Reply to "Comment on 'Long lasting low energy thunderstorm ground enhancements and possible Rn-222 daughter isotopes contamination'"

A. Chilingarian[1,2,3]

[1]A. Alikhanyan National Lab (Yerevan Physics Institute), Yerevan 0036, Armenia
[2]National Research Nuclear University MEPhI, Moscow 115409, Russia
[3]Space Research Institute of RAS, Moscow 117997, Russia

(Received 26 January 2019; published 22 May 2019)

To identify the role of the gamma radiation from radon progenies in the long lasting thunderstorm ground enhancement (TGE) flux, a differential energy spectrum was measured with various spectrometers, including a precise $3'' \times 3''$ NaI(Tl) spectrometer from ORTEC (FWHM ~7.7% at 0.6 MeV). Measurements demonstrate that radon progenies radiation significantly contribute to the winter enhancements in the energy range below 0.3–2 MeV. However, performed Monte Carlo simulations and observation of TGEs with plastic scintillators of various thickness and energy thresholds show that TGEs originate in intracloud electric fields. Recent registration of gamma glows by spectrometers located on board aircraft flying at 12–20 km altitude also confirms an "electric" nature of particle flux enhancements.

DOI: 10.1103/PhysRevD.99.108102

I. INTRODUCTION

The emerging field of high energy atmospheric physics (HEAP) [1] studies processes producing high energy particles in the terrestrial atmosphere, such as thunderstorm ground enhancements (TGEs) [2,3], terrestrial gamma ray flashes [4], and gamma ray glows [5,6]. Understanding these phenomena requires developing of appropriate models of the interaction of electrons, positrons, and photons with air and electric fields [7–9]. It is widely accepted that all three processes are mainly driven by electric fields, ionization, scattering, and bremsstrahlung. One of the underlying processes, namely runaway breakdown (RB) [10], now mostly referred to as relativistic runaway electron avalanche (RREA) [11,12], is a "threshold" process controlled by the strength of the electric field. RB/RREA is responsible for the development of electron-gamma ray avalanches in the atmosphere and, consequently, for the large-scale multiplication of the particles detected on Earth's surface or observed in the atmosphere by spectrometers located on balloons and aircraft. The second process, modification of the electron energy spectra (MOS) [13,8], operates on much fewer scales; however, it is effective for almost all strengths of atmospheric electric fields.

Although a lot of TGEs were observed in mountain-top and sea-level experiments (see Ref. [14]), the spatial structure of electric fields and time evolution of the electron acceleration in the atmosphere are still poorly understood. The "electric" origin of the ionization radiation from clouds is sometimes put into question. Bogomolov *et al.* [15] argue that the significant contribution to the low energy part of the TGE spectrum was originated by the Rn-222 decay chain, including daughter isotopes ^{214}Bi and ^{214}Pb, that are clearly identified in the spectrum of the background radiation. Although we demonstrate that the hypothesis of the precipitation as a source of gamma ray radiation is not valid [16], it was proposed that Rn-222 can be concentrated in the clouds above Aragats research station, and radiation of its daughter isotopes can lead to the observed prolonged low energy part of TGE [15]. To clarify the origin of TGE we performed an experiment on Mt. Aragats with a precise NaI spectrometer from ORTEC. Experiments demonstrated that indoors fluctuation of radon is much smaller than observed in open air. The analysis of winter count rate enhancements allows us to confirm the contribution of the gamma radiation from radon progenies to the count rate enhancement in the energy range below 3 MeV.

However, by measurements with a variety of spectrometers operated on Aragats and by performing Monte Carlo simulations, we also confirmed the "electric" nature of the TGEs. Energy spectra of hundreds of TGE events observed during the last decade on Aragats demonstrate that the hour-length enhancements of the particle flux include energies well above 2 MeV, where radon progenies cannot contribute to the TGE counts. CORSIKA code was used to investigate the "small fields" effect on particle detector count rates. We show that even for the rather low values of the atmospheric electric fields strengths, the modification of the cosmic ray electron energy spectra (MOS process) [8] lead to additional bremsstrahlung radiation sustaining additional gamma ray flux. Each TGE observed on Aragats is accompanied by disturbances of the near-surface electric field and, in turn, each disturbance of the electric field has its roots in the

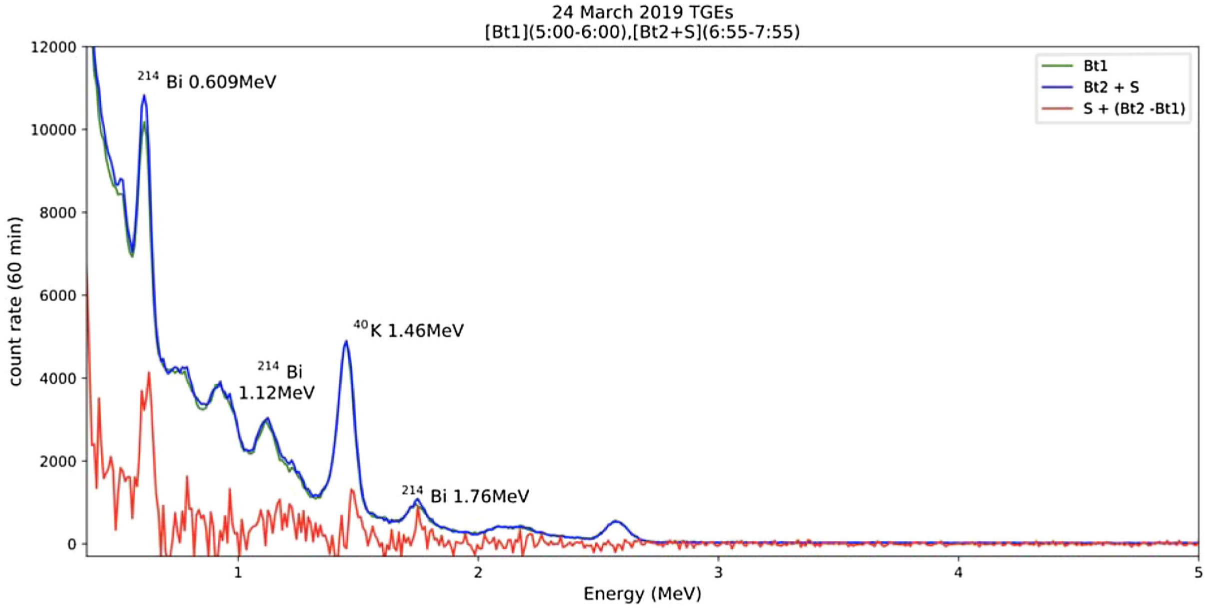

FIG. 1. Energy spectra of the natural gamma radiation measured before the enhancement of count rate and during the enhancement. Bottom: energy spectrum of the "pure" signal obtained by extracting the background sample from the signal + background one.

enhanced concentration of hydrometeors above the station. Radar data and modeling with the WRF code proves the existence of charged layers above the station simultaneously with TGE detection [17]. Thus, the electrical origin of both low energy and high energy parts of TGEs is supported by theory, modeling, and observations of particle fluxes, electric fields, atmospheric discharges, and hydrometeor concentrations (microphysics).

II. MEASUREMENTS OF THE PARTICLE FLUX ENHANCEMENTS IN THE WINTER 2018/2019

Thunderstorms do not occur on Aragats in the winter; there are no lightning flashes, large disturbances of near-surface electric field, or bursts of high energy particles. Thus, we do not expect any large particle flux enhancements in winters. However, after precise scanning of the count rate monitoring results, we outline several events with particle flux enhancements in the NaI network and in the newly installed precise spectrometer, which is a type 905-4 (ORTEC) spectrometer and is $3'' \times 3''$ in diameter and length, has 1024 channels, high stability, and relative energy resolution (FWHM ~7%) at 0.3–2 MeV energies.

In Fig. 1 we demonstrate 2 energy release histograms measured on 24 March 2019 (two upper curves). We measure the energy release histogram before flux enhancement (5:00–6:00) and during flux enhancement (6:55–7:55). To estimate the energy release spectrum of enhancement we subtract the histogram of "background" (spectrum without any enhancement) from the histogram of energy releases measured during enhancement (lower curve). Subtracting the background sample, we obtain an estimate of "pure" signal with superimposed spectral lines (spectral peaks) originated from natural isotope gamma decay. Obtained in such a way, peaks corresponding to the ^{214}Bi spectral lines (0.609, 1.12, and 1.76 MeV) are well pronounced, as seen in Fig. 1.

The fluctuations after 2 MeV are not reliable due to small statistics. They can occur due to changes in the natural gamma radiation during a rather long time of background and event signal collection. The continuum spectrum in a 0.3–2 MeV region can be explained by the Compton scattered gamma rays effect. Because of finite sizes of NaI crystal, many of decay gamma rays leave only a portion of their energy in crystal and scattered out of it. The continuous energy spectrum of the enhancement after 2 MeV demonstrates no noticeable features and tends to zero with a few discrepant random outbursts.

Thus, this winter gamma ray flux enhancement was most probable connected with natural radiation of the radon progenies and not with the acceleration of electrons in the intracloud electric fields.

TABLE I. Enhancement $(N(\mathrm{Ez}) - N(0))/N(0)$ of secondary photons in different energy intervals in percent to no-field case $N(0)$.

Ez	0.3–2 MeV	2–5 MeV	5–10 MeV
0.1	7,86	5,82	6,06
0.2	15,97	12,59	13,0
0.3	24,75	20,41	18,88
0.9	116,02	96,35	88,24
1.7	776,08	534,95	417,10
2.0	4909,99	2886,43	1778,76

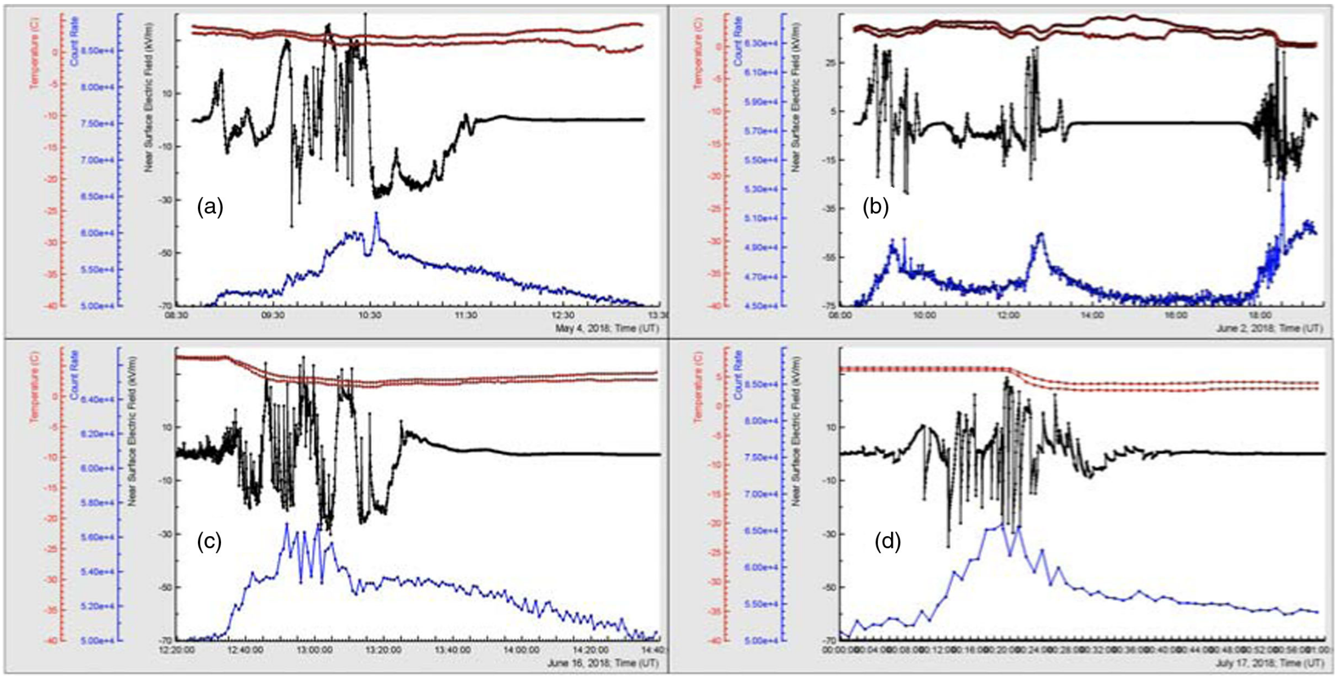

FIG. 2. Selected TGE events of 2018. Bottom: one-minute time series of count rate of first NaI crystal from the Aragats NaI network. Middle: disturbances of near surface electric field measured by the EFM-100 electric mill located on the roof of MAKET experimental hall. Top: outside temperature and dew point measured by Davis automatic weather station located on the roof of same building.

III. MODELING OF THE MOS PROCESS IN ATMOSPHERIC ELECTRIC FIELDS

The MOS mechanism of a gamma ray flux enhancement in atmospheric fields, introduced in Refs. [13,8] and measured on Aragats [18], was recently confirmed by registration of gamma glows by spectrometers on board of aircraft. Gamma ray glows have been observed by the Airborn Detector for Energetic Lightning Emissions [19]. During flight at a cruising altitude between 14 and 15 km they detected 12 gamma ray glows with durations from 4 to 112 s. The authors of Ref. [20] reported two gamma ray glows (100 keV–10 MeV) lasting ~30 s observed by the In-Flight Light82ning Damage Assessment System (ILDAS) when flying inside the thundercloud at 12 km altitude in Australia. Short radiation pulses were seen throughout longer lasting considerably weak gamma ray glows (2–3 times the background) during active thunderstorms. In 2017 an ER-2 aircraft campaign was undertaken over the continental United States to observe energetic radiation from thunderstorms [21]. The comparison of two registered gamma ray glow events with subsequent simulations shows that the MOS mechanism is the most probable candidate for explaining observed radiation. Thus experiments on high altitudes where the Rn progenies contribution is too doubtful prove the reliability and efficiency of the MOS process and "electric" nature of registered radiation.

We perform simulations with CORSIKA code [22] to get clues in the recent observations of the long lasting TGEs not obligatory accompanied with large intracloud electric fields. From the consideration of the ~500 TGE events in the last decade, we conclude that by far not all TGEs are due to the RB/RREA process. To investigate the "small fields" effect, we use in simulations rather low values of the atmospheric electric fields strengths. Each simulation set consists of 10^8 showers originated from vertically traversing cosmic rays electrons with energies in the interval 1–300 MeV. The differential energy spectrum of electrons follows the power law with spectral index $\gamma = -1.21$. Avalanche particles were followed until Earth's surface ($H_{\mathrm{obs}} = 3200$ ma.s.l.) or until their energy became less than $E_{\mathrm{cut}} = 0.05$ MeV.The intracloud electric field was introduced in a kilometer above the "cloud base." In Table 1 we enumerate the gamma ray flux enhancements of the gamma ray flux after crossing a 1 km long electric field of 0.1 to 2 kV/cm above Aragats research station. The cloud height above the detectors was assumed to be 50 m, and the electric field in the cloud was changed from 0.1 to 2 kV/cm. After reaching RB/RREA threshold, the number of particles exponentially rose in the electron-gamma ray avalanches. However, ever for the small electric fields, we have a significant enhancement that can be reliably registered by the spectrometers and counters located on Aragats. The MOS process continuously enlarged the flux of bremsstrahlung gamma rays in the energy domain 0.3–2 MeV and for larger energies ever for the minimal fields started from 0.1 kV/cm.

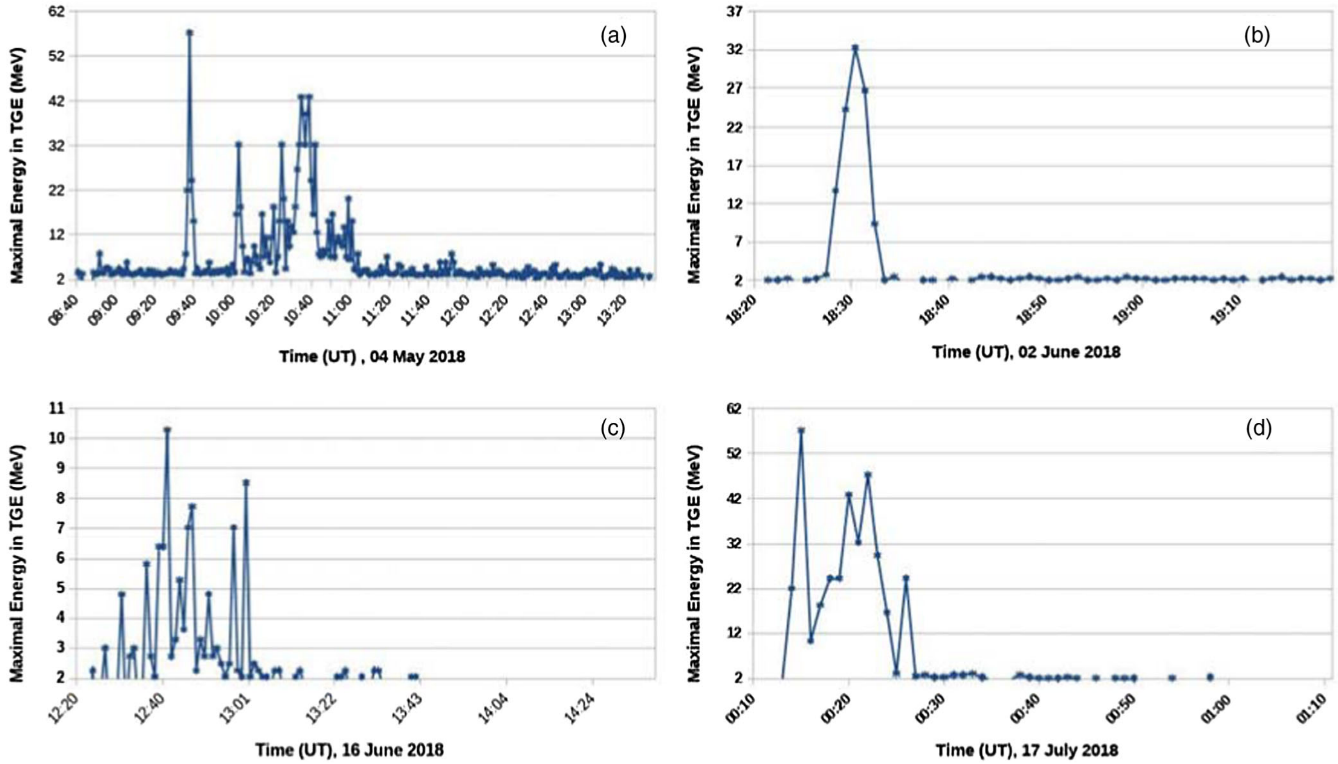

FIG. 3. One-minute time series of the maximal energies of the recovered differential energy spectra with NaI network (4 Na crystals were used).

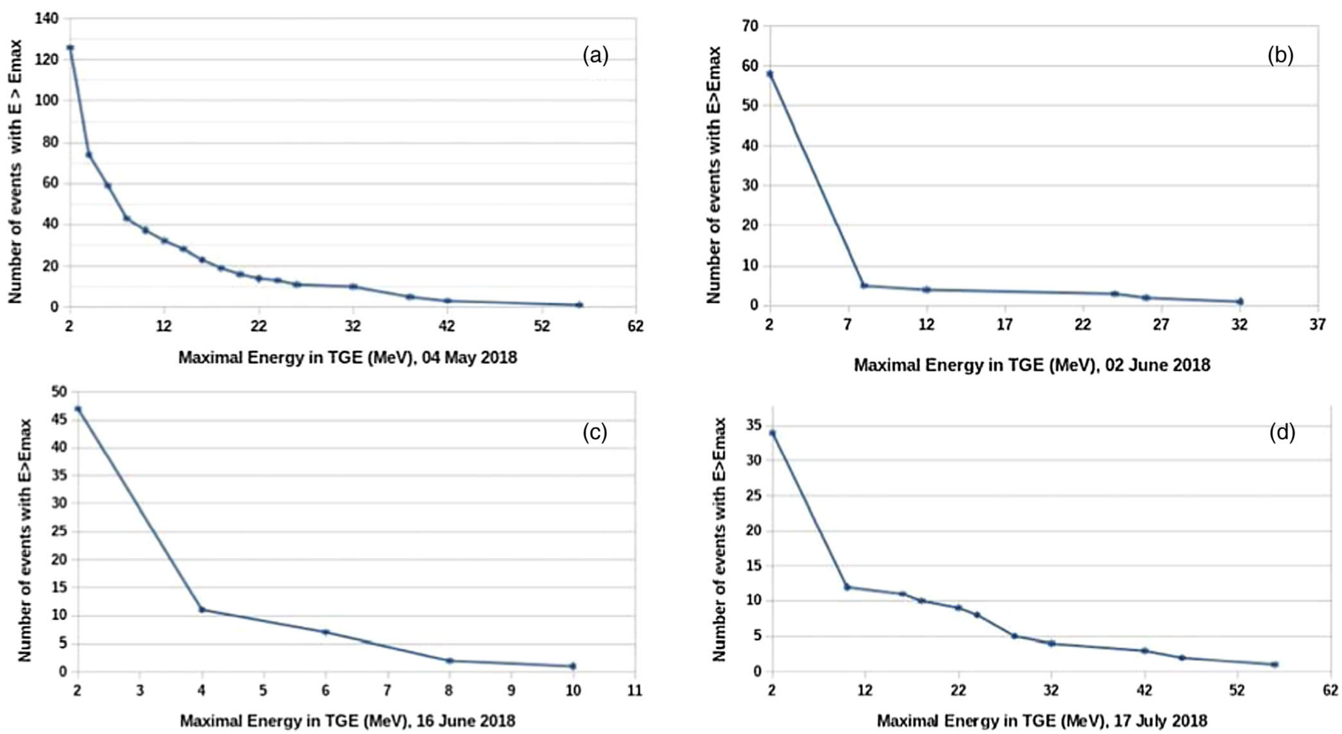

FIG. 4. Cumulative distribution of the one-minute maximal energies corresponding to TGE events depicted in Fig. 1.

IV. ENERGY SPECTRA OF TGEs REGISTERED IN 2018

In this section, we will prove that the energy of gamma rays and electrons belonging to long lasting TGEs are well above 3 MeV, which proved the "electric" nature of TGEs.

Spring-Summer 2018 was plenteous on the TGE events. In Fig. 2 we present several randomly chosen for the analysis TGE events of 2018. In the top of frames a-d we show the outside temperature and dew point used for estimation of the cloud base height above Earth's surface; in the middle, disturbances of the near-surface electric field; and in the bottom, one-minute time series of count rates of the NaI detector. The disturbances of the electric field were rather large reaching and sometimes slightly exceeding the reliable range of EFM-100 electric mill's measurements. The significance of the peaks in selected TGE events was rather high (10%–20%) but by far not the largest. The distances to the cloud base vary from 25 to 100 m.

In Figs. 3 and 4 we show the maximal energy distributions of the same four selected events. In Fig. 3 the whole-time history of selected TGEs is shown outlining the minutes with maximal energy larger than 2 MeV, which we cannot explain with emerged gamma radiation from surplus radon progenies. In Fig. 4 we show the cumulative distribution of the maximal energies for the same events.

From Figs. 3 and 4 we can see that a significant portion of the maximal energies of gamma ray spectra, calculated each minute, can be explained only by the bremsstrahlung of electrons accelerated in strong atmospheric electric fields. The large fluctuations of maximal energies can be explained by the fast changes in the meteorological parameters during thunderstorms. Strong winds are moving thunderclouds relative to detector locations, lightning flashes are reducing net potential in the cloud, etc. Unfortunately, we cannot keep fixed the location and energy of the electron accelerator operating above the Aragats mountain.

V. CONCLUSION

After performing measurements with the high-precision ORTEC spectrometer on Aragats in winter season, we confirmed that radon progenies radiation contributes to the winter particle flux enhancement in the low energy domain (0.3–2 MeV), as it was claimed in the Comment [15] for the summer TG.

New series of simulations with CORSIKA code confirm our previous results obtained with GEANT4 code that the MOS process lead to additional bremsstrahlung radiation reaching Earth and sustaining a sizable gamma ray flux.

We also cite the results of recently registered gamma glows during high altitude flights that confirm the MOS process and exclude the contribution of radon progenies in their measurements.

The analysis of energy spectra of TGEs measured in 2018 unambiguously proved the "electric" nature of long lasting TGEs.

The winter gamma ray flux enhancement should be confirmed by the measurements in the spring-summer season with precise HP Ge spectrometer for resolving the spectral lines and clarifying the possible sources of additional natural gamma radiation during TGEs.

ACKNOWLEDGMENTS

We thank the staff of the Aragats Space Environmental Center for installing and maintenance of the Na(Tl) spectrometer from ORTEC. We thank A. Avetisyan and the staff of Isotope Research Department for assistance in performing measurements with the ORTEC spectrometer. We are thankful to Pokhsraryan David for the modernization of the spectrometer software. Special thanks go to G. Hovsepyan and B. Sargsyan for numerous discussions and support during performing experiments. M. Zazyan and G. Karapetyan were instrumental in performing simulations. Authors thank Ekaterina Svechnikova for modeling with WRF code density of hydrometeors above Aragats. We appreciate the support of the Russian Science Foundation Grant, Project No. 17-12-01439.

[1] J. R. Dwyer, D. M. Smith, and S. A. Cummer, High-energy atmospheric physics: Terrestrial gamma-ray flashes and related phenomena, Space Sci. Rev. **173**, 133 (2012).

[2] A. Chilingarian, A. Daryan, K. Arakelyan *et al.*, Ground-based observations of thunderstorm-correlated fluxes of high-energy electrons, gamma rays, and neutrons, Phys. Rev. D **82**, 043009 (2010).

[3] A. Chilingarian, G. Hovsepyan, and A. Hovhannisyan, Particle bursts from thunderclouds: Natural particle accelerators above our heads, Phys. Rev. D **83**, 062001 (2011).

[4] G. J. Fishman, P. N. Bhat, R. Mallozzi *et al.*, Discovery of intense gamma-ray flashes of atmospheric origin, Science **264**, 1313 (1994).

[5] M. McCarthy and G. Parks, Further observations of x-rays inside thunderstorms, Geophys. Res. Lett. **12**, 393 (1985).

[6] N. A. Kelley, D. M. Smith, J. R. Dwyer *et al.*, Relativistic electron avalanches as a thunderstorm discharge competing with lightning, Nat. Commun., **6** 7845 (2015).

[7] J. R. Dwyer, A fundamental limit on electric fields in air, Geophys. Res. Lett. **30**, 2055 (2003).

[8] A. Chilingarian, B. Mailyan, and L. Vanyan, Recovering of the energy spectra of electrons and gamma rays coming from the thunderclouds, Atmos. Res. **114–115**, 1 (2012).

[9] D. Sarria, C. Rutjes, G. Diniz *et al.*, Evaluation of Monte Carlo tools for high-energy atmospheric physics II: Relativistic runaway electron avalanches, Geosci. Model Dev. **11**, 4515 (2018).

[10] A. V. Gurevich, G. M. Milikh, and R. A. Roussel-Dupre, Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm, Phys. Lett. **165A**, 463 (1992).

[11] J. R. Dwyer, Relativistic breakdown in planetary atmospheres, Phys. Plasmas **14**, 042901 (2007).

[12] L. P. Babich, E. N. Donskoy, I. M. Kutsyk *et al.*, Comparison of relativistic runaway electron avalanche rates obtained from Monte Carlo simulations and kinetic equation solution, IEEE Trans. Plasma Sci. **29**, 430 (2001).

[13] L. I. Dorman and I. V. Dorman, Possible influence of cosmic rays on climate through thunderstorm clouds, Adv. Space Res. **35**, 476 (2005).

[14] A. Chilingarian, Thunderstorm ground enhancements–model and relation to lightning flashes, J. Atmos. Sol. Terr. Phys. **107**, 68 (2014).

[15] V. V. Bogomolov, A. F. Iyudin, I. A. Maximov, M. I. Panasyuk, and S. I. Svertilov, Comment on "Long lasting low energy thunderstorm ground enhancements and possible Rn-222 daughter isotopes contamination", Phys. Rev. D **99**, 108101 (2019).

[16] A. Chilingarian, Long lasting low energy thunderstorm ground enhancements and possible Rn-222 daughter isotopes contamination, Phys. Rev. D **98**, 022007 (2018).

[17] E. K. Svechnikova, N. V. Ilin, and E. A. Mareev, Recovery of electrical structure of the cloud with use of ground-based measurement results, *Proceedings of TEPA-2018 Conference* (Nor-Amberd, Armenia, 2018).

[18] A. Chilingarian, Energetic radiation from thunderclouds: Extended particle fluxes directed to Earth's surface, Rendiconti Lincei. Scienze Fisiche e Naturali (2019), http://dx.doi.org/10.1007/s12210-018-0755-y.

[19] N. A. Kelley, D. M. Smith, J. R. Dwyer *et al.*, Relativistic electron avalanches as a thunderstorm discharge competing with lightning, Nat. Commun. **6**, 7845 (2015).

[20] P. O. Kochkin, A. P. J. van Deursen, M. Marisaldi *et al.*, In-flight observation of gamma ray glows by ILDAS, J. Geophys. Res. **122**, 12801 (2017).

[21] N. Østgaard, H. Christian, J. E. Grove *et al.*, Gamma-ray glow observations at 20 km altitude, J. Geophys. Res. Atmos. (to be published).

[22] D. Heck, J. Knapp, J. N. Capdevielle, G. Schatz, and T. Thouw, Report No. FZKA 6019, 1998, Forschungszentrum, Karlsruhe, https://www.ikp.kit.edu/corsika/70.php.