Bursts of gamma-rays, electrons and low-energy neutrons during thunderstorms at the Tien-Shan

G G Mitko¹, V P Antonova², A P Chubenko¹, A N Karashtin³, M O Ptitsyn¹, V A Ryabov¹, A L Shepetov¹, Yu V Shlyugaev⁴, L I Vildanova¹, K P Zybin¹, and A V Gurevich¹.

¹ P.N. Lebedev Physical Institute of RAS, Moscow, Russia
² Institute of Ionosphere, National Center for Space Research and Technology, Almaty, Kazakhstan
³ Research Radiophysics Institute, Nizhny Novgorod, Russia
⁴ Institute of Applied Physics of RAS, Nizhny Novgorod, Russia

E-mail: umena6@yandex.ru

Abstract. New data of the last measurement season held at the Tien-Shan complex for investigation gamma-radiation, accelerated electrons and low-energy neutrons during thunderstorms are presented. The flux of gamma-radiation in the energy range of 40 – 1200 keV shows a strict correlation with instantaneous intensity of atmospheric discharge. Its energy spectra measured for the first time with riches statistics and improved resolution typically have an absolute intensity about 50 – 100 quanta·cm⁻²·s⁻¹, and demonstrate considerable evolution in the course of discharge. The signals from an avalanche of accelerated electrons have been directly observed inside thunderclouds. A lower energy estimation for these electrons is about 10 MeV. For the first time, during electric discharge moments in thunderstorms, there were found considerable intensity enhancements of the neutron intensity in the range of thermal energies: up to 100 – 200 standard deviations, or 3 – 8 times above the background, so the observed neutron flux reaches the values of (20–40) · 10³ m⁻² · min⁻¹.

1. Introduction

The Tien-Shan high-altitude cosmic ray station is a unique site for investigations in the field of the physics of lightning discharge. "Thunderstorm" complex at Tien-Shan is designed especially for a systematical study of atmospheric discharges by the means of simultaneous recording of the different kinds of radiation: the accelerated charged particles (electrons) [1], the gamma- and X-ray radiation [2], the atmospheric neutrons and other hadronic particles [3], and the radio-emission in the frequency range of medium waves 0.1 – 30 MHz, so as in the ultra-short wave diapason of about 250 MHz [4]. The presence of a wide-spread extensive air shower trigger set-up at the Tien-Shan station permits to study the role of energetic cosmic ray particles in lightning development [5].

An important advantage of the "Thunderstorm" complex is its location in the range of altitudes between 3340 and 4000 m above the sea level, i.e. at the very height were the thunderstorm clouds form in the mountains of northern Tien-Shan. This favourable circumstance is one of the major preferences of the "Thunderstorm" facility in comparison with other experiments aimed to study of radiation emitted in thunderstorms. The maximum possible spacing between the detectors in horizontal plane at Tien-Shan is up to 2–2.5 km, and up to 550–600 m in vertical direction.
makes it possible an observation of both the temporal and spatial distributions of the different kinds of radiation in the cloud, and even a continuous monitoring of the movement of radiation sources together with cloud [6–8].

2. “Thunderstorm” complex at Tien-Shan

Experiments in the field of thunderstorm exploration are carried out uninterruptedly at Tien-Shan during the last decade. At present time, it comprises the following facilities: an EAS registering system, the system of NaI scintillation detectors for registration of the gamma- and X-ray emission in atmosphere, the multi-layer ionization detectors of energetic charged particles, the neutron supermonitor for registration of the high-energy hadronic component of cosmic rays, a set of the detectors of low-energy (thermal) neutron background, two independent radio-systems, and electrostatic detectors of the local electric field and its high frequency component.

All kinds of radiation were recorded by using trigger signals of the three different types. First trigger was a randomly coming signal indicating the passing of extensive atmospheric shower. Another trigger indicated the strong electromagnetic pulse, the third one indicated the rapid change of the electrostatic field (jump). The last two types of triggers are never formed in the absence of a thunderstorm. Each record of the radiation was 2 s long (1 s before and 1 s after trigger pulse) with high-time resolution of 160 – 200 μs.

3. Gamma-radiation measurements

Four scintillation detectors based on NaI crystals were used to register gamma radiations. Detectors were placed in four registration points situated as a chain on the slopes of the surrounding mountains, across the usual direction of motion of thunderstorm clouds. Further on, we will consider the identification of gamma-radiation bursts with the moments of atmospheric discharges on an example of one of the thunderstorms. The discharges with the presence of a gamma radiation demonstrate the prolonged radiation bursts, the mostly intensive bursts being concentrated in an active thunderstorm period, about 20 minutes since its beginning. During this period the local electric field remains to be strongly lowered relatively to its zero level. Examples of such negative and positive discharges are shown in Figure1, where gamma-flashes are clearly seen during the burst. Positive discharges (right) are spread somewhat more compactly while the negative ones (left) seem to be more scattered, many splashes with different durations.

![Figure 1. Temporal scans of gamma-ray bursts from negative (left) and positive (right) atmospheric discharges. From top to bottom: 1) scans of gamma-ray emission – numbers of gamma-quanta in 200 μs time interval, 2) quasi-static electric field, measured by “field-mill”, 3) electric field variations measured by the capacity sensor. The 0-point corresponds to the trigger.](image-url)

The greatest intensity of flashes is observed in an active phase of a thunderstorm, but they also are present and at very weak atmospheric discharges at attenuation of storm process. The characteristic
time of gamma flashes in the active phase of the thunderstorm is 200 – 400 ms. The flux of gamma-radiation in the energy range of 40 – 1200 keV shows a strict correlation with intensity of atmospheric discharge. Its energy spectra measured for the first time with riches statistics and improved resolution typically have an absolute intensity about 50 – 100 quanta·cm⁻²·s⁻¹, an integral power index in the limits – (1.0 – 1.5), and demonstrate considerable evolution in the course of discharge.

In our experiment we also observed exponential fast falling of intensity of gamma radiation flashes with a diminishing of height from the upper scintillation detector, located at the 3880 m a.s.l.

4. Registration of accelerated electrons
Another interesting phenomenon seen in ionization detectors during the thunderstorms is the signal from the fast avalanche of energetic charged particles (accelerated electrons), being observed in the moments of the close electric discharge. A sample of this kind of events is presented in the Figure 2. In these plots, the bursts of counting rate are seen not only in records of the separate counter layers, but also in the intensity of mutual coincidences both between the upper, middle and lower layers. The presence of coincidence signal enhancements immediately around the moment of an electric discharge indicates undoubtedly to registration of the electrons, being accelerated by the thundercloud’s electric field and initiating the lightning discharge in atmosphere as a result of the runaway breakdown mechanism [9]. As it is seen in Figure 2, the statistical assurance of the signal from charged particles is quite sufficient. Indeed, the mean background counting rate in coincidence channels being 510 s⁻¹ and 320 s⁻¹ (for the 2- and 3-fold coincidences correspondingly), the observed number of 8 – 10 coincidence pulses in a single 200 µs time interval is above its background level up to 80 – 125 times. Such intensity of coincidence pulses detected in a burst corresponds to the intensity of the charged particle flow of 2 – 5 s⁻¹sm⁻². Also, because of the total absorber thickness between the counter layers being about 1.5–2 g/cm², the observation of the signal coincidences means, that the energy of accelerated electrons being registered inside a thundercloud should be above 3 – 6 MeV.

![Figure 2. From top to bottom plots: amplitude of radio-emission; the signal from the upper, middle, and lower ionization counter layers; the 2- and 3-fold coincidence signals between the layers. Zero time coincides with arrival moment of the electrostatic jump trigger.](image)

5. Observation of an intensive bursts of low-energy neutrons
During of thunderstorms observed in seasons 2010-2011, the detectors of thermal neutrons and the neutron supermonitor were operating simultaneously with the sensors of electric field, the ionization detectors, and both radiosystems. The temporal dependencies of the neutron counting rate one of thunderstorms are plotted in the Figure 3. It is obvious, that the minutely thermal neutron pulse counts, both in external and in internal detector, which overlap with the moments of an electric discharge are above their mean background levels up to 2.5 – 3 times. The short-time intensity enhancements in same moments of time are also visible in the underfloor detector, thou their amplitude here is only about 20 – 30%; and even in the neutron supermonitor, where the typical enhancement amplitude of 2.5 – 5% is noticeable due to the high counting statistics. Statistically, the observed excesses in neutron intensity are quite satisfied: their relative amplitudes above corresponding background level of counting rate in maximum point are 68 σ, 54 σ, 15 σ, and 4 σ for external, internal, underfloor, and supermonitor correspondingly.
6. Conclusions
The prolonged (100–600 ms) gamma-radiation bursts are found and for the first time identified with electric atmospheric discharges during a thunderstorm. For the first time shown that the intensive gamma radiation is generated at the all stages of an atmospheric discharge. The intensity of gamma radiation of the short flashes is by two orders of magnitude higher than that of the background.

We have detected the short-time outbursts of the counting intensity which may be interpreted as signal from the fast electrons accelerated inside the strong electric fields of a thundercloud. Typical duration of the registered electron flows is of the order of some hundreds of microseconds, while the integrated flux of charged particles is \(2 \sim 5\) s\(^{-1}\) sm\(^{-2}\), and the presence of the particles accelerated up to some MeV is immediately estimated in the avalanche. These values are in an agreement with the mechanism of runaway breakdown effect.

A series of events was found, in which temporal correlation of the flashes of thermal neutrons with atmospheric discharges is observed. Statistical confidence of observable excesses in thermal neutron intensity over background level exceeds more than 100 \(\sigma\). The low-energy neutron fluxes registered during thunderstorms reach the values of \((20 \sim 40) \times 10^3\) neutrons per m\(^2\) per minute. These firstly observed extremely high neutron fluxes are a challenge for the theory.

We have shown that the complex observation of gamma radiation, accelerated electrons and neutrons at the height 4–8 km could serve as a new important method of the investigation of physical processes occurring in atmospheric discharges.

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