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

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I. INTRODUCTION

Large enhancements of gamma-ray radiation relative to the stable background are often observed during (cosmic and terrestrial) thunderstorms [1–3]. The problem of observing additional gamma-ray sources (besides the known cosmic and terrestrial sources) is connected with the determination of the energy and temporal characteristics of this new phenomenon in comparison with previous ones in an attempt to find any differences in their physical parameters. These phenomena—called thunderstorm ground enhancements (TGEs)—can be caused by bremsstrahlung radiation of electrons accelerated in the thundercloud's electrical field. The background increase can also be connected with gamma rays emitted by natural radioactive isotopes such as Rn-222 and its daughter nuclei like Pb-214 and Bi-214 that are present in the atmosphere, including in thunderstorm clouds and raindrops. The change of conditions for Rn-222 emanation can also cause an increase in the gamma-ray background. We indicate wet soil and aerosol transport by wind as possible conditions for such increased emanation. This can be associated with convection (active cumulus or cumulonimbus cloud formation) or with frontal systems. All mentioned factors work together, leading to the appearance of TGEs with different temporal and spectral parameters.

A number of such excesses of gamma-ray background flux were observed during the last several years on Mount Aragats by Armenian scientists [1–3]. In many cases, the time profile of TGEs appears as a combination of narrow peaks of hard gamma radiation with durations of several minutes, followed by a long increase of gamma radiation lasting for more than one hour. One such TGE observed on 17 August, 2017 was considered in detail in Ref. [4]. The author stated that both high-energy radiation (observed in a narrow peak) and low-energy gamma radiation (observed during the TGE outside of the peak) are produced by bremsstrahlung gamma rays from the electrons accelerated in thunderclouds. Reference [4] concluded that the long-lasting low-energy part of TGE was not caused by gamma rays from the daughters of Rn-222 because no precipitation was observed during this period of time. However, the concentration of Rn-222 in the near-ground layer of the atmosphere can not only be changed by precipitation: one must take into account that the distance between the cloud possibly containing Rn-222 and its decay nuclei of Pb-214 and Bi-214, for example, and the gamma-ray detectors on Mount Aragats was less than 200 m for the considered event [4]. The Mount Aragats cosmic-ray station is located at an altitude of 3200 m, on a plateau near a large lake, and the height of the cloud base above the ground is typically 2550 m in spring and increases to 100 200 m in the summer, as quoted in Ref. [4].

For the standard model of atmospheric density, the absorption length is about 185 m for 1 MeV gamma quanta, which are typical for Rn-222 daughter isotopes. This means that 34%, 6.7%, and 0.5% of the initial flux can penetrate through 200, 500, and 1000 m of air, respectively. Thus, depending on the gamma-ray flux intensity in the source, i.e., in the cloud, the real maximal height above the Earth's surface from which Rn-222 gamma rays can reach detectors could be estimated to be about 500 m or even more. Indeed, gamma-ray enhancements from clouds located 500 and 1000 m above the detectors were observed at Aragats, as claimed by Ref. [5].

II. THE SINP MSU EXPERIMENT

The monitoring measurements with the gamma-ray spectrometer designed by Skobel'tsyn Institute of Nuclear Physics of Moscow State University (SINP MSU) specialists [6] started in 2016 at the same location on Mount Aragats where the experiment of Chilingarian *et al.* was performed. The SINP MSU spectrometer used a 5 cm $\times$ 5 cm (H) NaI(Tl) crystal which provided measurements of gamma radiation in the energy range from 80 keV to 7 MeV, with a typical energy resolution of $\sim$12% at 662 keV. The position of the prominent background line of the ^{40}K isotope ($E = 1.46$ MeV) was used for calibration during the long-duration remote measurements in order to compensate for the temperature dependence of the NaI(Tl) light output. The data were recorded to an SD card in a gamma-by-gamma mode. The time of each photon detection was

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recorded and referenced to UTC using GPS a signal receiver with an accuracy of ~10 μs.

III. RESULTS OF TGE MEASUREMENTS

The SINP MSU spectrometer was operational during events described in Ref. [4]. The time profile of TGE 17.08.2017 as recorded by the SINP MSU instrument is presented in Fig. 1, where one can see the behavior of the TGE radiation over time at different energy intervals. The long-lasting increase of the gamma-ray flux with a duration of ~2 h is observed at 200–550 and 550–3000 keV, while a narrow peak at 18h 55m UTC with a duration of about half of a minute is prominent at energies of 3 to 7 MeV. The time interval of the hard peak and the time sequence of the slowly varying low-energy gamma emission detected by the SINP MSU instrument are very similar to those presented in Fig. 4 of Ref. [4].

We will not interpret the hard gamma radiation of the narrow peak detected by both Chilingarian [4] and the SINP MSU instrument. Instead, we will concentrate on the discussion of the origin of the low-energy part of TGE,

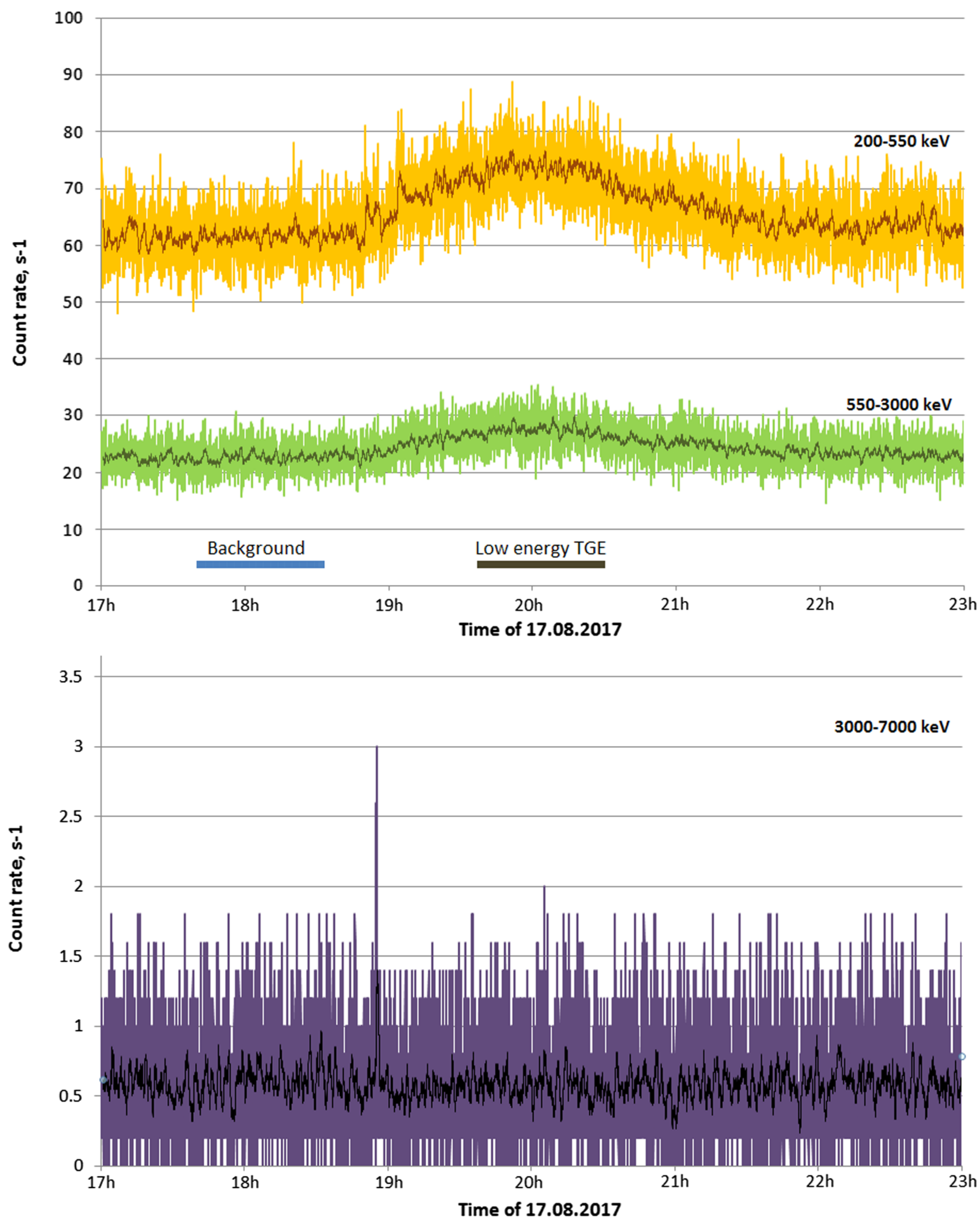

FIG. 1. Time profiles of TGE 17.08.2017 at different energy intervals, as measured at the Mount Aragats station by the gamma-ray spectrometer provided by SINP MSU.

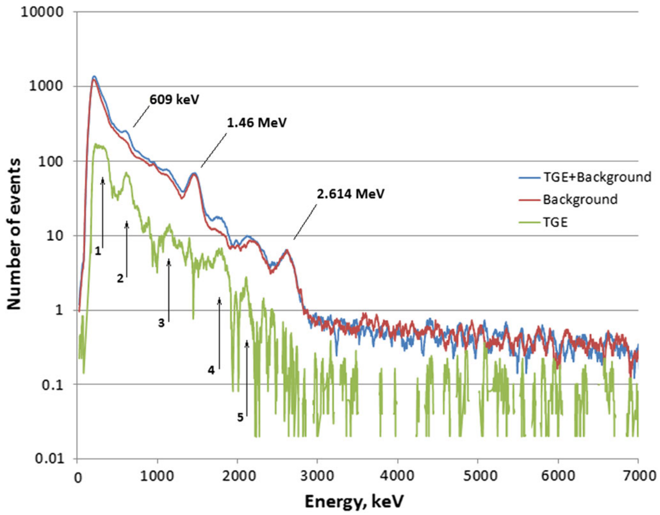

FIG. 2. Energy spectrum of the slowly varying, long part of TGE 17.08.2017 collected during the time interval 19:40–20:30. The background spectrum was derived for the time interval 17:40–18:30 of the same day. The numbers indicate lines from the Rn-222 daughter isotopes: (1) 242, 295, and 352 keV (unresolved); (2) 609 keV; (3) 1120 keV; (4) 1764 keV; (5) 2204 keV.

which can be tested by accurate spectral measurements. The energy spectra measured by the SINP MSU spectrometer during the time interval before the TGE (background) and during the long-soft phase of the TGE (TGE + background) are presented in Fig. 2, together with the difference spectrum marked as TGE. The time intervals when the spectra were collected are marked in Fig. 1. We note here that the spectrum of secondary gamma radiation produced by accelerated particles is expected to be continuous. Quite opposite to these expectations, we observe at least four excesses in the background spectrum, and at least five excesses (lines) in the background-subtracted TGE emission spectrum measured with sufficiently good energy resolution by our instrument. These lines are numbered in Fig. 2. The background emission lines from naturally occurring isotopes that we identified are as follows. There is a 1.46 MeV line of ^{40}K, a 2.614 MeV line of ^{208}Tl (which is a daughter of ^{232}Th), and there are a number of lines produced by decay products of ^{222}Rn; in particular, ^{214}Pb has notably bright lines with energies of 242, 295, and 352 keV, which substantially overlap. One can also observe lines of 609, 1120, 1764, and possibly 2204 keV produced by ^{214}Bi. The brightness of the 609, 1120, and 1764 keV lines can be used to monitor the amount of radiation produced by ^{222}Rn. The statistical significances of these lines were estimated from the Poisson dispersion of count numbers in the energy interval where correspondent line is observed (TGE + background, blue line in Fig. 2), background (red line in Fig. 2), and TGE (green line in Fig. 2) spectra as well as in the continuum substrate of the TGE (green line) spectrum. The values obtained were 10.4σ for the 609 keV line, 5.1σ for 1764 keV, 2.7σ for 1120 keV, 1.5σ for 2204 keV, and 13.7σ for the unresolved aggregate of the 242, 295 and 352 keV lines. The most prominent natural radionuclide in surface air is radon-222 (^{222}Rn, $t_1/2 = 3.825d$). It is produced in the soil from decaying radium-226 as a part of the natural decay series of uranium-238. In addition to isotope 222, Rn-220 from the thorium-232 series can be found in the atmosphere. Some of the radon produced in the surface soil can escape to the atmosphere because it is a noble gas.

Radon-222 decays via several short-lived daughter nuclides to the relatively long-lived lead-210. Radon can be used as a tracer for continental air masses because its emission rate from oceans is negligible compared to that from land areas [7]. The energy spectra measured by the SINP MSU spectrometer during the time interval before the TGE ("background") and during the long-soft phase of the TGE ("TGE + background") are presented in Fig. 2 together with the difference spectrum marked as "TGE." The time intervals when the spectra were collected are marked in Fig. 1.

One can see that the intensity of the difference spectrum (which can be attributed to the continuum radiation coming from just the TGE source) is about 1 order of magnitude smaller than the intensity of the background spectrum. However, the line excesses at 609 keV (10.4σ) and 1764 keV (5.1σ) are more pronounced in the TGE spectrum, which supports the interpretation that the emission of ^{222}Rn decay products (like ^{214}Bi and ^{214}Pb radiation lines) coming from the long-lasting TGE source is relatively larger than the fraction of this component in the natural background.

There are a number of features in the spectrum of the long-part of TGE on 17 August, 2018 besides the peak of 609 keV. Some of those features can also be interpreted as gamma-ray lines of the daughter isotopes ^{214}Bi and ^{214}Pb arising from the decay of ^{222}Rn. To check whether these features were the result of the decay of these isotopes, the relative brightness of the observed lines was compared with the branching ratios of the corresponding transitions of the radon decay and of its daughter isotopes. Peaks with energies of 609, 768, 1120, and 1764 keV from ^{214}Bi decay were considered, as well as a wide feature at the lowest energies of the spectrum formed by the sum of the unresolved lines from ^{214}Pb transitions with energies of 242, 295, and 352 keV. For each of these features, the number of photopeak counts with the total energy absorption in the scintillation crystal N(Ei) was determined by calculating the area under the corresponding peaks in the spectrum. Previously, the subtraction of a continuum approximated by a power law with empirically selected parameters was performed. The numbers of expected gamma-line counts B(Ei) were obtained by multiplying the values of the branching ratios of gamma lines in the decay chain of Rn-222 with daughter nuclei ^{214}Bi and ^{214}Pb by the full energy peak efficiency of the detector at the line energy calculated with the use of the formula introduced in Ref. [8]. Then, the ratios of the corresponding values B(Ei) were calculated by taking into

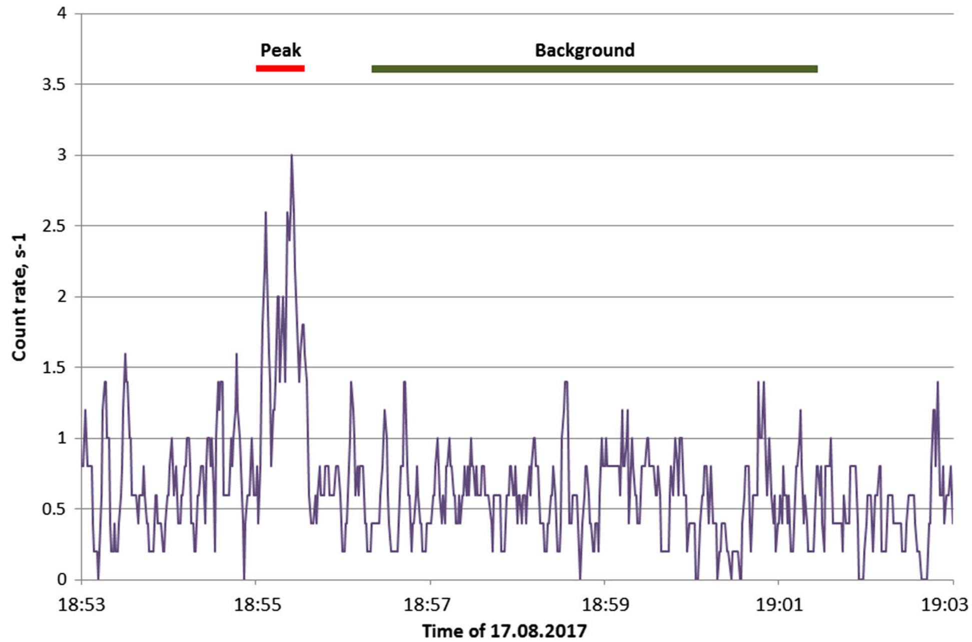

FIG. 3. Detailed time profile of the narrow peak of TGE 17.08.2017.

account the total number of counts in all gamma-ray lines considered in the analysis. The values of these ratios differ from the expected one by no more than $\pm 25\%$. We therefore argue that the main contribution to the long part of the TGE spectrum was provided by the radiation from the Rn-222 decay chain, including the daughter isotopes ^{214}Bi and ^{214}Pb, which are clearly identified in the spectrum of the long part of TGE.

The detailed time profile of the narrow hard peak at in 3–7 MeV energy interval is presented in Fig. 3. The duration of the hard phase of TGE is about 30 s. To obtain the energy spectrum of gamma radiation observed during a narrow peak, the entire energy range was divided into several intervals. For each of the intervals, the total number of events during the peak and during the period when no increase was observed were obtained. The required spectrum—calculated as the difference of these values and normalized by the length of the corresponding intervals—is shown in Fig. 4. The approximation line of the energy spectrum obtained by the Armenian group for the same time moment [4] (adjusted for the difference in sensitive areas) is also presented in Fig. 4. One can see quite good correspondence between the spectra measured by the Armenian and SINP MSU groups, in both the shape and the fluxes.

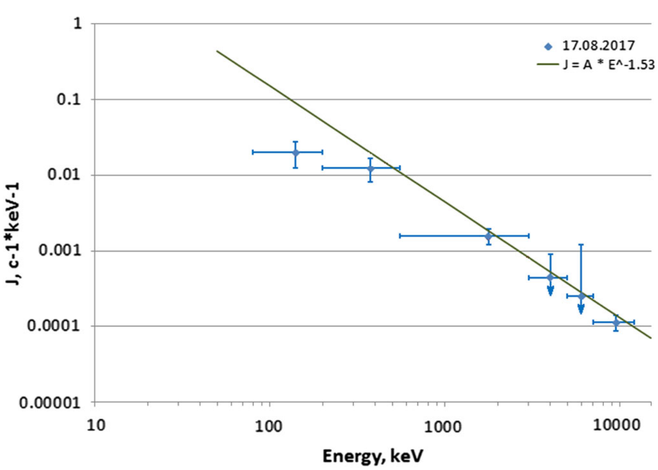

FIG. 4. Energy spectrum of the narrow peak of TGE 17.08.2017 taken for the period of time marked by the red line in Fig. 3.

IV. DISCUSSION

Several bright TGE events were observed by the Armenian group on Mount Aragats during the spring, summer, and autumn of 2017. Usually, bright TGEs have timing characteristics similar to the event of 17 August, 2017, which shows a combination of one or several hard narrow peaks and a long part with a softer spectrum. Hard radiation with $E > 3$ MeV was detected by the SINP MSU spectrometer during the four brightest events, including the 17 August, 2017 event. A detailed analysis of those events will be published in forthcoming publications, but one important remark is in order here. Namely, the spectra of the slowly varying part of the gamma radiation in all of these events are similar to the spectrum presented in Fig. 2 of this Comment, clearly demonstrating the presence of a 609 keV line of ^{214}Bi. This means that ^{222}Rn and its daughter nuclei are responsible for a significant part of the gamma radiation appearing in the long-soft phase of TGEs. The ^{222}Rn uptake location and the origin of the variation in the TGE radiation flow will be studied in a forthcoming publication.

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