Correlation of Radio and Gamma Emissions in Lightning Initiation

A. V. Gurevich,[1,*] V. P. Antonova,[2] A. P. Chubenko,[1] A. N. Karashtin,[3] G. G. Mitko,[1] M. O. Ptitsyn,[1] V. A. Ryabov,[1] A. L. Shepetov,[1] Yu. V. Shlyugaev,[4] W. M. Thu,[5] L. I. Vildanova,[6] and K. P. Zybin[1]

[1]*P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, 119991, Russia*
[2]*Institute of Ionosphere, National Center for Space Research and Technology, Almaty, 050020, Kazakhstan*
[3]*Radiophysical Research Institute, Nizhny Novgorod, 603950, Russia*
[4]*Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, 603950, Russia*
[5]*Moscow Institute of Physics and Technology. State University, Moscow, 117303, Russia*
[6]*Tien-Shan Mountain Cosmic Ray Station, Almaty, 050020, Kazakhstan*

(Received 8 July 2013; published 14 October 2013)

The results of simultaneous radio and gamma emission measurements during thunderstorms are presented. A gamma detector situated at the height 3840 m and two radio detectors of Tien-Shan Mountain Scientific Station (altitude 3340 m) registered intensive gamma flashes and radio pulses during the time of lightning initiation. The radio-gamma correlation grows abruptly at the initial moment (a few hundred microseconds), and the correlation coefficient reaches 0.9–0.95. The gamma-energy spectrum measured during lightning initiation is close to the characteristic spectrum of runaway breakdown. Radio pulses observed at the same time have highest amplitudes. Combined observation of gamma and radio emissions confirm the conception of lightning initiation due to multiple simultaneous electric discharges at hydrometeors stimulated and synchronized by low-energy electrons generated in the runaway breakdown process.

DOI: 10.1103/PhysRevLett.111.165001 PACS numbers: 52.80.Mg, 28.20.Gd

Introduction.—Lightning initiation is a long-standing mystery [1,2]. Decades of electric field measurements in thunderclouds have given a maximum value about an order of magnitude less then the critical electric field of conventional air breakdown [3]. Besides, the physical mechanism of an extremely strong amplification of ion conductivity, needed for lightning start and development, remains unclear. In this Letter, we present the results of the lightning initiation (LI) investigation which continues and supports our previous studies [4].

In Ref. [4] we have described the series of short intensive radio pulses observed during LI in multiple cloud-to-ground lightning discharges. These radio pulses are random in time; their width is about 100 ns, and the rate is about 20–30 per ms. The radio pulses are generated by strong unidirectional current pulses in thunderclouds. What are the current pulses generated by? Streamer discharge usually considered for a LI does not generate such pulses [5]. In Ref. [4] it was supposed that these pulses are generated in multiple simultaneous electric discharges at hydrometeors (HM) stimulated and synchronized by low-energy electrons generated in runaway breakdown (RB) process. We call them the RB-HM pulse discharges.

The analysis in Ref. [4] was based solely on the study of radio pulses. At the same time, an RB-HM discharge must also lead to the generation of gamma emission fluxes. Gamma emission does not propagate for a long distance due to its absorption and scattering in air. The characteristic length l of the exponential fall of gamma intensity at a thundercloud height (4–5 km) depends on the energy ε of gamma quanta. For gamma emission energies under discussion the characteristic length increases from $l = 50$ m for $\varepsilon = 40$ keV to $l = 200$ m for $\varepsilon =$ MeV. This leads to a serious difficulty in gamma observations during lightning events: the gamma detector should be situated at a distance not larger than 100–200 m from the source of gamma quanta. Exactly such a special situation is realized at the highest (3840 m) gamma detector included in the set of NaI(Tl) detectors of the "Thunderstorm" installation of the Tien-Shan Mountain Scientific Station (43°15′0″N, 76°54′0″E, 3340 m above sea level). Thunderclouds move at the altitude close to the detector placement, and therefore the detector is often immersed deep into clouds during a thunderstorm and can register the strong fluxes of gamma emission.

Thunderstorm high-frequency radio emission is measured independently by two radio detectors situated near the Station. That allows studying both radio and gamma emissions of lightning.

The intensive fluxes of gamma emission are registered. The high correlation of radio and gamma emissions during LI is observed with correlation coefficient reaching 0.9–0.95. The gamma energy spectrum measured is close to the characteristic spectrum of runaway breakdown. The results of observations presented in this Letter confirm the RB-HM concept of LI.

Experimental setup.—The scintillation detector [6] consists of a cylindrical NaI(Tl) crystal (110 mm in diameter and 110 mm in height) which is coupled with a FEU-49 type photomultiplier tube (PMT). The crystal and PMT are enclosed by a common aluminum housing with a wall thickness of 1 mm. During measurements the detector can be regarded as a vertically placed cylinder with a bottom fully screened from any radiation. Its full effective area is 475 cm^2 and the effective area for the one-side gamma emission beam is 120–150 cm^2. Analog pulses from the PMT's anode are transmitted to the system of data recording which consists of a set of amplitude discriminators with a lower discrimination threshold corresponding to the gamma-radiation energy of 40 keV. The next discrimination thresholds are 80, 160, 320, 640, and 1280 keV. The (digital) discriminator outputs are connected to the pulse intensity measurement system which counts the number of pulses on its inputs separately in the 4000 sequential temporal intervals, each 160 μs long. At every given moment a record of the temporal behavior of the input pulse intensity during the last 0.64 s is kept in the internal memory of the system, and can be written down upon arrival of a special control signal (a trigger).

The short electromagnetic pulses were registered using two specially designed radio installations (Radio-I and Radio-II) working in the frequency range 0.1 to 30 MHz with a 16 ns sampling rate [7]. Each installation contains three receiving antennas that can be separated up to 50 m from the receiving apparatus (central unit). Each receiving antenna of the installation (antenna assembly) actually consists of three individual antennas: two mutually perpendicular loop antennas for horizontal magnetic field measurements, and an End-Fed antenna to measure the vertical electric field. All three antennas are active and include transistor amplifiers. The signals from the amplifiers are transferred to the registration unit equipped with the differential amplifiers. It allows us to avoid the interference over the 50 m cables.

Both radio installations are placed on the Station at the altitude 3340 m above sea level. Radio-I is situated 200 m south, and Radio-II 180 m northwest from the Station. The altitude of the NaI(Tl) scintillation detector placement is 540 m above the Station, while the horizontal distance between radio installations and the detector is 1400 m.

All the detectors are triggered during a thunderstorm by a sharp change of electric field measured at the Station or by a strong electromagnetic pulse [6].

Results of observations.—A sharp change in the electric field measured at the Station usually coincides with a beginning of a series of short intensive radio pulses. Therefore, the moment when the series of radio pulses starts should be considered the beginning of a lightning. A series of random radio pulses are routinely observed during LI. They have the frequency rate 20–30 per ms and the growth and decay time about 100 ns. The physical characteristics of radio pulses are quite analogous to those observed at Nizhny Novgorod [4].

We note that when the discharge is sufficiently close, at a distance of a few km, the series of radio pulses is observed at the lightning beginning both at Tien-Shan and Nizhny Novgorod. As regards the far discharges the trigger is mainly formed a few dozen ms after the lightning start, most probably at the moment of a return stroke. The important peculiarity of Tien-Shan measurements is in the observation of intensive gamma fluxes.

The comparison of simultaneous observations of radio pulses and gamma emission during LI is shown in Fig. 1. A sharp increase in the radio emission amplitude and the count number of gamma quanta in the lightning beginning is demonstrated. Fair agreement in time development of radio and gamma emissions can be seen. We note that the intensity of gamma emission during LI is almost 2 orders of magnitude higher than the gamma emission intensity at quiet conditions.

The gamma count number for different energy thresholds is shown in Fig. 2. The abrupt initiation is seen at all gamma energies up to the highest measured energy 1.28 MeV.

In Fig. 3 the correlation between gamma and radio emissions is presented. It can be seen that the correlation function can reach the very high value 0.9–0.95. The abrupt growth of the correlation, lasting for a few hundred μs, is clearly seen at all energy thresholds. The high correlation lasts for the initial 2–4 ms.

The integrated spectrum of gamma emission and its time dependence are shown in Fig. 4. It was determined using

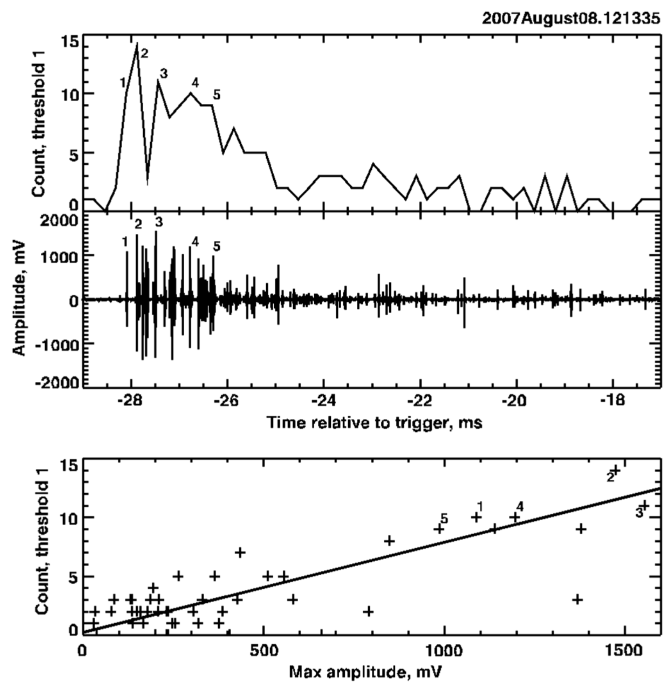

FIG. 1. Correlation of radio and gamma emission in the lightning initiation during 10 ms starting from −28.2 ms before the return stroke. Upper two panels: the time dependence of gamma counts during 200 μs time intervals and the corresponding radio emission waveform. Bottom panel: gamma count number vs maximum radio pulse amplitude at the same intervals. The first five strong radio pulses are marked by numbers. (08 August 2007, 12:13:35 UT event.)

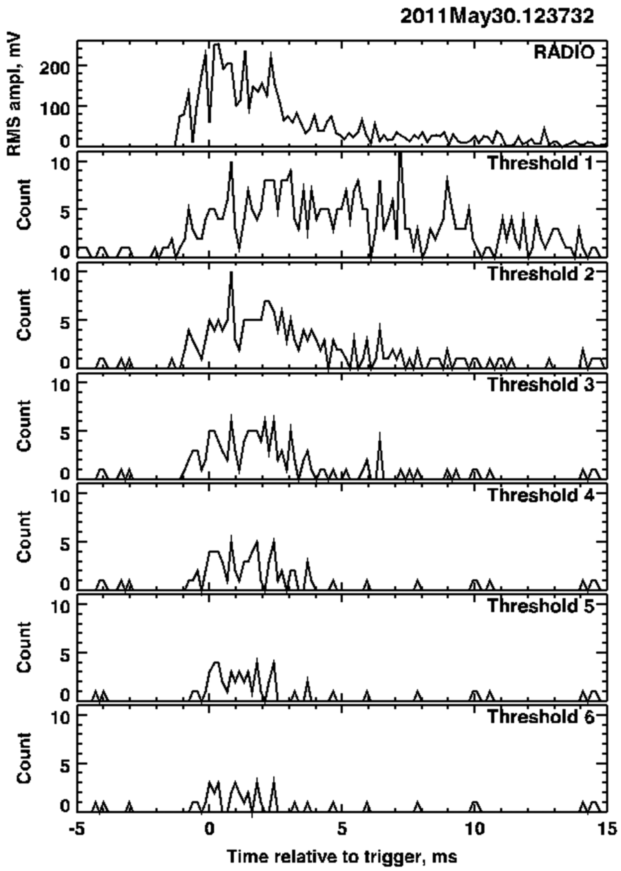

FIG. 2. Time dependence of radio and gamma emissions at the beginning of lightning discharge. Upper panel: the root mean square amplitude of radio emission over 160 μs intervals corresponding to the accumulation time of gamma detectors. Other panels: counts of gamma quanta per 160 μs bin for different energy threshold levels. From top down: above 40, 80,160, 320, 640, and 1280 keV. (30 May 2011, 12:37:32 UT event, return stroke at 86.4 ms.)

both the scintillation detector count rate at different thresholds and the corresponding registration efficiency coefficients. These coefficients were obtained by a combined approach based on the direct pointlike standard gamma-source measurements (using the ^{241}Am and ^{137}Cs sources) and GEANT3 simulation of the gamma-quantum registration process inside a NaI(Tl) [8].

Near the LI moment the integrated spectrum of gamma emission is characterized by a long tail stretched to the highest observed energies (the top panel of Fig. 4). The spectrum is quite similar to the theoretically predicted characteristic RB spectrum [9,10]. It is registered within the initial time interval about 2–3 ms and then changes to another type of spectrum that rapidly falls with the gamma quanta energies. In the bottom panel of Fig. 1 the two types of integrated gamma-emission energy spectra are presented. The RB-type spectrum is well time correlated with the radio pulses having the highest amplitudes as can be seen from Fig. 5.

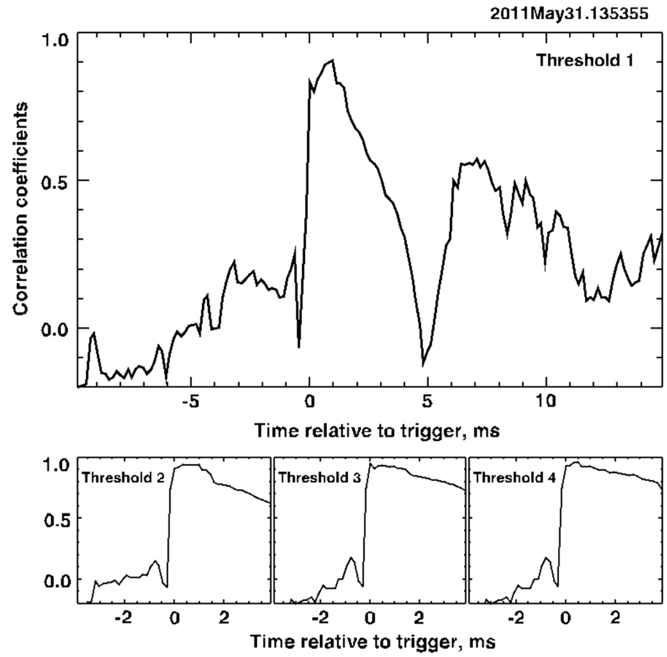

FIG. 3. Sliding correlation coefficients between radio and gamma emissions for different gamma-energy threshold levels. The correlations are computed using a 5 ms window. (31 May 2011, 13:53:55 UT event, return stroke at 98.5 ms.)

Discussion.—Analysis of the data obtained during a thunderstorm has a specific difficulty connected with the concrete conditions in which this complicated natural phenomenon is realized. In particular, peculiarities of the Tien-Shan Mountains structure near the Station could affect the development of lightning and the emission propagation. The gamma detector is situated 1.4 km to the south from the Station at a high altitude among nonconductive granite rocks close to the ridge. There is a sharp precipice 300 m deep in the nearby detector locality. Thunderclouds move along the precipice. The Station itself is situated on a pass. The ground at the pass and around (through about 700 m in horizontal direction to the north and up to 170 m in altitude) is conductive. The inductive electric field could be induced in the ground under the action of a thundercloud electric charge. The small surface irregularities could then serve for the charge emission. All that could result in a significant difference between the lightning development and the emissions propagation at Tien-Shan Mountains and in a plane, e.g., near Nizhny Novgorod.

Our observations show that the series of radio pulses often starts at the trigger moment, that is the moment of a sharp change of the electric field measured at the Station. In particular, on 30 and 31 May 2011 such kinds of events were observed in about 70% of all events. It is clear that the bipolar form of the pulses demonstrate that each of them is generated by the unipolar electric current of electrons supported by ions. The current of all the pulses has the same polarity. Initial pulses are very intensive, being integrated over a short time interval, they lead to a sharp

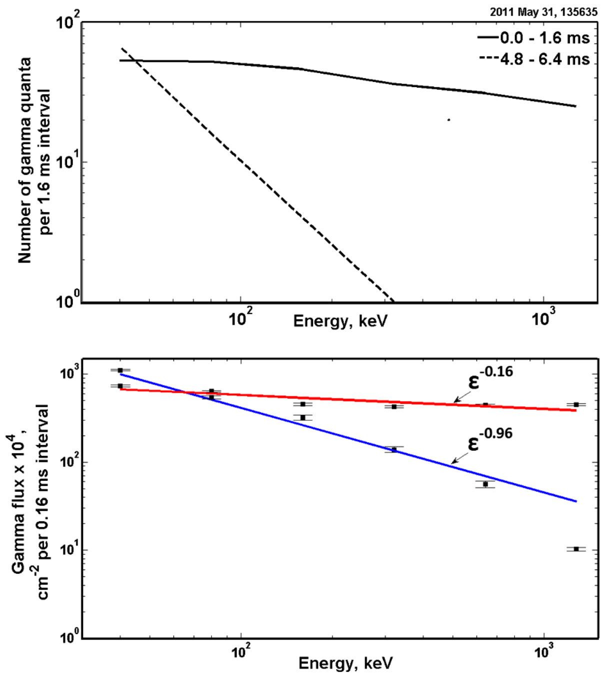

FIG. 4 (color online). Top panel: time evolution of the gamma-emission integrated energy spectrum at the beginning of the lightning discharge (31 May 2011, 13:56:35 UT event). Solid line, spectrum at the very beginning; dashed line, about 5 ms after the trigger. Bottom panel: two types of integrated gamma emission energy spectrum averaged over the data from fourteen lightning events registered on 30 and 31 May 2011. The data selected to obtain both the flat spectrum and the rapidly falling one belong to the time interval less than 10 ms near the trigger. In all the events the spectrum changes between these two types during LI similar to the example presented in the top panel. Power-law approximations to the spectrum are shown by solid lines.

change in the electric charge in thunderclouds, which is reflected in the result of the electric field measurement.

We estimate the total number of energetic gamma quanta observed during one time interval (160 μs). The RB-type flux at the highest measured energy 1.28 MeV is about 0.05 quanta per cm^2 per interval. The scale of the pulse discharge region is 30 m (see [4]). Hence, the number of energetic gamma quanta during the pulse is about 5×10^5. Assuming that the pulses are initiated by cosmic-ray particles having the energy about 10^{12} eV, we can conclude that the amplification of the number of the energetic gamma quanta due to the runaway breakdown process is 3 to 4 orders of magnitude. Quite similar RB amplification of the low-energy electron number is needed to stimulate the simultaneous multiple discharge at hydrometeors that generate the observed radio pulses. Therefore, the same RB process leads to the simultaneous generation of gamma and radio emissions. The observed high correlation of both emissions gives an additional confirmation of their deep connection.

Another confirmation of the simultaneous strong amplification of the number of gamma quanta and the radio pulse amplitude can be obtained from the data presented

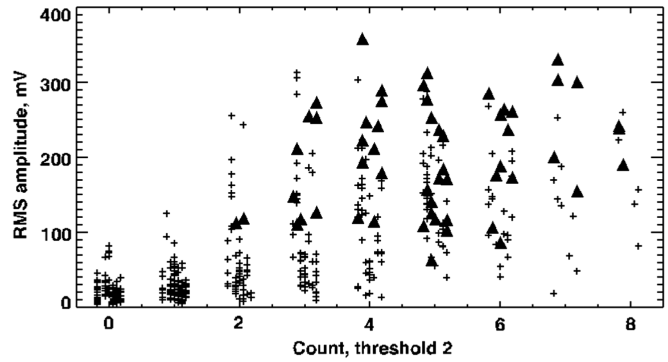

FIG. 5. The root-mean-square amplitude of radio emission versus gamma quanta count at the first energy threshold (above 40 keV) plotted for seven lightning events registered on 30 and 31 May 2011. Solid triangles correspond to samples with at least two counts at the highest energy threshold (above 1280 keV), and the plus signs, to other samples. Different events are slightly shifted with respect to the x axis to improve visibility (all counts are actually integer). The rms amplitude 200 mV is approximately equivalent to the electric field strength 200 mV per m.

in Fig. 5. The ratio of the gamma quanta number for RB-type processes (solid triangles) to the radio signal rms amplitude is $N\gamma/A \approx 0.02$ quanta per mV. On the other hand, we can estimate this ratio assuming that the RB is initiated by a cosmic-ray particle having the energy at about 10^{12} eV, the gamma detector effective area is 120–150 cm^2, and the distance from the pulse current region to the radio detector is 1.4 km. Supposing that the distance from the gamma source to the detector is 100 m and the pulse electric current is 10 A allows estimating the value of the ratio. The estimation shows that 10–12 avalanche exponential multiplication is needed to reach the observed value of the ratio. The same avalanche multiplication value is needed to explain the observed radio pulse amplitude according to the estimations in Ref. [4]. Thus, the results presented in Fig. 5 demonstrate once more that the observed gamma and radio emissions are generated in one and the same RB-HM process.

Conclusions.—It is demonstrated that the series of random radio pulses observed during the initial stage of negative cloud-to-ground lightning are accompanied by intensive gamma fluxes. Radio and gamma emissions are highly correlated with the correlation coefficient reaching 0.9–0.95. The correlation grows abruptly in the initial moment (a few hundred μs) in all energy ranges. The gamma spectrum of RB type is observed during the time interval close to the moment of lightning initiation. The observed relation of the number of gamma quanta to the radio pulse amplitude demonstrates that the gamma and radio emissions are generated in the same RB-HM process. Our observations confirm the runaway-breakdown-hydrometeor concept of lightning initiation.

The authors are grateful to A. M. Semikhatov for multiple helpful remarks. This work was supported by the RAS Programs 29Π and 11ОФ and by RFBR Grant No. 12-02-01294.

*alex@lpi.ru

[1] D. R. MacGorman and W. D. Rust, *The Electrical Nature of Storms* (Oxford University Press, New York, 1998).
[2] V. A. Rakov and M. A. Uman, *Lightning. Physics and Effects* (Cambridge University Press, Cambridge, 2003).
[3] M. Stolzenburg, T. C. Marshall, W. D. Rust, E. Bruning, D. R. MacGorman, and T. Hamlin, Geophys. Res. Lett. **34**, L04804 (2007).
[4] A. V. Gurevich and A. N. Karashtin, Phys. Rev. Lett. **110**, 185005 (2013).
[5] E. M. Bazelyan and Yu. P. Raizer, *Spark Discharge* (CRC Press, Boca Raton, 1998).
[6] A. V. Gurevich *et al.*, Phys. Lett. A **375**, 1619 (2011).
[7] A. V. Gurevich, L. M. Duncan, A. N. Karashtin, and K. P. Zybin, Phys. Lett. A **312**, 228 (2003).
[8] A. P. Chubenko *et al.*, Phys. Lett. A **373**, 2953 (2009).
[9] A. V. Gurevich and K. P. Zybin, Phys. Usp. **44**, 1119 (2001).
[10] J. R. Dwyer and D. M. Smith, Geophys. Res. Lett. **32**, L22804 (2005).