Discharges Produced by Negatively Charged Aerosol Clouds in the Presence of a Moving Conducting Object

A. S. Aleshchenko[4], M. G. Andreev[1], N. A. Bogatov[2], A. Yu. Kostinsky[3,*], V. E. Kuznetsov[4],
L. M. Makal'sky[5], E. A. Mareev[2], V. A. Rakov[6], D. I. Sukharevsky[1], and V. S. Syssoev[1]

1. High-Voltage Research Center of the All-Russia Institute of Electrical Engineering,
Istra, Moscow region, Russia
2. Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia
3. National Research University Higher School of Economics, Moscow, Russia
4. National University of Science and Technology MISIS, Moscow, Russia
5. Power Engineering University of Moscow, Russia
6. University of Florida, Gainesville, Florida, USA

ABSTRACT: The possibility of modeling of altitude-triggered lightning (ATL) under laboratory conditions using charge initiation by a crossbow bolt, in the electric field of an artificial cloud of a negatively charged water aerosol, has been demonstrated for the first time. Over one hundred of such events have been registered. For each event, a high-speed camcorder recorded the dynamics of the upward positive leaders with streamer corona, followed by a return stroke and channel plasma decay. Integrated photos of the events have also been obtained. Simultaneously, we measured the current flowing through the bolt in the plasma channel. A similarity of the discharge initiated by the bolt in the electric field of an artificial cloud of charged aerosol to the altitude-triggered lightning in nature is discussed.

INTRODUCTION

The lightning discharges initiated by aircraft that are in the field of a thundercloud pose a serious risk to equipment [Rakov and Uman, 2003]. Such discharges are also of independent interest for studying the physics of lightning and thunder as a kind of altitude-triggered lightning [Lalande et al., 1988]. However, the study of this phenomenon in nature is difficult because of the extremely small number of events that can be recorded in the thunderstorm season and the high cost of field experiments. Therefore, the laboratory methods of research which model these phenomena with a high degree of similarity and greatly facilitate the study of the basic parameters of the process become important.

It is well known that the trigger lightning technique (in two versions, namely, classical triggering and altitude triggering) has allowed significant progress in addressing some of the key problems in the physics of lightning discharge, including the development of a mechanism of the M component, determination of characteristics of the opposite leader and the negative stepped leader, the generation of X-ray radiation in the vicinity of the leader, etc. However, a number of fundamental questions remain open, including those

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[*] Contact information: A. Yu. Kostinsky, National Research University Higher School of Economics, Moscow, Russia, Email: kostinsky@gmail.com.

related to the above problems, but primarily the issue about the mechanisms of initiation of discharges of different types, as well as the issue about the role of energetic particles in these processes. The issues about initiation of the positive ascending leaders with grounded and insulated bodies are of particular practical importance for lightning protection.

The method of modeling of lightning discharge processes in the laboratory using Marx generators (for solving problems in the theory and practice of lightning protection) is widely used by researchers. These studies also yield valuable information on physical processes in the development of a long-spark discharge and in some cases permit one to use the obtained data for understanding of the physics of lightning and lightning protection. However, serious questions remain about similarity of the processes in a long laboratory spark to the processes in the lightning.

Usually, the following scheme is used for testing the aircraft for lightning protection. A fixed model of the aircraft hangs on insulators between the electrodes of a high-voltage pulse generator, and the most damageable areas of the aircraft are examined. Despite the frequent use, this scheme is far from reality due to the lack of movement of the aircraft and significant differences in the breakdown conditions in a pulsed electric field of the electrode system in the laboratory setup compared with the breakdown in the electric field of a thundercloud where the charge is located on the hydrometeors and the discharge is most often initiated by the aircraft itself [Rakov and Uman, 2003; Lalande et al., 1988].

In this paper, we managed for the first time to get around these limitations of laboratory experiments and initiate discharges with high frequency by using flying isolated conducting bolts (bolt is a crossbow arrow) shot from a crossbow into a cloud of charged aerosol. We have measured the key parameters of the initiated discharges, which opens up the possibility for an extensive program of laboratory studies that simulate the lightning discharges initiated by aircraft and full-scale discharges of altitude-triggered lightning. This will make it possible to prepare new field experiments to fix the most difficult-to-measure parameters using the ATL technique.

DESCRIPTION OF THE EXPERIMENTAL SETUP

Long sparks more than one meter long and starting from a conducting object rising above the grounded plane in the field of an artificially created cloud of charged aerosol we obtained (with the participation of the authors of this paper) a long time ago [Vereshchagin et al., 1988; Anshilov et al., 1990]. In this work, we use a similar [Vereshchagin et al., 1988; Anshilov et al., 1990] scheme of the experimental facility for generating a charges aerosol cloud of negative polarity (Fig. 1). Outlet nozzle (2.3) of the charged-aerosol generator was located at the center of a flat metal screen of 2 m in diameter with rounded edges (3). The charged-aerosol generator consisted of two main parts, namely, steam generator (2.4) and charger (2.2). A steam-air jet from steam pipe (2.1) at a temperature of about 150 °C under a pressure of 0.2-0.6 MPa flew out at a velocity close to the speed of sound of the mixture (about 400-450 m/s from nozzle (2.3) with an aperture angle of 28°, forming an adiabatically extending submerged jet. This produced a cloud of charged aerosol (1). As a result of rapid cooling, the steam condensed into droplets of about 0.5 μm (as confirmed by measurements [Vereshchagin et al., 1988; Anshilov et al., 1990]). The ions charging the aerosol were formed in the corona discharge, between a thin pointed needle located in nozzle (2.3) and the nozzle. A DC voltage of 10-20 kV with negative polarity was fed to the needle from high-voltage source (2.2). The current of charge removal by the submerged jet

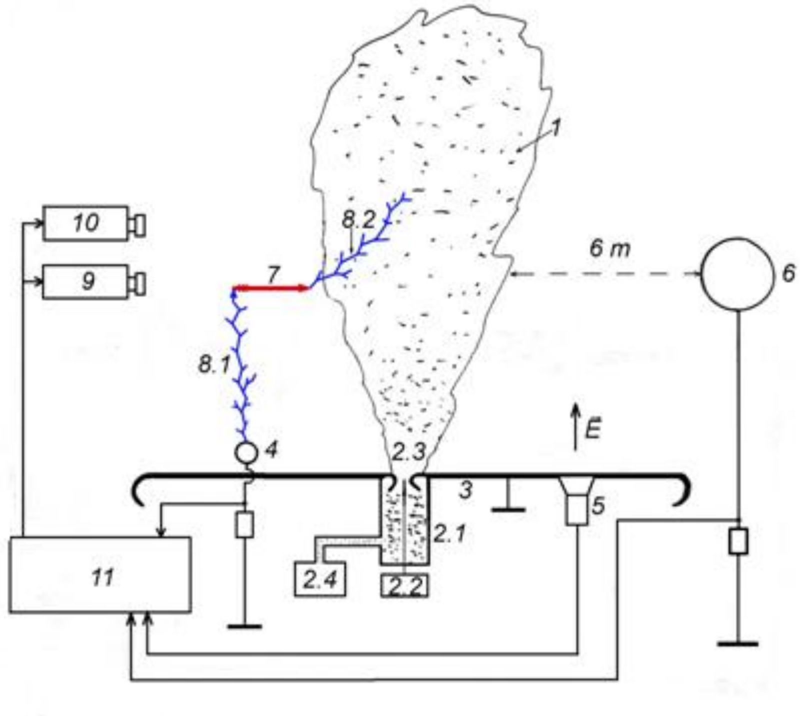

Fig. 1. Layout of the experiment. 1 – charged-aeriosol cloud; 2.1 – steam conduit; 2.2 – high-voltage source; 2.3 – nozzle and corona needle; 2.4 – steam generator; 3 – grounded metal screen; 4 – the receiving electrode in the form of a metal sphere; 5 – fluxmeter; 6 – insulated copper sphere of 50 sm in diameter for monitoring of the cloud field (charge); 7 – crossbow projectile; 8.1 – plasma channel of the ascending leader to the tail of the projectile; 8.2 – plasma channel of the ascending leader from the tip of the projectile; 9 – high-speed camcorder; 10 – camera; 11 – oscilloscope.

was in the range 60-150 μA. Long spark discharges arose spontaneously as a total charge of up to about 60 μC arose spontaneously in the aerosol cloud.

Conducting projectiles (aluminum or carbon crossbow projectile) (7) 0.58 m long, 8.8 mm in diameter, and 0.03 kg in weight were shot from a crossbow at a velocity of 75 m/s into the cloud of charged aerosol (1) 10-12 m away from the jet axis, at a height of 0.5-1.2 m from a flat grounded metal screen (3). In order to simulate the ATL, some of the projectiles had a 0.1 mm long copper wire attached to them or a 0.5-1 m long conducting metal-dielectric strip. The metal-dielectric strip was attached to visualize the projectile trajectory. To measure the current passing through the flying projectile, we used a shunt with 1 Ω resistance, the signal from which was fed to Tektronix DPO (11), a digital oscilloscope with 500 MHz band. The shunt was connected to the receiving electrode in the form of a metal sphere 5 cm in diameter (4), the uppermost point of which was 10 cm above the flat screen. The sphere was 0.8 m away from the screen center. As the current in the shunt exceeded a given value, an oscilloscope was started, which, in turn, generated a pulse to run FASTCAM SA4 (9), a high-speed camcorder in the visible range. Color camcorder FASTCAM SA4 was operated during the measurements in the continuous "circulated" record mode at a rate of 225,000 frames per second (fps) and was stopped at the frame at which a synchronization pulse came to it from the oscilloscope during record. With this rate of record, each frame fixed the image on a part of the camera matrix having 128x64 pixels (128 vertical and 64 horizontal). Each frame had a shutter speed of 4.44 μs and followed the previous one end-to-end, without a time gap. For control of the dynamics of the total charge located on the aerosol cloud, we used an insulated copper sphere (6) 50 cm in diameter, which was connected through a 100 MΩ resistor to the oscilloscope. This allowed us to record the charge accumulation dynamics during the cloud charging and fast processes of the charge departure from the cloud. An overall picture of the charge was recorded using Canon (10), a color digital camera. The speed of flight of a projectile was measured using a high-speed camcorder.

RESULTS OF THE EXPERIMENTS

In these experiments, the aerosol cloud was charged up to 50-80 μC, at which long spark discharges spontaneously appeared. As measured by fluxmeter, the electric field generated by an aerosol cloud on the surface of the grounded screen at about 0.8 m from the jet axis was 4-5 kV/cm and weakly increased in the cloud direction. Positive streamer flash s and spark discharges spontaneously appeared from the surface of the sphere. Estimates show that the electric field of the cloud nowhere exceeded 10-11 kV/cm. This was also confirmed by the absence of the negative streamer corona on the side of the aerosol cloud towards the grounded surface since the motion of long negative streamer is maintained by a field of the mentioned values [Vereshchagin et al., 1988; Anshilov et al., 1990].

The projectile shot from a crossbow flew through an aerosol cloud at a velocity of 75 m/s almost in parallel to the plane at a height of 0.5-1 m over the sphere with a measuring ohmic shunt. On the average, in 20% of the cases of the projectile launching we managed to initiate the aerosol cloud – projectile – earth discharge, and in about 10% of the cases, a cloud – projectile – sphere discharge was initiated, which allowed us to measure the current of the initiated discharge. In most of other cases, we managed to record a flash from the projectile from the tip of the projectile as the projectile approached the cloud at a distance of less than one meter from the jet axis. In this case, the flash did not lead to a long-spark discharge. The uppermost point of the sphere, which was 0.1 m above the plane, in this configuration of electric fields plays the role of a high- altitude structure bellow the storm cloud under natural conditions. Simultaneously, we recorded the current from the sphere, the synchronous signal from an isolated sphere of 50 cm in diameter (showing the charge variation dynamics of the cloud) and obtained a video of the discharge development and an integrated photo. The viewing angle of the camcorder operated at a rate of 225,000 fps precluded recording simultaneously the motion of the leaders on both ends of the projectile. Therefore, a high-speed camcorder synchronized with the oscillogram of the current signal from the sphere recorded in one experiment the motion of the emerging leaders either from the tip of the projectile to the cloud or from the sphere to the tail of the projectile (followed by a return stroke and a plasma decay in both cases). The synchronization of the oscilloscope and the camcorder allowed us to recover the sequence of events on both ends of the projectile with 1-2 μs accuracy by simultaneous observation of the current and video frames. Simultaneously, we obtained an integrated photo of the whole discharge using a camera.

Integrated photos of the discharge (Figs. 2a and 2b) show all characteristic elements of the ATL recorded under natural conditionsx [Lalande et al., 1988; Laroche et al., 1991]. A plasma channel between the measuring sphere (or screen) overlaps the gap from the sphere to the end of the projectile (or to the wire if it is attached to the projectile). Then the current is closed on the conducting projectile, which is not seen on a night photo. A plasma channel is seen on the photo closer to the cloud. This channel leaves the

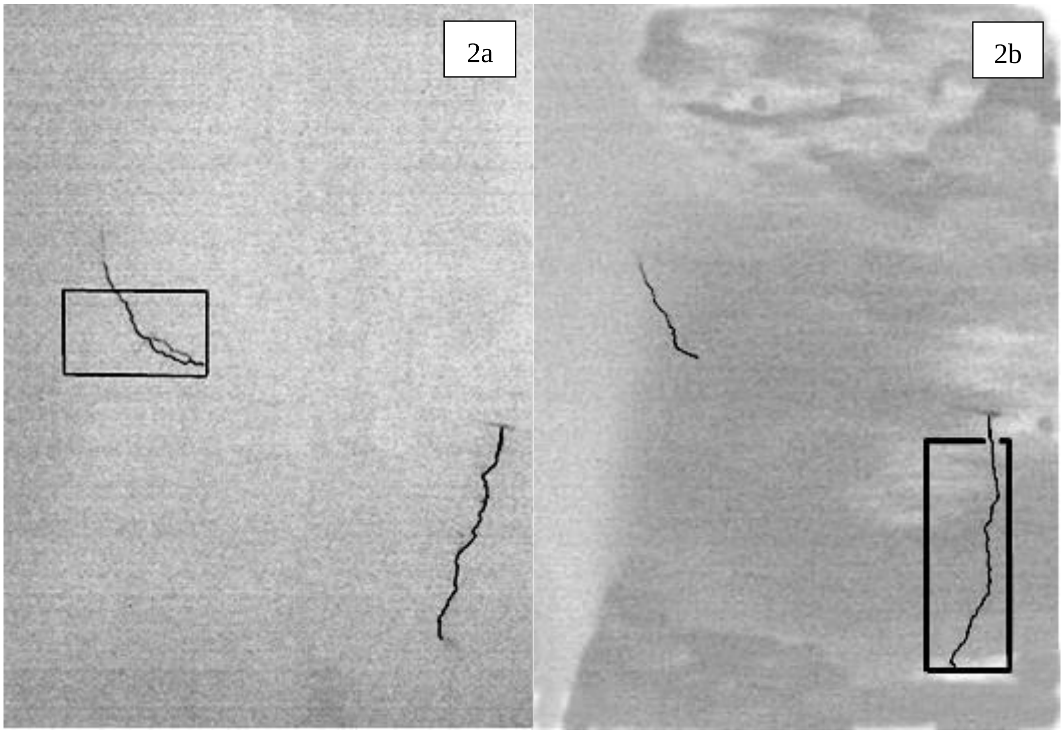

Fig. 2. Integrated photos of the discharges. 2a – camcorder is focused on the leader (discharge) ascending from the tip of the projectile (the rectangle shows the shoot area); 2b – camcorder is focused on the leader (discharge) ascending from the sphere to the tail of the projectile (the rectangle shows the shoot area, the projectile is not seen on the night photo, a visible boundary of the charged-aerosol cloud is on the left of the discharge ascending from the tip of the projectile).

tip of the projectile and comes into the aerosol cloud along an ascending trajectory at an increasing angle of 20-60° to the projectile. The projectile in these experiments (Fig. 2) flew at a distance of 0.5-0.6 m above the sphere.

We now describe the sequence of events based on the data obtained in the experiment. Probably, the initial events in the cloud – projectile – earth discharge are a streamer flash and the start of a positive leader from the tip of the projectile in the direction of the aerosol cloud. This hypothesis is favored by the fact that in cases where we could not initiate a long spark cloud – projectile – earth discharge, a cloud-directed flash from the tip of the projectile was observed in 90% of cases. During the initial flash, a positive leader is formed from the tip of the projectile. The motion of the leader ascending to the cloud is recorded by a high-speed camcorder, the frames from which are synchronized with the oscillogram of the current which flows at this time from the sphere through a shunt to the oscilloscope (Fig. 3). Almost simultaneously (no more than 1.5 μs after the leader startup from the tip of the projectile), another positive leader starts from the sphere towards the tail of the projectile (in some cases, several leader start from the plane near the sphere). Propagation of this leader is also recorded by a sequence of frames of the camcorder synchronized with the oscillogram of the current from the sphere (Fig. 4). Figures 3 and 4 belong to different experiments, but the sequence of events is reliably established due to the synchronization of the camcorder with the discharge current in both cases. With the available temporal resolution of the camcorder, it can be concluded that the leader from the tip of the arrow and the leader from the sphere move most of the time simultaneously with similar velocities until the backfire. After a

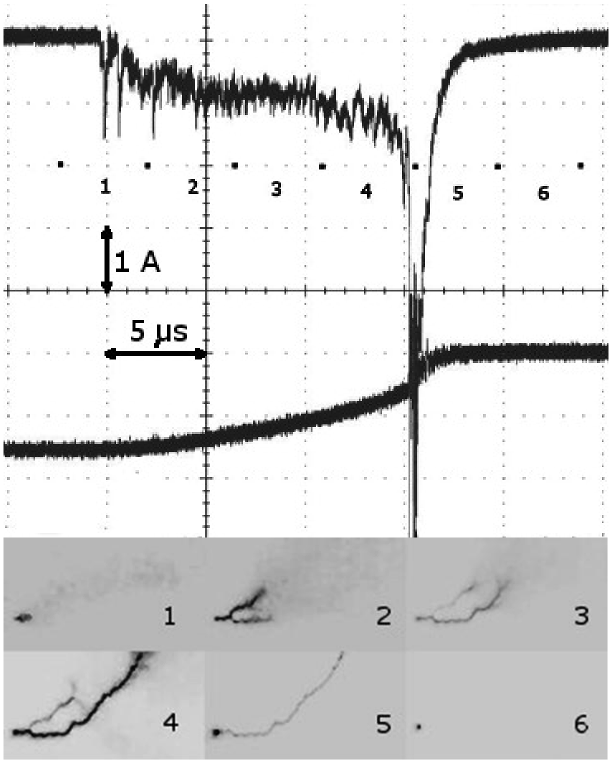

Fig. 3. Measuring the current through the shunt, and synchronized with the current images upward leader, ascending from the tip of the projectile to the cloud, fixed speed camera. Digits in the oscillogram correspond to successive shots taken with a shutter speed of 4.44 µs end-to-end, without a time gap. The upper curve records the current from the sphere through a shunt, the lower curve records the variation dynamics of the cloud charge. The event corresponds to the integrated photo in Fig. 2a showing the approximate field of view of the camcorder. Integral photo was shot at an angle of 150 degrees relative to the direction of shooting high-speed video camera.

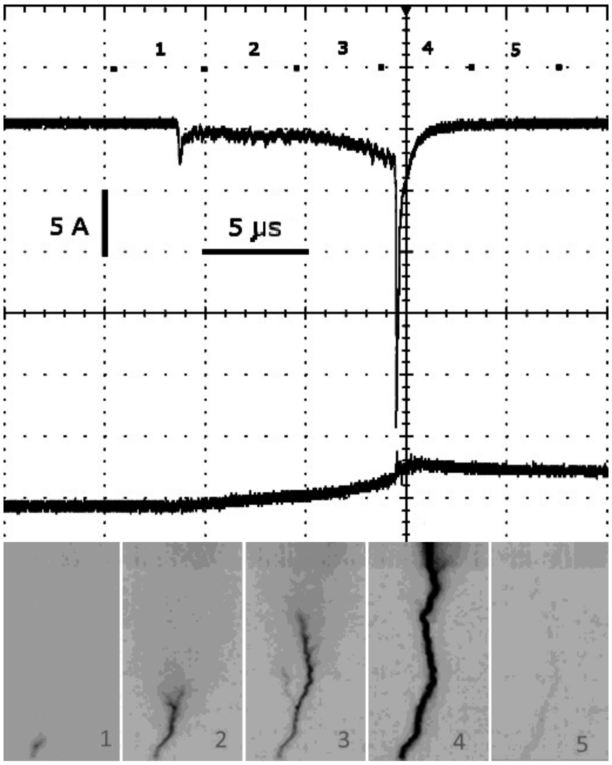

Fig. 4. Measurements of the current ascending from the sphere positive-leader to the tail of the projectile and the camcorder frames synchronized with it. Digits in the oscillogram correspond to successive shots taken with a shutter speed of 4.44 µs end-to-end, without a time gap. The upper curve records the current from the sphere through a shunt; the lower curve records the dynamics of the cloud charge variation. The event corresponds to the integrated photo in Fig. 2b showing the approximate field of view of the camcorder.

gap between the sphere and the tail of the projectile is closed by the plasma channel, a quasi-return stroke follows, in which the current increases rapidly for about 150 ns, the half-width time of the return stroke at the half-height of the current being about 400-500 ns. The quasi-return stroke also corresponds to an abrupt increase in glow. In cases where the cloud – projectile – earth discharge is initiated by the transit projectile, the quasi-return stroke is always observed. This makes the initiated discharge different from the spontaneous one which leads to a quasi-return stroke in no more than 5% of the cases.

The sort of propagation and the current parameters of a positive leader ascending from the sphere and starting spontaneously are very different from the same leader initiated y the projectile. Oscillograms of the current from the sphere (Fig. 4) and the synchronized frames recorded by a camcorder show that during the projectile transit over the sphere and initiation of the positive leader from the tip of the projectile, a positive leader starts from the sphere and moves almost perpendicularly ascendings for about 12 µs until the gap between the sphere and the projectile end is closed. After the first maximum of the current in the oscillogram (Fig. 4, frame 1), which records the moment at which the ascending leader from the sphere is started, the leader current slightly falls off and then rises until the gap between the sphere and the tail of the projectile is closed by the plasma channel, followed by a discharge phase corresponding to the return stroke in the lightning and a long spark. The current and the discharge glow increase abruptly (Fig. 4, frame 4). In the first three frames (Fig. 4, frames 1-3), besides the growing channel of a positive leader with the dying side branches, one can see a long streamer corona, which covers all the gap from the sphere to the projectile end, at least from the second frame (3.2.2). All this time the charge of an aerosol cloud decreases (as is shown by the lower curve in the oscillogram in Fig.4, which records an overall decrease in the field from an aerosol cloud). The charge decreases at the time of a quasi-return stroke especially rapidly. As a result of this process, a large part (up to 20-30%) of the total charge embedded into the cloud volume leaves the aerosol cloud. Restoration of the field to its previous values takes about 0.5-1 s. The discharge is followed by a plasma decay, which is seen in frame 5 and the next frame (not shown in Fig. 4). The glowing (obviously, hot) point at the tail of the projectile is visible in the next, more than ten frames after the plasma glow is over. Unfortunately, in none of the experiments, could we record the descending negative leader from the projectile tail meeting the ascending positive leader from the sphere. However, based only on the experiments presented above, it cannot be excluded that the descending negative streamer exists since the rate of record from a camcorder is too slow to examine the processes in a long spark (4.44 µs per frame).

When the projectile flew over the sphere at a height of one meter above the grounded plane (higher than in the first case (Figs. 3 and 4)), the sort of propagation of the leader ascending from the sphere changed. This is clearly seen in the current oscillogram (Fig. 5, the upper curve). The first phase of constant rise in the leader current, which lasted for 20 µs, is similar to the case of a low transit of the projectile over the sphere, but then the leader current reaches a steady-state value of 1.5 A. The DC phase continues as the leader propagates (for about 12 µs) until the quasi-return stroke is started. The lower curve in the oscillogram (Fig. 5) shows that again the charge from an aerosol cloud decreases all the time the charge from an aerosol cloud is in motion and fall off abruptly at the time of the quasi-return stroke.

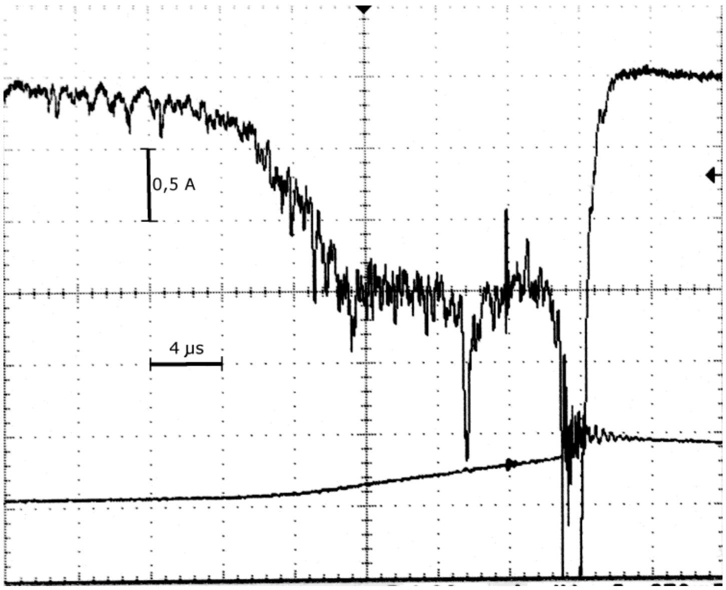

Fig. 5. Oscillogram of the discharge where the projectile flew at a height of about 1 m. The upper (jagged) curve records the current from the sphere through a shunt; the lower (smooth) curve records the dynamics of the cloud charge variation.

DISCUSSION OF THE EXPERIMENTAL RESULTS

The discharge between the aerosol cloud and the earth initiated by the flying projectile has been implemented many times under conditions of a laboratory experiment. The parameters of the positive leader ascending from the sphere and initiated by the projectile differ significantly from the parameters of the leader ascending from the sphere but started spontaneously (without the projectile initiation).

In the case of a low transit of the projectile (about 0.5 m above the sphere), the current, constant increase, and average velocity of the leader ($3\text{-}5\cdot10^4$ m/s) make the leader propagation mode similar to the final jump mode of a long spark.

In the case of a high transit of the projectile (1 m or more), the entire process before the quasi-return stroke becomes longer. The current oscillogram has two distinctly seen phases, namely, the phase of a constant rise and the phase of stabilization at a relatively high level. The current of the ascending positive leader equal to 1-1.5 A in the case of the projectile-initiated discharge through a shunt is a factor of 4 to 7 higher than the usual currents of the spontaneously ascending leader from the sphere into the charged-aerosol cloud without the projectile initiation [Andreev et al., 2008].

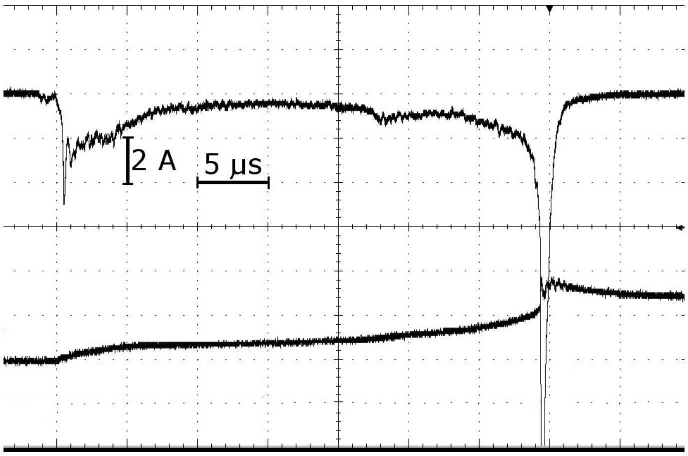

Fig. 6. The current of the positive leader ascending from the sphere without the projectile initiation. The upper curve records the current from the sphere through a shunt; the lower curve records the dynamics of the cloud charge variation.

Comparison between the process in which the leader ascending from the sphere is initiated by the transit projectile and the process in which the ascending leader is started spontaneously, i.e., without the projectile initiation, shows that there major differences in the leader phase after the initial maximum of the current, which occurs due to the leader initiation. It was mentioned above that the current of the projectile-initiated positive leader ascending from the sphere increases constantly after the initial maximum until the quasi-return stroke. If the sphere-projectile gap is more than one meter, then the leader current increases in the first phase and then reaches a steady-state value before the quasi-return stroke. In both cases, this behavior of the leader is very different from the current of the leader spontaneously ascending from the sphere (without the projectile initiation) when after the first maximum the current steps down to 0.25-0.5 A and stays at this level with small maxima until the quasi-return stroke phase, as is seen from the oscillogram in Fig. 6 (in this case, is double stroke follows). It is also important that the current of the projectile-initiated positive leader ascending from the sphere is much greater than the current of the spontaneous (non-initiated) leader ascending from the sphere to the cloud. This difference in the behavior of the spontaneous positive leader ascending from the sphere and the positive leader initiated by the projectile enhances the hypothesis that in the initiated discharge, the positive leader starts earlier from the tip of the projectile, thereby initiating the ascending positive leader from the sphere. In this case, through the positive leader extended from the tip of the projectile and its positive corona closing on the cloud, as well as through the projectile itself, a positive current begins to flow, generating necessarily the current of the negative streamers (and possibly the current of the negative leader) on the opposite, tail side of the projectile, which propagate in the direction of the positive leader, and the streamers started from the sphere. The streamer area of the positive leader ascending from the sphere interacts with the negative streamers started from the tail of the projectile till the entire gap between the sphere and the projectile end is covered by the leader current. This process precludes the accumulation of the positive space charge before the head of the positive leader ascending from the sphere. Thus, the current of the positive leader ascending from the sphere closes on the aerosol cloud through the streamer corona towards the projectile, as well as on the projectile and the positive leader ascending from the tip of the projectile. Probably, this is the reason why the manner in which the current of the projectile-initiated positive leader ascending from the sphere is similar to the final jump of a long spark, during which the streamer corona of the positive leader begins to interact with the opposite electrode and the space charge before the leader head does not stay in the gap, which makes the current rise all the time before the quasi-return stroke.

As was mentioned above, we have not managed for now to record with a high-speed camcorder the downward negative leader from the projectile tail that meets the positive leader ascending from the sphere. Probably, the gap from the sphere to the tail of the projectile is too small and/or the temporal resolution of the camcorder is not sufficient for detection of the descending negative leader. The possible existence of the negative descending leader is favored by the fact that all the static photos and video frames show a significant enhancement of the plasma channel glow brightness at a distance of about 10 cm from the projectile tail (the possible point where the leaders or streamers meet). However, it is not excluded that in the case of a low transit of the projectile over the plane the negative descending leader has no time to form and we are dealing with a case similar to a short isolated gap on a Kevlar cable for the ATL under natural conditions where the downward negative leader was not recorded or its sizes were smaller than the time resolution of the video [Rakov and Uman, 2003; Saba et al., 2005]. The enhancement of the plasma channel glow at a distance of 10 cm from the tail of the projectile can also be explained by a contact between the positive and the negative streamer coronas.

Another interesting result of this work is demonstration of the positive leader initiated from the tip of the projectile (followed by a discharge) by a body flying with a relatively low velocity (no more than 75 m/s) in an external electric field of the order of 5 kV/cm (much greater than in field experiments). Usually, in field experiments the minimum speed of the rocket initiating the ATL should reach 200 m/s [Rakov and Uman, 2003; Lalande et al., 1988; Saba et al., 2005]. Rationale for that the minimum required speed of the rocket is about 200 m/s is based on the fact that the ions formed in the streamer flash s from the head of the rocket decrease by their space charge the field at the head of the missile so that it becomes less than that required for the start of the leader. However, it is seen that in this case the speed of the projectile initiating the discharge from an aerosol cloud is two and a half times smaller than the optimal speed for triggered lightning in nature. This fact might also be explained by the absence of the accumulation of a space charge before the leader head.

The further experiments will aim at studying in more detail the charge dynamics to find the time difference between the start of the positive leader from the sphere to the tail of the projectile in direct experiments. In the experiments with projectile-initiated discharge, we will also increase significantly the distance from the flying projectile to the plane for a possible record of the descending negative leader emerging, if it does, from the end of the projectile.

CONCLUSIONS

1. In this paper, it has been demonstrated for the first time that the altitude-triggered lightning from a crossbow projectile flying in the electric field of an artificial cloud of the charged water aerosol can be physically modeled under laboratory conditions.
2. It is shown that the positive leader emerging from the tip of the projectile and the positive leader ascending from the sphere to the tail of the projectile start simultaneously with an accuracy of up to 1.5 μs and move with similar velocities until the return stroke.
3. The current of the positive leader ascending from the sphere, if it is initiated by the projectile, increases most of the time, as the final jump of a long spark, exceeding by a factor of 4 to 7 the current of the spontaneous ascending leader occurring without the projectile initiation.
4. A return stroke is always observed if the cloud – projectile – earth discharge is initiated by a transit projectile.
5. The discharge initiation by an extended conducting object in the field of the charged-aerosol cloud, which is about 5 kV/cm, was obtained with the initiating projectile (crossbow bolt) moving at a speed not exceeding 75 m/s, which is significantly lower than the values that were previously considered minimal for the discharge initiation in triggered lightning.

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