S E S 2 0 1 7
Thirteenth International Scientific Conference
S P A C E , E C O L O G Y , S A F E T Y
2 – 4 November 2017, Sofia, Bulgaria

STUDY OF ATMOSPHERIC GAMMA-RAY BACKGROUND VARIATIONS FROM NATURAL RADIOACTIVE ISOTOPES AND ACCELERATED ELECTRONS DURING THUNDERSTORMS

Vitaly Bogomolov, Sergey Svertilov, Mikhail Panasyuk, Ivan Maksimov

Physical Department, Skobel'tsyn Institute of Nuclear Physics, Moscow State University
e-mail: bogovit@rambler.ru

Keywords: *gamma-ray background, thunderstorm, particle acceleration in clouds.*

Abstract: *Some of the high-energy phenomena in atmosphere appear as fast (<1s) or slow (~1h) increases of gamma-ray flux probably connected with natural radioactivity or particle acceleration in atmospheric discharges. The study of both kinds is important for safety. Several experiments for the study of long-term and short-term flux and spectral variations of gamma-ray background were provided at sea level and in mountains. Scintillator detectors of moderately large size (from 50 to 100 mm) with energy resolution up to ~7% at 662 keV were used. The data were recorded in event-by-event mode with ~15 µs time resolution thus permitting detection of the terrestrial gamma-ray bursts at the moment of lightning during thunderstorms as well as slow variations on hour time scale. Measurements were done on the ground at Moscow region, and at mountain altitude in Armenia at Aragatz station. A number of flux increases (so-called Thunderstorm Ground Enhancements, TGE) were detected. Measured low-energy gamma-ray spectra usually contain a set of lines that can be interpreted as radiation of Rn-222 daughter isotopes. The increases of Rn-222 radiation reaching several tens of percent were detected during rainfalls with thunderstorm, as well, as during rainy weather without thunderstorms. The dynamics of the background changes can be described by the presence of solved Rn-222 in the rain water. High energy (>3 MeV) radiation sometimes appearing during thunderstorms can be caused by bremsstrahlung from electrons accelerated in thunderclouds. Such events with duration of several minutes and less were detected in mountains. Time and spectral characteristics of these events in 80-7000 keV energy range will be presented.*

Introduction

Natural gamma-ray background is connected with a number of long-live isotopes with half-life of thousands of years and more. Well known considerably bright gamma-ray line with energy 1.46 MeV always appearing in the background spectra is connected with ^{40}K. This Isotope with period of decay ~1.2 billion of years is present in most of materials surrounding the detector and even in the detector itself. Another gamma-ray line with energy 2.614 MeV is produced by ^{208}Tl. It is one of the daughters of ^{232}Th with half-life period ~ $1.4*10^{10}$ years.

The intensity of the mentioned gamma-ray background does not vary with time because there are no changes in concentration of the radioactive material. About one half of the background is produced by daughters of ^{222}Rn appearing in atmosphere after the decay of ^{226}Ra. Radon is a heavy radioactive gas living about 4 days. After its decay the series of nuclear transformations lead to gamma radiation appearing in energy range of hundreds of keV up to 2.2 MeV. Most of gamma-ray lines including the contrast 609 keV peculiarity belong to ^{214}Bi isotope living about half of an hour. This radiation demonstrates significant changes with weather. During the rain the background caused by ^{222}Rn with daughters usually increases

Some hard radiation additional to the background from natural radioactive isotopes sometimes appears during thunderstorms. The detected gammas are mostly described as the bremsstrahlung radiation of the electrons accelerated in large electric fields existing in thunderclouds. In some cases the accelerated electrons can be directly detected. Spectral characteristics of the high-energy radiation can be described in general by the model of relativistic electrons avalanche (Gurevich, 1992, Dwyer, 2012).

Phenomena in gamma rays connected with atmospheric electricity are observed in wide range of time scale including fast flashes in sub-millisecond range (so-called Terrestrial gamma flashes (TGFs) (Briggs et al, 2013) and such slow phenomena as so-called Thunderstorm ground enhancements (TGEs) lasting up to several hours (Chilingaryan, 2014, 2015a). TGFs are usually studied in orbital experiments with gamma spectrometers working in "classical" energy range from several hundreds of keV to several MeV. It must be noted that the radiation from TGFs is hard up to several tens of MeV. Other fast phenomena observed in past few years is the termination of TGE at the moment of lightning (Chilingaryan et al, 2015b). The flux of hard radiation drops to pre-TGE level during several seconds or even less.

The best conditions for study of TGEs are present in mountains because of low distance between the clouds and the detector leading to less absorption of measured radiation. Many measurements of gamma-ray and electron flux variations were made with large detectors based on organic scintillators specialized for cosmic ray study (Chilingaryan, 2015a). These detectors usually measure count rates in high energy range from MeVs to GeVs and unfortunately can't provide accurate spectral measurements of gamma radiation in energy range of several hundred keV and below (Chilingaryan et.al., 2013). To complete the observations in low energy range well-calibrated detectors based on inorganic scintillator crystals were used in this work. The results of correspondent experiments will be presented and discussed below.

Instrumentation

To perform observations of low-energy gamma-ray background variations of different nature during thunderstorms well-calibrated detectors based on scintillator inorganic crystals were used. They provide measurements in wide range from ~20 keV to ~10 MeV that is very important because a large part of gamma-ray flux variations in the range E<2.5 MeV can be explained by changes of Rn-222 concentration connected with rainfalls during thunderstorms (Bogomolov et.al., 2015) while another part comes from particles accelerated in thunderclouds. Energy resolution of the detectors must be suitable for detection of discrete gamma-ray lines produced by the decay of radioactive isotopes in order to control Rn-222 and its daughters concentration, also allowing one to make real time on-line calibration of the spectrometer during the experiment with background lines. The instrument has to have stable (up to ~1%) performance characteristics for long-duration measurements, as well, as sufficiently good time resolution to detect possible short flashes of gamma ray emission.

Several instruments used in this work for atmospheric transient events study were based on such well known non-organic scintillators as NaI(Tl) or CsI(Tl). Electronic circuits developed for use in these spectrometers can work with single-crystal detector as well as with multilayer one. In this case the determination of the crystal type in which interaction took place is realized via the pulse-shape analysis. Such kind of analysis allows one to remove imitations of gamma-events by the lightning following pulses of electric field.

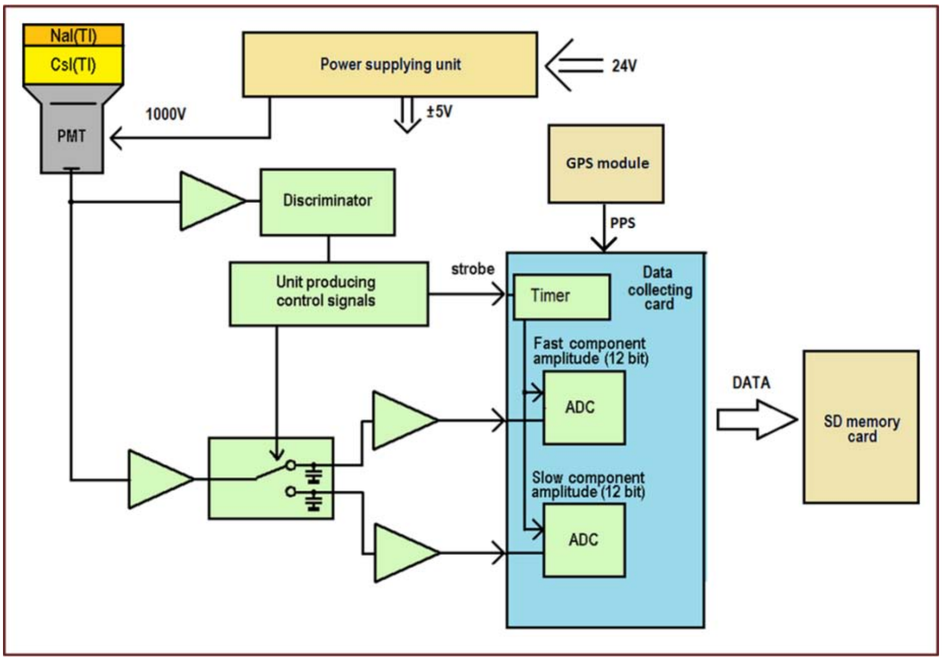

Fig. 1. Structural diagram of scintillator gamma-ray spectrometer

The structural diagram of electronics of gamma-spectrometer is presented in Fig.1. It consists of "Power supplying unit" providing high voltage (~1000V) for PMT and low voltage for analog and digital electronics, "Event" card containing analog electronics for event triggering and pulse-shape analysis, and "Data collecting card" based on the board STM32F4DISCOVERY with Cortex M4 microcontroller. GPS module with PPS is used for exact timing providing the synchronization of gamma-ray spectrometer readings with the world time with accuracy ~10 microseconds. The output data are recorded to SD card with a one second cycle. The data are recorded in the event-by-event mode and contain detailed time and amplitude information for each recorded interaction in the detector.

Detailed spectral information that is present in the data allows one to do real-time calibration with the use of background gamma-ray lines observed during the measurements. The algorithm of data processing determines the position of the detected 1.46 MeV background gamma-ray line of ^{40}K. The actual instrumental channel of ^{40}K line peak position is calculated every 300 seconds. Then energy of each detected gamma-quantum is calculated just in units of energy using corresponding linear formula. Such procedure allows one to minimize effect of the variations caused by temperature drift of the detector characteristics. It is very important for the long-lasting observation series because day and night temperature can differ by more than 20 degrees. The measurements taken during sunny day and/or thunderstorm weather can also greatly differ. The position of K-40 gamma-ray line measured during one-week measurements session is presented by Fig. 2 demonstrates ~10% variations.

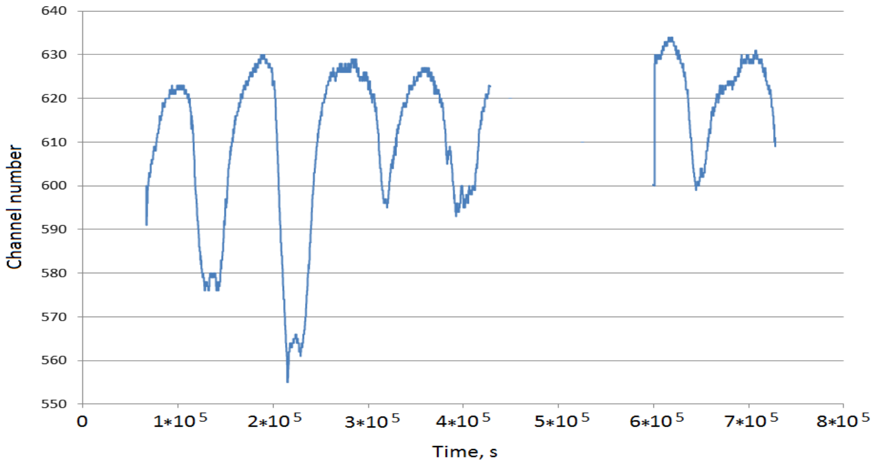

Fig. 2. Time variations of the position of K-40 gamma-ray line measured during one session of measurements

Several gamma-ray spectrometers were produced by us for measurements of natural gamma ray background variations. One of them (see photo at fig. 3a) was operating in Moscow region. It has detector based on 80x80 mm CsI(Tl) crystal coupled with Hammamatsu R1307 PMT. It was designed to record gamma-ray background spectra in 30-6000 keV energy range with energy resolution of 7.2% at 662 keV. Another one (see photo at fig. 3b) was used for the experiment at Aragatz mountain station. The size of its detector was some smaller (50x50 mm of NaI(Tl) but the measurements in the range up to 7 MeV were also done with this instrument.

All of the spectrometers used for monitoring of gamma-ray background were calibrated with a number of radioactive sources. Some of the energy spectra obtained during calibration sessions are presented in fig. 4. One can easily recognize well known peak of 662 keV line from Cs-137 decay, and a set of background lines that are corresponding to the most intense radiation of naturally occurring isotopes of ^{40}K, ^{208}Tl (daughter of ^{232}Th) and ^{214}Bi (daughter of ^{222}Rn).

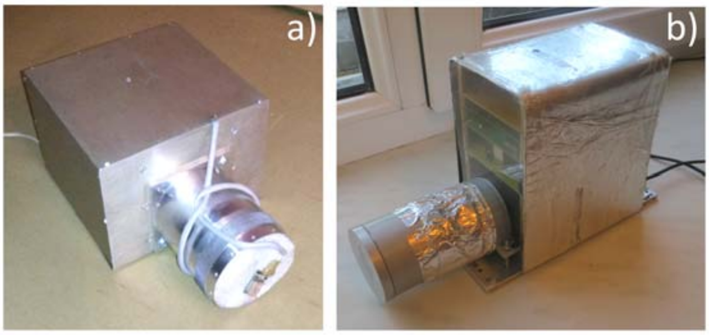

Fig. 3. Photos of the gamma-spectrometers used for the study of TGEs and for the search for gamma-flashes from lightning in Moscow region (a) and in mountains (b)

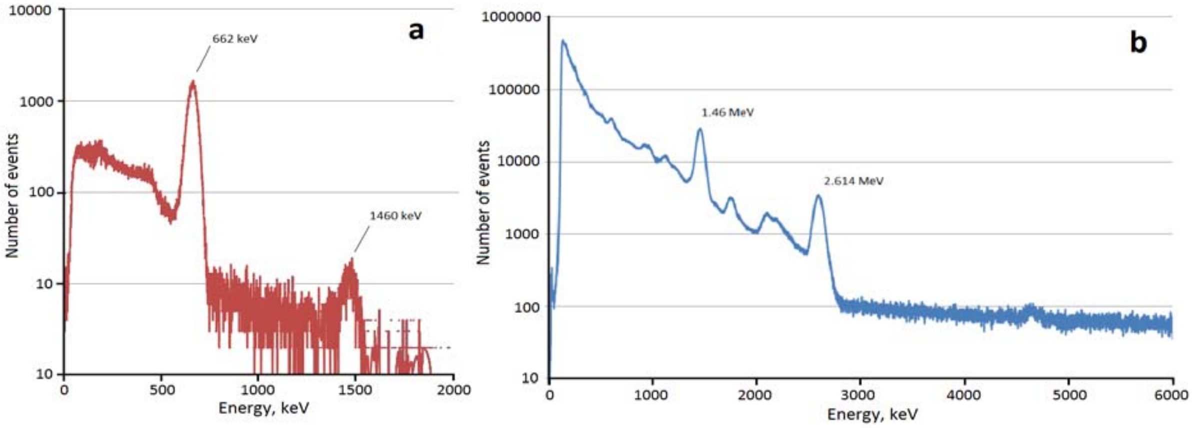

Fig. 4. Spectrum of Cs-137 (*a*) and background spectrum (*b*) obtained with the 80 mm diameter CsI(Tl) detector. Lines at 1.46 MeV and 2.614 MeV correspond to the naturally occurring isotopes ^{40}K and ^{208}Tl.

Results of the observation of ^{222}Rn radiation

The variations of the radiation from ^{222}Rn daughters appearing during rainy weather were detected many times at sea level and in mountains. The example of time behavior of gamma-ray background during the intensive rain is presented at fig. 5a. The conditions of observations on 27 of September, 2015 provided the possibility to estimate the rate of additional Rn-222 appearance near the detector. There was a clear weather more than for a day, then the thundercloud suddenly appeared and thunderstorm with rain shower rapidly started for ~5 min. After that there was ~5 min pause when there was no rain. Then the thunderstorm with intensive shower started again. The rain with thunderstorm continued for ~1.5 hours and then stopped and the sun appeared.

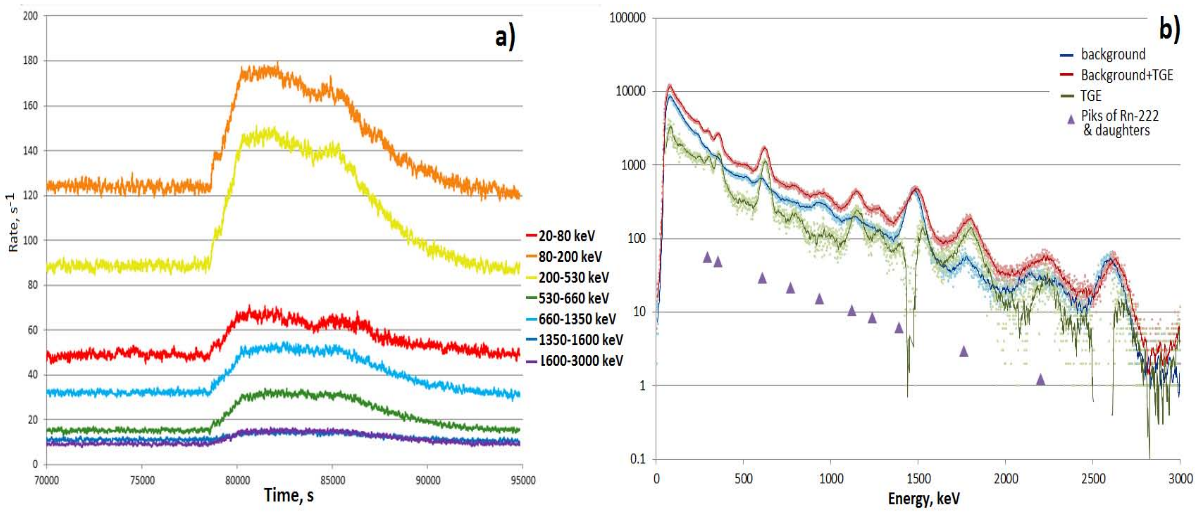

Fig. 5. Variations of γ-ray background (a) and energy spectra (b) observed during the rain in Moscow region

The spectrum of the observed enhancement is presented at fig. 5b. A number of lines of ^{222}Rn daughters are present in the spectrum of the additional radiation. One can see a step at the front of the curve at fig. 5a that shows that ^{222}Rn radiation changes together with rain. Possible explanation of the details of its behavior is that ^{222}Rn was solved in the water of raindrops. Radon could be collected from air during the movement of the storm cloud. Other way of experimental data description is to propose that near-ground concentration of ^{222}Rn is changed with the change of the conditions of ^{222}Rn escape from ground. However it is difficult to explain the observed speed of ^{222}Rn by this way.

After the rain stopped the intensity of radiation dropped with characteristic time ~0.5-1h. It can be explained by the decay of daughter isotopes of ^{214}Bi and ^{214}Pb. Other processes leading to the fall of the experimental curve are the diffusion of gaseous radon in the air and the leakage of the rain water to the ground.

The presence of ^{222}Rn and its daughters in the rain water was confirmed by the experiment when a glass with ~2L of the rain water was placed several times to the top of the detector with 2 min period. At the time sequence of the gamma-detector readings presented at fig. 6. one can see the variations of 609 keV line intensity while the intensity of 1.46 MeV radiation from ^{40}K remains stable. When the same experiment was done with water from water pipeline no variations were observed.

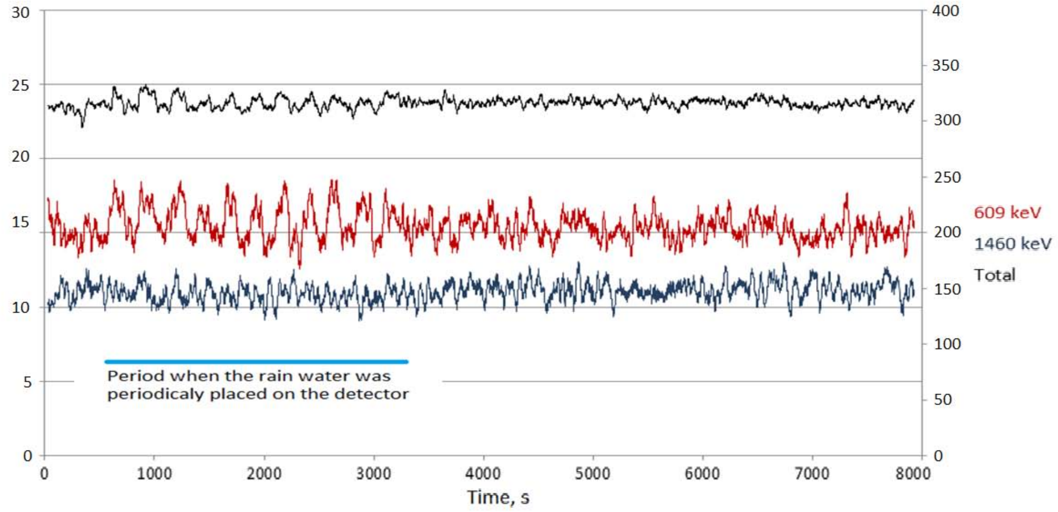

Fig. 6. Readings of gamma-spectrometer when the rain water was periodically placed to the detector

Observation of the radiation connected with accelerated particles

No significant increases of the flux of gamma-radiation with energy E>3 MeV were detected in Moscow region during thunderstorms in 2016 and 2017 seasons. It can be possibly explained by the absorption of gamma-quanta by air between the charged cloud and the detector. 3 sigma upper limit for 3200-6000 keV radiation obtained for one of the powerful thunderstorms is $2.4*10^{-4}$ $cm^{-2}*s^{-1}$. This value is of the same order that one of typical TGE fluxes observed by scientists of A. I. Alikhanian National Science Laboratory (Yerevan Physics Institute) at Aragatz cosmic ray station.

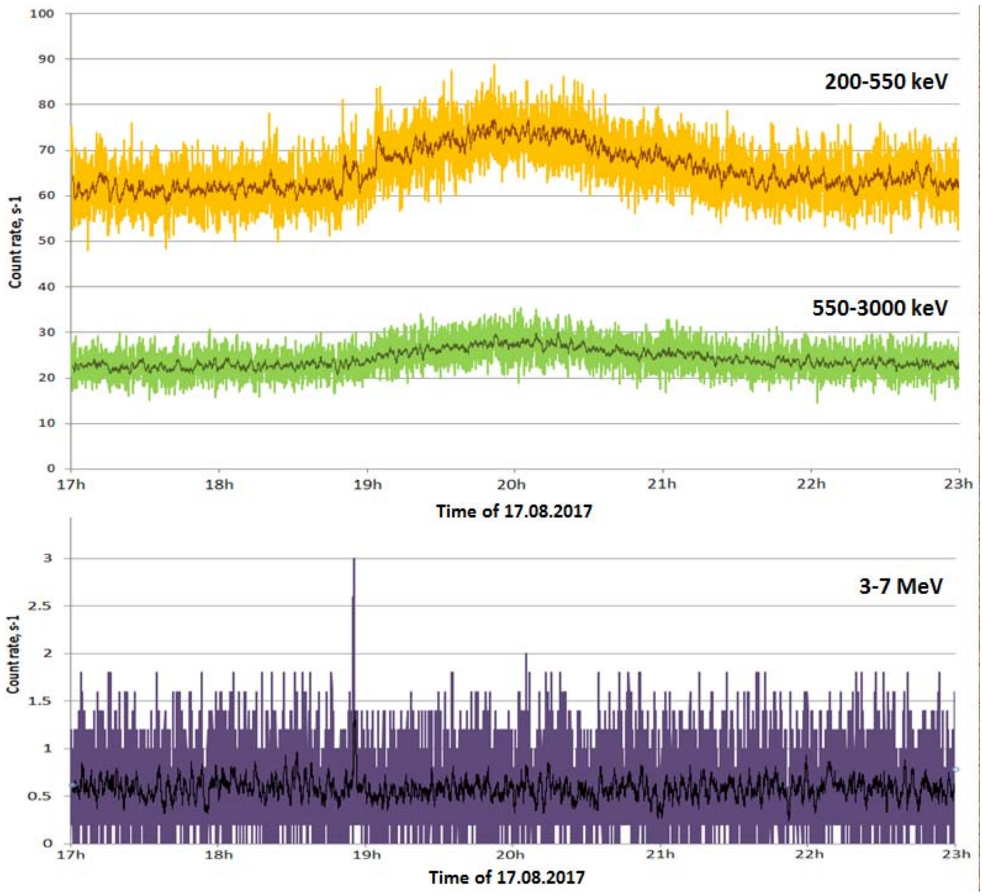

Fig. 7. Time behavior of 5 cm NaI(Tl) gamma-ray spectrometer readings at Aragatz on 17.08.2017

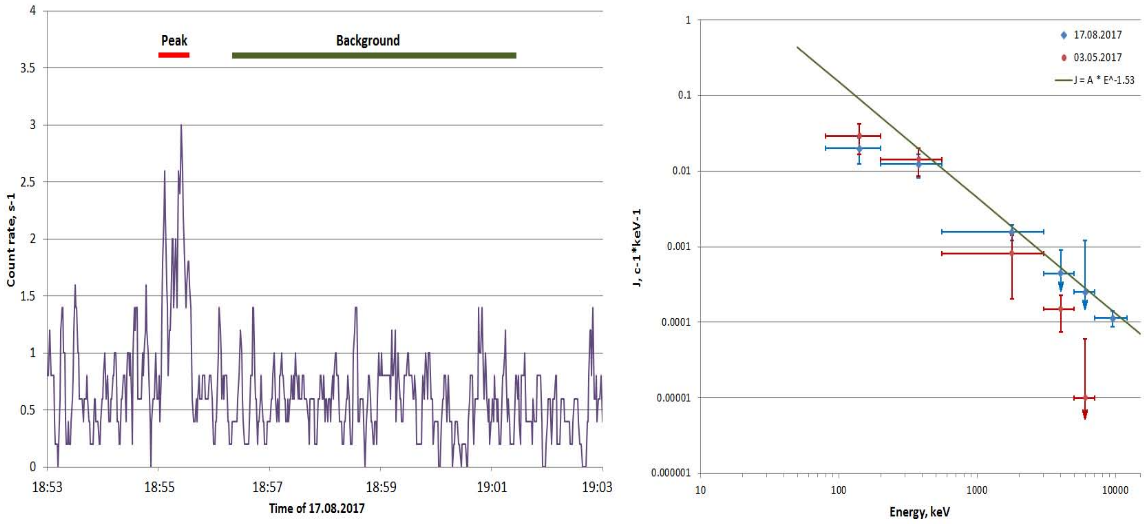

Fig. 8. Light curve in 3-7 MeV energy channel (left) and energy release spectrum (right) of TGE 17.08.2017

The measurements of 50-7000 keV gamma-ray flux with 5cm NaI(Tl) gamma-ray spectrometer (see fig. 3b) were realized at Aragatz in spring and summer of 2017. The significant increases of >3 MeV hard radiation were detected on May, 3 and on Aug, 17. Both events in hard radiation appeared as narrow peaks with duration ~1 min. The time behavior of readings on Aug, 17 is presented at fig.7. The energy spectra of the peak radiation were obtained by subtraction of the mean count rate during the background time interval from the mean count rate for the 30-s long interval of the peak (see fig 8a). Energy spectrum is presented at fig. 8b. The power-low approximation is plotted at the same figure. The parameters of this approximation were taken from the measurements of ErPhI group. One can see very good agreement of the slopes of the spectra as well as of the count rates normalized for the detector area. The detector used by Armenian scientists is more thick so its total absorption efficiency for hard gamma-radiation is several times higher. Possible interpretation of the coincidence of the normalized count rates is that the direct detection of accelerated electrons can be responsible for significant part of the measured flux. Such situation can take place when the distance between the detector and the region of particle acceleration is no more than few hundred meters.

Acknowledgements

Authors thank Ashot Chilingarian and his group from A. I. Alikhanian National Science Laboratory (Yerevan Physics Institute) providing the continuous measurements with our instrument in mountains of Armenia at Aragatz cosmic ray station.

References:

1. Bogomolov, V. V., Svertilov S. I., Maximov I. A., et al, Study of TGEs and Gamma-Flashes from thunderstorms in 20-3000 keV energy range with SINP MSU Gamma-Ray spectrometers, Proceedings of International Symposium TEPA-2015, Nor-Amberd, Armenia, 2015, pp.41-46
2. Briggs, M. S., Xiong S., Connaughton, V., et al., Terrestrial gamma-ray flashes in the Fermi era: Improved observations and analysis methods, Journal of Geophysical Research: Space Physics, 2013, vol. 118, 3805–3830, doi:10.1002/jgra.50205
3. Chilingarian, A., Hovsepyan G and Kozliner L., Thunderstorm Ground Enhancements: gamma ray differential energy spectra. Proceedings of International Symposium TEPA-2013, Nor-Amberd, Armenia, 2013, pp.32-41
4. Chilingarian, A., Thunderstorm Ground Enhancements - model and relation to lightning flashes, Journal of Atmospheric and Solar-Terrestrial Physics, 2014, 107 68–76.
5. Chilingarian A, Hovsepyan G, Mnatsakanyan E. Mount Aragats as a stable electron accelerator for atmospheric High-energy physics research, Proceedings of International Symposium TEPA-2015, Nor-Amberd, Armenia, 2015a, pp.2-9
6. Chilingarian, A., Hovsepyan G., Khanikyanc G., et al, Thunderstorm ground enhancements (TGEs) abruptly terminated by negative cloud-to-ground lightnings, Proceedings of International Symposium TEPA-2015, Nor-Amberd, Armenia, 2015b, pp.71-78
7. Gurevich, A. V., Milikh G. M., Roussel-Dupre R. Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm. Phys. Lett. A. V. 1992, 165, 463– 468.
8. Dwyer, J.R., D.M. Smith, and S.A. Cummer, High-energy atmospheric physics: Terrestrial gamma-ray flashes and related phenomena, Space Sci. Rev., 2012, 173, 133-196, doi:10.1007/s11214–012-9894-0.