Runaway Breakdown and Hydrometeors in Lightning Initiation

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The particular electric pulse discharges are observed in thunderclouds during the initiation stage of negative cloud-to-ground lightning. The discharges are quite different from conventional streamers or leaders. A detailed analysis reveals that the shape of the pulses is determined by the runaway breakdown of air in the thundercloud electric field initiated by extensive atmospheric showers (RB-EAS). The high amplitude of the pulse electric current is due to the multiple microdischarges at hydrometeors stimulated and synchronized by the low-energy electrons generated in the RB-EAS process. The series of specific pulse discharges leads to charge reset from hydrometeors to the free ions and creates numerous stretched ion clusters, both positive and negative. As a result, a wide region in the thundercloud with a sufficiently high fractal ion conductivity is formed. The charge transport by ions plays a decisive role in the lightning leader preconditioning.

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Introduction.—The processes that govern lightning initiation within a thunderstorm remain largely unknown [1]. Decades of electric field measurements in thunderclouds give a maximum value about an order of magnitude less than the critical electric field $E_k \approx 30$ kV/cm of conventional air breakdown [2]. That created a long-standing mystery about the origin of lightning. Note that all of the electric field values in this Letter are related to normal atmoshperic pressure.

The important role of hydrometeors (HM)—water droplets or icelets charged and polarized in the thundercloud electric field—has been discussed. Laboratory studies and numerical calculations confirmed the possibility of a streamer discharge formation at HM in an electric field much lower than E_k [3].

Another possibility is related to runaway breakdown (RB), an avalanche of runaway electrons generated in the thundercloud electric field about an order of magnitude lower than E_k [4]. Simultaneously, a very large number of low-energy electrons are produced due to the cascade ionization. Runaway breakdown initiated in a thundercloud by an extensive atmospheric shower (RB-EAS) was supposed to serve for the lightning initiation [5]. In Ref. [6] RB-EASs were identified by the presence of the first strong radio pulse observed during lightning events, but its role in the lightning initiation process remained unclear [7,8]. The role and the nature of the whole observed series of radio pulses were not discussed.

The electric field values measured in thunderclouds are sometimes close to and even higher than those needed for RB. But the data analysis showed that not only high values of the electric field but also some additional factors could be necessary for lightning initiation [2].

The major issue of lightning initiation in a thundercloud is the electric charge accumulation process, which allows the creation of the current of the lightning leader. The charge in the clouds is set at HM and distributed in a wide kilometer-scale region. The conductivity in the cloud is low, less than in normal air [1]. To initiate lightning, the charge must be reset from the HM to free ions and the conductivity should be amplified exceedingly. To reach the characteristic leader time scale (around 10 ms), conductivity growth up to 4–5 orders of magnitude in comparison with normal air is needed.

In this Letter, the results of radio emission measurements during the lightning initiation stage are presented. The emission consists of a long series of radio pulses. A detailed analysis of the pulse structure shows that the radio pulses are generated by the pulsed discharges in thunderclouds, which are a specific type of electric discharges in air, quite different from conventional streamers and leaders. We explain the pulse shape and scale length as determined by the RB-EAS discharge [9]. The pulse current amplitude is due to the synchronized multiple HM discharges stimulated by low-energy electrons generated in the RB process.

The specific pulse discharges generated by runaway breakdown in a thundercloud serve for the lightning initiation process.

Results of observations.—The initial stage of a lightning discharge lasts 10–100 ms [10]. To study the structure of lightning radio emission, a radio interferometer with time resolution of 16 ns and wide bandwidth 0.1–30 MHz was designed and constructed [6]. Nearly 3800 lightning events have been recorded in Russia (near Nizhniy Novgorod, 56°19′37″N, 44°00′27″E) and in Kazakhstan (Tien-Shan Mountain Station, 43°15′0″N, 76°54′0″E). The detailed time structure of radio emission during lightning was studied.

We present the results of high frequency radio emission measurements for a rather distant one-stroke negative cloud-to-ground lightning observed on August 6, 2008 at

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12:05:47 local summer time. It is known that the horizontal extent of the lightning active region can reach several kilometers. A rather distant lightning was chosen to diminish the possible influence of range variations on the observed radio emission intensity. The distance to the particular discharge was estimated as 30 km.

The temporal behavior of the registered lightning radio emission is shown in Fig. 1. The abrupt beginning of the radio emission is evident. As was shown previously [11,12], the emission consists of a series of short bipolar pulses. Two stretched out 1 ms scans of radio emission are presented, clearly showing its pulse structure. The pulses are bipolar, which reflects the fact that the parental current pulses are unipolar and have the same negative polarity throughout the series. The electric current in all the pulses is directed mainly upward, which means that free electrons forming the current move downward under the action of the thundercloud electric field.

We analyze the pulse component of lightning radio emission. We consider pulses with sufficiently large amplitude to prevent occasional mixing with the low-amplitude pulses of the noise background. In terms of the input voltage, we chose pulses with amplitudes exceeding 20 mV, while the rms background amplitude is about 2 mV with a standard deviation of the same order. In the whole discharge, we found 8373 such pulses. We chose the first 2100 pulses for the data processing in the study of the initial stage.

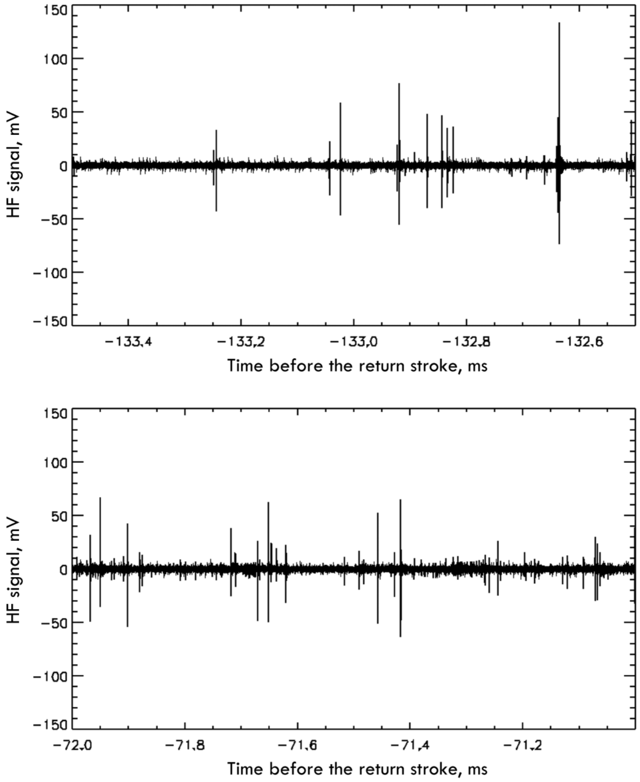

FIG. 1. Short (1 ms) scans of the radio emission at the initial stage of the discharge. Top: Beginning of discharge radio emission: the first pulse occurs 133.25 ms before the return stroke. Bottom: Intermediate scan.

Distribution of time intervals between pulses is shown in Fig. 2. During the initial stage of the discharge, it is quite close to the logarithmic distribution, which indicates that the pulses in the series are random and independent. The average time interval is about 20–40 μs.

Distribution of the pulse growth time for the initial part of the discharge is shown in Fig. 3. The growth time of the main part of the pulses is between 40 and 150 ns. The pulses with growth time less than 30 ns are absent. Radio emission is strongest when the speed of the ionization wave that generates free electrons is close to the speed light. Therefore, the size of the radio emitting region is about 20–50 m.

The pulses are bipolar. Distribution of time intervals between the peaks of different polarity is shown in Fig. 4. The average time interval is 100 ns, and hence the characteristic width scale of the emitting region is 30 m. The pulse full width is about 0.3–0.4 μs. The pulses have random amplitude. The pulse amplitude distribution decreases exponentially with the amplitude [13].

Discussion.—Producing the observed form of the pulse discharge in an electric field much lower than E_k requires the RB process—an avalanche of runaway electrons stimulated by a cosmic ray shower. This is confirmed by the theory of pulse discharge in an atmosphere, initiated in the thundercloud electric field by an extensive atmospheric shower [5]. Calculations show that the electric field of the pulse has a bipolar form. The form is quite similar to the observed one [9,14] (Fig. 4, inset). The pulse amplitude is proportional to the number of secondary electrons and therefore to the energy of the primary cosmic ray particle that generates the shower. To obtain the observed pulse amplitude, the EAS should be very intensive, i.e., generated by the primary cosmic ray particle having the energy 10^{17} eV or even higher. That is a rare event. It occurs only once a day on the characteristic thundercloud scale (10 km^2). On the contrary, the observed pulse rate in a thundercloud is 20–50 per ms. It corresponds to the shower

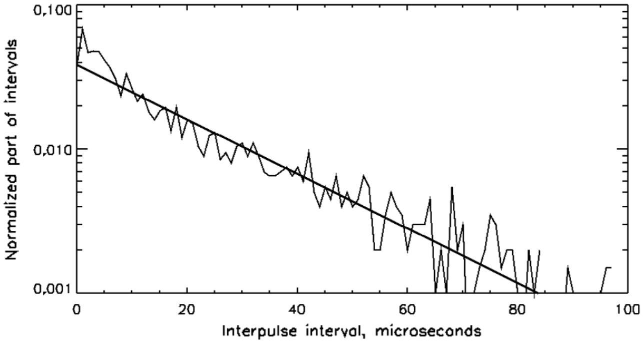

FIG. 2. Interpulse interval distribution at the initial stage of discharge. Solid line shows the best logarithmic fit to the data.

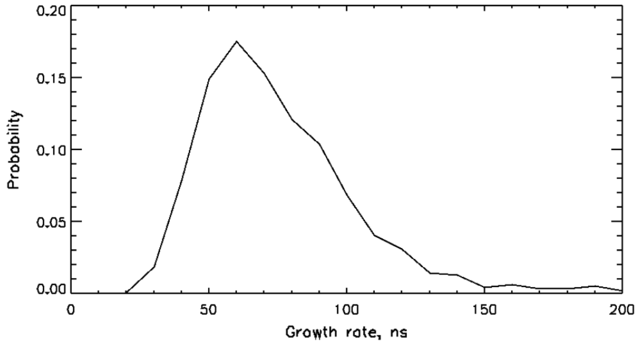

FIG. 3. Pulse growth time distribution derived from the shape of pulses at the initial stage of the discharge.

generated by a primary cosmic ray particle having the energy 10^{11}–10^{12} eV.

This makes a fundamental contradiction. The shape and the rate of the observed radio pulses agree well with the RB-EAS process in the atmosphere, but the pulse amplitude is 5–6 orders of magnitude higher.

The following solution of the problem is proposed. The runaway breakdown should be considered not in pure air but in a more complex medium—in a thundercloud that contains a large number of electrically charged hydrometeors. HM charging and polarization is correlated with the growth of the ambient electric field. The electric field accelerating electrons downward in the thundercloud usually reaches the maximum value in the region between the main negative and lower positive charge (heights 5–6 km [1,10,15,16]). As the field becomes equal to or greater than the RB critical value $E_{\mathrm{RB}} \approx 2.8$ kV/cm, an avalanche of runaway electrons is generated and, with them, a very large number of thermal electrons and ions (see Fig. 5). We estimate it. The air shower generated by a cosmic ray particle having energy 10^{12} eV produces 10^3 secondary electrons with the average energy 30 MeV. About 10% of them form a central beam and initiate a RB avalanche in a sufficiently strong thundercloud electric field. After 10–12 avalanche exponential multiplications, the number density of low-energy electrons in the discharge region (50 m along and 30 m across) reaches 10^2 cm^{-3}. This means

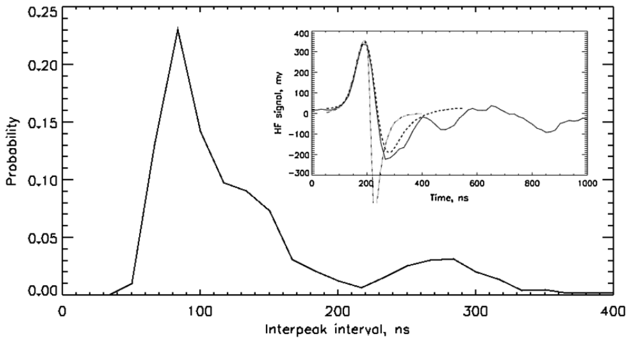

FIG. 4. Distribution of time intervals between different-polarity peaks for bipolar pulses at the initial stage of the discharge. The interval between peaks is related to the horizontal scale of the source region. Inset: Comparison of the observed form of characteristic radio pulse (solid curve) with the theoretical predictions [9] (dash-dotted curve) and [14] (dashed curve). The observed and predicted pulse amplitudes are normalized to the maximum value.

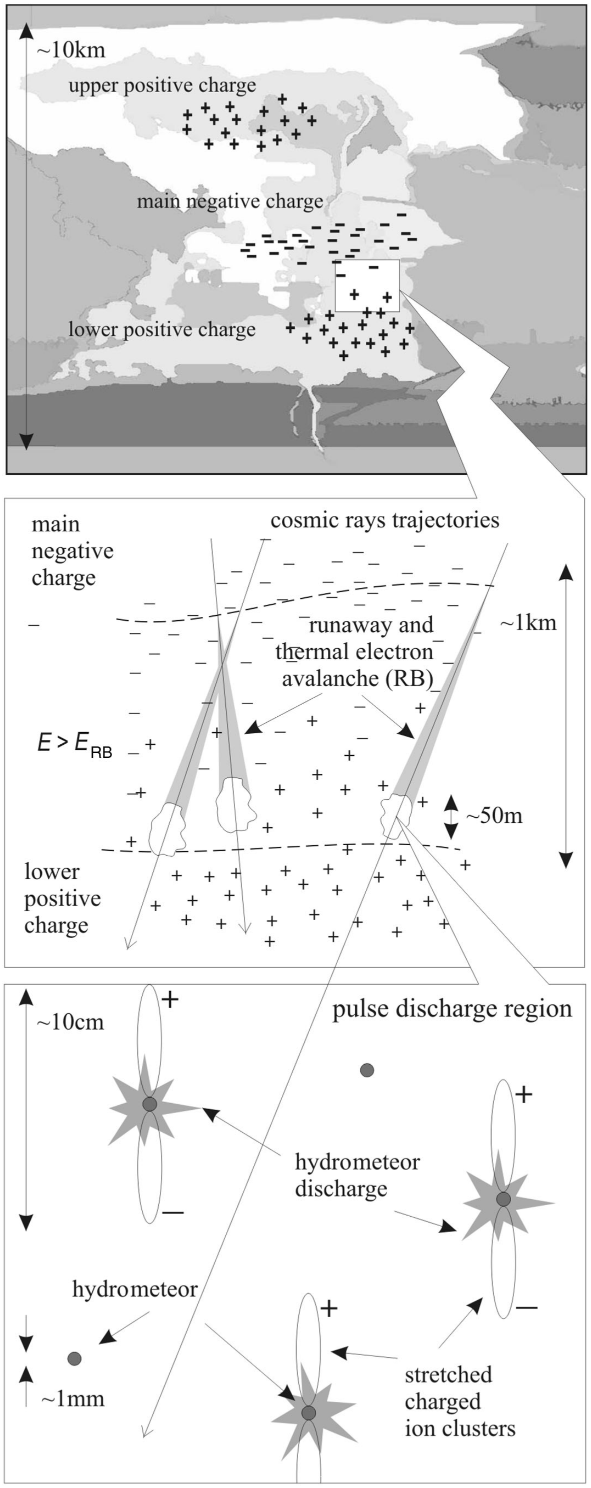

FIG. 5. Illustration of the pulse discharge region formation.

that free electrons appear in close vicinity of each HM (the HM dimension is $D = 1\text{–}2$ mm [16]). These low-energy particles initiate a large number of discharges in air near HM simultaneously. Thus, runaway breakdown can initiate and synchronize multiple HM discharges in a thundercloud. This leads to a strong amplification of the pulse discharge electric current.

We estimate the current. The electric field near the hydrometeor could be amplified strongly due to the HM electric charging and polarization in the ambient electric field. It can reach values of $E_m \approx (2\text{–}5) \times E_k$, where E_k is the critical field of air breakdown [3,17]. Note that such a high value of the field near HM cannot exist for a long time as the free electrons generated in atmosphere by cosmic rays will initiate an electric discharge. The cosmic ray ionization rate at the thundercloud height is about $10\ \mathrm{cm}^{-3}\,\mathrm{s}^{-1}$ [18]. Because of HM millimeter scale the discharge will have a delay of about 10 s. Therefore, the electric field due to HM polarization can grow higher than E_k within a few seconds, up to the considered high values. That agrees well with the observed sharp growth of the electric field in a few seconds before a flash [2]. Note also that the growth of the ambient electric field up to 1–2 kV/cm can effectively accelerate the nonlinear process of icelet growth as follows from laboratory experiments [1]. The discharge initiated in air near HM in a high electric field by a free low-energy electron develops in $10\text{–}10^2$ ns. The maximal number of generated electron-ion pairs in the discharge near HM can be estimated as $n \approx W/\varepsilon \approx 4 \times 10^{12}$, where W is the electric field energy $W \approx E_m^2 D^3$ and $\varepsilon \approx 30$ eV is the energy spent to the electron-ion pair production. The HM number density measured directly in thunderclouds is about $10^2\ \mathrm{m}^{-3}$ [16]. The volume filled by the pulse discharge considered here is more than $10^4\ \mathrm{m}^3$. Hence, if a local air discharge occurred near the largest part of the HM, the full number of electron-ion pairs produced in the pulse discharge volume would be about $10^{18}\text{–}10^{19}$. Under the action of the ambient electric field the newborn electrons generate a current, its maximum value can reach 10^2 A. This agrees with the results of our observations: the maximum pulse current observed is about 100 A and the average current is around 10 A. The low-amplitude pulse discharges can also be generated not only by an EAS but by the solitary cosmic ray secondary electrons having the energy $10^7\text{–}10^9$ eV. We note that the electric current generated in the RB-EAS process without HM is much lower, about $10^{-2}\text{–}10^{-3}$A.

The observed characteristic decay time of the pulses is 10^2 ns. It is determined by electron-ion recombination and free electron attachment to air oxygen molecules and to HM. Note that, due to polarization of HM, the electric discharge develops effectively near it positive end. We supposed that the ambient electric field value being higher than E_{RB} remains less than the value needed for streamer generation ($E_s = 4.65\text{–}4.9$ kV/cm; see Ref. [3]). So, there is no additional source of electrons and a plasma cluster composed of both positive and negative ions is created near each discharged HM in a few microsecond time scale. The number of ions in the cluster initially decreases due to the ion recombination [19] and attachment to HM. But in a short time (less than 1 ms), the positive and negative components are separated under the action of the ambient electric field, thus forming two residual stretched charged clusters moving in opposite directions (Fig. 5). The number of positive and negative charges in the clusters could be different due to HM charging. Negative charges move mainly downward and positive, upward. This charge separation is probably manifested in the ground observations as a gradually diminishing electric field after a large number of pulses occur [12].

The large number (hundreds or thousands) of pulse discharges observed during the lightning initial stage lead to the formation of a wide region in the thundercloud with a sufficiently high fractal ion conductivity. The estimated number density of ions in the stretched clusters near the HM is not less than $10^7\text{–}10^8\ \mathrm{cm}^{-3}$, which gives the characteristic charge transport time scale about 10 ms. In that way, a charge drain system can be created, which allows the lightning leader to start.

Conclusion.—Our observations demonstrate that the radio emission during the initial stage of negative cloud-to-ground lightning consists of a long series of random and independent bipolar radio pulses. The radio pulses are generated by the pulse discharges in thunderclouds, which are a specific type of electrical discharge in air, quite different from conventional streamers and leaders. The pulse time dependence and length scale are determined by the RB-EAS discharge. The pulse current amplitude is due to the synchronized multiple HM discharges stimulated by low-energy electrons generated in the RB process.

The multiple pulse discharges serve for the lightning leader preconditioning.

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