilingarian, A., Arakelyan, K., Avakyan, K. et al., 2005. Correlated measurements of secondary cosmic ray fluxes by the Aragats space-environmental center monitors, *Nucl. Instrum. Methods A* 543, 483.
- Chilingarian A., Melkumyan L., Hovsepyan G., Reymers A., 2007. The response function of the Aragats Solar Neutron Telescope, *Nuclear Instruments and Methods in Physics Research, A* 574, (255-263).
- Chilingarian, A., A. Daryan, K. Arakelyan, A. Hovhannisyan, B. Mailyan, L. Melkumyan, G. Hovsepyan, S. Chilingaryan, A. Reymers, and L. Vanyan L., 2010. Ground-based observations of thunderstorm-correlated fluxes of high-energy electrons, gamma rays, and neutrons, *Phys. Rev. D*, 82, 043009, doi:10.1103/PhysRevD. 82.043009.

- Chilingarian, A., Hovsepyan, G., Hovhannisyan, A., 2011. Particle bursts from thunderclouds: natural particle accelerators above our heads. *Phys. Rev. D: Part. Fields* 83 (6), 062001.
- Chilingarian, A., Mailyan, B., Vanyan, L., 2012. Recovering of the energy spectra of electrons and gamma rays coming from the thunderclouds. *Atmos. Res.* 114–115, 1–16.
- Chilingarian, A., Mkrtchyan, H., 2012. Role of the lower positive charge region (LPCR) in initiation of the thunderstorm ground enhancements (TGEs). *Phys. Rev. D: Part. Fields* 86, 072003.
- Chilingarianb A., Hovsepyan G., Kozliner L., 2013. Thunderstorm ground enhancements gamma ray differential energy spectra. *Phys. Rev. D: Part. Fields* 88, 073001.
- Chilingarian A., 2014. Thunderstorm Ground Enhancements - model and relation to lightning flashes, *Journal of Atmospheric and Solar-Terrestrial Physics* 107, 68–76.
- Chilingarian, A., Chilingaryan, S., and A. Reymers, 2015. Atmospheric discharges and particle fluxes, *J. Geophys. Res. Space Physics*, 120, 5845–5853, doi: 10.1002/2015JA021259.
- Chilingarian A., Chilingaryan S., Hovsepyan G., 2015. Calibration of particle detectors for secondary cosmic rays using gamma-ray beams from thunderclouds, *Astroparticle Physics* 69, 37–43
- Chilingarian A., Hovsepyan G., Khanikyanc G., Reymers A. and Soghomonyan S., 2015. Lightning origination and thunderstorm ground enhancements terminated by the lightning flash, *EPL*, 110, 49001.
- Dwyer, J. R., and M. A. Uman 2014. The physics of lightning, *Phys. Rep.*, 534(4), 147–241.
- Dwyer, J. R., D. M. Smith, and S. A. Cummer 2012. High-energy atmospheric physics: Terrestrial gamma-ray flashes and related phenomena, *Space Sci. Rev.*, 173, 133–196.
- Fishman, G.J., Bhat, P.N., Mallozzi, R., Horack, J.M., Koshut, T., Kouveliotou, C., Pendleton, G.N., Meegan, C.A., Wilson, R.B., Paciasas, W.S., Goodman, S.J., Christian, H.J., 1994. Discovery of intense gamma ray flashes of atmospheric origin. *Science* 264 (5163), 1313–1316.
- Kelley N.A., Smith D.M., Dwyer J.R., et al. 2015. Relativistic electron avalanches as a thunderstorm discharge competing with lightning, *Nature communications* 6, Article number: 7845.
- Wilson C. T. R., 1925. The Acceleration of β -particles in Strong Electric Fields such as those of Thunderclouds, *Proc. Cambridge Phil. Soc.* 22, 534.