COMPARISON OF THE ELECTRIC FIELDS IN A BOLT OF LIGHTNING AND IN A SLIDING SPARK

E. A. Zobov and A. N. Sidorov

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Lightning discharge is a random and uncontrolled event, and the experimental data dealing with this event involves considerable difficulties. Numerous results have been obtained in laboratory studies of long sparks [1, 2], which are occasionally used to simulate lightning in tests conducted to determine the vulnerability of fuel systems and the electronic equipment of aircraft to the effect of atmospheric electricity [3]. Naturally, this effect on the equipment can be simulated by any discharge with an appropriate current; however, in these simulation tests, in order to determine the probability of a lightning strike [4, 5], the value of such tests is frequently doubtful [6], since both lightning and long sparks are distinguished from one another through many characteristics.

In our opinion, virtually the only form of discharge in which the breakdown process is close to that of lightning involves the formation of a staged leader, i.e., the sliding spark (SS). The reasons as to why these phenomena, incomparable as to scale, are subject approximately to identical quantitative relationships have, as yet, been inadequately studied. The development of a theory or of models of high-current lightning stages [7, 8] have been made difficult owing to the absence of the initial conditions under which the corresponding discharge channels are formed. The development of an experimental model of lightning, which is what the SS is in the breakdown stage, represents a useful approach for purposes of understanding the breakdown processes in lightning.

It is the purpose of the present study to compare the electric fields in SS and in lightning, generated by the developing leader process, as well as to compare, on this basis, the subsequent breakdown stages. The lightning data have been taken from the literature, while the SS investigations have primarily been carried out by the authors.

Each lightning pulse begins with a barely glowing preliminary discharge which has come to be known as the leader process [1, 2, 9, 10]. Most frequently this leader moves from the clouds to the ground in individual steps whose characteristic length is around 50 m. At the ends of each of these steps the leader is halted for about 50 μsec, and this is then followed by the subsequent step, for which reason it is frequently referred to as a stepped leader. After the discharge gap (DG), i.e., cloud-crown, has been closed, a so-called reverse shock (direct or reverse discharge) develops along the channel conduit formed from the ground to the clouds, forming, in effect, a brightly glowing spark channel. After some pause, a second (arrow-shaped) leader is propagated, as is the second reverse shock.

Existing stepped-leader theories provide no clear qualitative patterns for the processes under way. Many researchers ([10] and the literature cited) regard it as fact that such unobserved light processes as the pilot streamer which moves continuously at a velocity equal to the effective velocity of propagation for the stepped leader, the corona discharge from the apex of the leader, the radial corona current as a consequence of which the leader channel is surrounded by a coronal discharge shell which has a radius of several meters, as well as primary and secondary streamers, all of these processes precede the observed stepped leader of a bolt of lightning. It has been asserted in [11] that the space immediately in front of the head of the leader channel is rather densely filled with streamers, and that for their generation it is necessary that the field strength E in the vicinity of the head be no lower than $3 \cdot 10^4$ V/cm.

The streamer stage and the pulse corona are preceded by a stage that is associated with the propagation of breakdown waves which, apparently, are present in any electrical breakdown [12] and are observed under entirely different conditions [13]. The glowing front that moves at velocities of approximately 1/3 of the speed of light are found also in the

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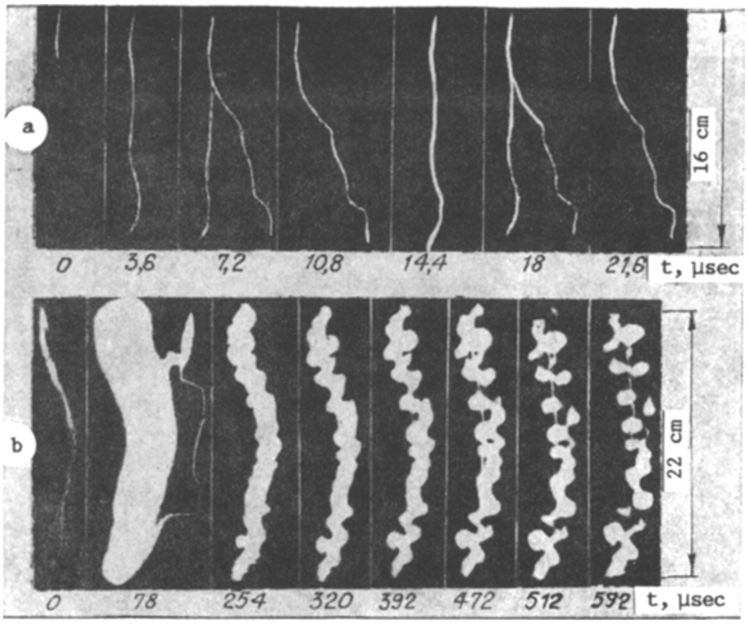

Fig. 1

pulse corona [9], in the discharges along the dielectric surface, in sparks, and in lightning [13].

The condition for the appearance of breakdown waves, i.e., the presence of large surges in voltages in the discharge gap. In short DG it is possible to observe several glowing fronts, direct and reverse. As a result of ionization and the excitation of the gas as these fronts move, the DG glows uniformly, as in a quasisteady glowing discharge [13].

Let us examine the basic processes in the breakdown of a SS. For our estimates we will take the following discharge conditions: A DG length of up to 100 cm, a voltage of U_0 = 80-90 kV for a high-voltage electrode of cosinusoidal shape, a thickness d = 0.1 cm for the dielectric between the high-voltage electrode and the conductor positioned beneath the dielectric layer (this conductor is referred to as the initiator). The dielectric material is polyethylene terephthalate with a dielectric permittivity of ε = 3-3.2. The experimental techniques and the method of controlling the SS have been covered in greater detail in [14].

In comparison with the long laboratory spark and with lightning, SS exhibits two fundamental differences: a different electric-field geometry, since there appears a normal to the surface of the dielectric that is a component of the field between the high-voltage electrode (or moving streamer) and the initiator, and the surface capacitance, given this electric-field geometry, which arises between the plasma formed at the surface of the dielectric and the initiator. The SS breakdown process depends to a considerable extent on the processes of discharge and recharging of this capacitance.

A unified terminology to identify the phases and stages of breakdown has not yet been established. The process of the propagation of the breakdown front in lightning, with a characteristic stage length of 10-50 m, is referred to as the stepped or staged leader. In an analogous process within the SS the characteristic stage length is 10-20 cm. The leader processes referred to in the literature as that process of stagewise increment in the length of the breakdown channel in comparatively short DG, where it is impossible to form a staged leader with an average length of 50 m. In the SS, the characteristic increment in the length of the breakdown channel in this case is 1-2 cm. For purposes of coordination with the terminology adopted in the literature, this breakdown channel will also be referred to by us as the leader. The term staged or stepped leader is reserved for the process with a stage length that is larger by an order of magnitude. In no way can this terminology be regarded as totally appropriate.

The SS begins from the stage of diffuse glow in the surface of the dielectric. This glow is probably associated with two processes: the propagation of breakdown waves [13]

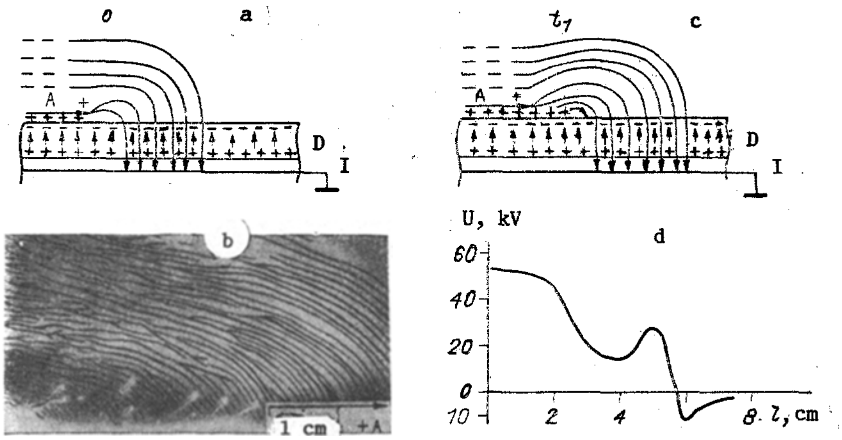

Fig. 2

and the polarization of the dielectric. The fact of the actual breakdown or nonbreakdown of the DG is determined by the propagation of breakdown waves over the entire length of the gap. When comparing motion-picture frames of a completed and incompleted SS (Fig. 1) we might note that they differ from one another from the very beginning. If in the case of the incomplete SS (Fig. 1a) the visible processes are limited by the motion of the leader and its subsequent heating, then in the case of the completed SS (Fig. 1b) the visible process begins from the diffuse luminescence of the discharge trajectory over which the streamers develop. This difference can be explained by the passage of the breakdown wave over the entire length of the DG, a result of which is the passage of an initial through current over the discharge trajectory being formed. Correspondingly, the changes for the formation of the streamer and leader discharge stages in the incomplete and completed SS must also change, as must the conditions for the propagation of the streamers at the breakdown front and in the radial direction.

The diffuse glow of the dielectric surface, moreover, can be generated by its polarization in strong electric fields [15]. The connected discharges which arise in this case at the surface have a significant effect on the distribution of the electric fields through the length of the DG. The maximum magnitude of dielectric-surface discharge σ can be estimated if we take into consideration that the thin-film dielectric which we have used, polyethylene terephthalate in particular, exhibits, in the electric field, an electret effect [16] of $\sigma = 100\varepsilon_0[200 + (3\varepsilon/d)^{1/2}]^2$ K/m², where $\varepsilon_0 = 8.85\cdot10^{-12}$ F/m, $\varepsilon = 3$. For a dielectric with $d = 0.1$ cm, $\sigma = 7.4\cdot10^{-9}$ K/cm². However, the maximum magnitude of the electret discharge is limited by the breakdown strength of the air and it cannot exceed $\sigma = \varepsilon\varepsilon_0 U_{br} = 2.65\cdot10^{-9}$ K/cm² ($\varepsilon = 1$, $U_{br} = 30$ kV/cm). If the electret field at any point in space exceeds U_{br}, breakdown occurs and the electret charge diminishes. The breakdown will continue until the discharge of the electret drops below $2.65\cdot10^{-9}$ K/cm². These partial breakdowns and the related initial current may be perceived as diffuse glow, not registered by the SFR-2M photographic recorder, but which can be recorded by other means [17, 18]. The estimate of σ for materials exhibiting no electret effect changes little; however, the time in which this connected discharge exists may prove to be significantly lower.

Thus, the boundary separating the gas from the dielectric as a result of the breakdown waves and the polarization of the dielectric at the breakdown front in the SS is given an initial conductivity. For breakdown in the air we need a longitudinal $E = 30$ kV/cm; however, since the boundary of separation between the gas and the dielectric is already in a state of shock ionization, this number can be reduced approximately by a third, depending on the thickness of the dielectric. By virtue of the same reason, the voltage for the appearance of the SS where $d = 0.1$ cm amounts to 18-20 kV.

Since the electric field is established in a part of the DG prior to the passage of the breakdown wave, the wave somehow acts as a starting mechanism for the onset of the breakdown processes on the surface of the dielectric, as a consequence of polarization. The initial conductivity is insignificant and in long DG cannot ensure the development of breakdown. However, even the slightest increase in the DG, such as, for example, the application of current control lines separated from one another through a distance of 0.5 cm, predetermines the trajectory of the discharge. The streamer formed in a channel with initial conductivity transfers the charge to the depth of the DG, and in this case the through current of the conductivity (or the current of the breakdown front) is directed toward offsetting the charge. The control line with a noticeable initial conductivity conversely, therefore, blocks the development of the breakdown along that line.

On approach to the opposite electrode the through conductivity current increases, the compensation of the leader charge is more complete, and the breakdown voltages also increase. This represents one of the reasons for the bends in the breakdown characteristics of the SS [19]. Another possible reason is the formation of an approaching streamer from the grounded electrode. It is frequently observed in lightning [10], in SS with a DG length of about 1 m the approaching streamer will virtually coincide as to time with the instant of the breakdown and isolation of its formation therefore becomes more complex. The approaching streamer is formed in the through current conductivity channel and, apparently, exhibits an excess charge of the same sign as at the high-voltage electrode. The formation of this approaching streamer is enhanced by the presence of effective resistance or reactance in the circuit of the grounded electrode.

Thus, the polarization of the dielectric produces the initial conductivity and plays an important role in the distribution of the electric fields over the length of the DG. Figure 2 shows a longitudinal cross section of a part of the DG, with an attempt to take into consideration the electric fields of the polarized dielectric. Figure 2a shows a graphic interpretation of the distribution of the electric field at the instant of time t_0, the basis for which is provided by the automatic method of breakdown recording. In this case, the discharge occurs either directly on the emulsion of the film covering the dielectric, or the film is positioned perpendicular to or at an angle to the surface of the dielectric. Figure 2b shows the automatic RT-5 film recording device positioned perpendicular to the surface of the dielectric D along the control lines. At the instant of time t_0 the field between the initiator I and the positively charged leader A and the entire breakdown process is applied primarily to the gas medium, while the field in the dielectric is weakened by polarization. Electron cascades develop in the direction of the field, leaving a trace on the film to reveal the distribution of the field in a manner analogous to iron filings in a magnetic field. When $t_1 > t_0$, as a consequence of the processes of ionization and charge separatoin, the surface of the dielectric charged negatively by polarization finds the positive space charge left behind by the electron cascades. This process is interpreted as the charging of a capacitance whose specific magnitude $C_{sp} \simeq 3$ pF/cm^2, up to $E = 100$-200 kV/cm in the transverse direction and up to $E = 20$-30 kV/cm in the longitudinal direction. The length of such a unified capacitance along the breakdown front is 1-2 cm, and the time constant of the charge is $\sim 1 \cdot 10^{-8}$ sec. These parameters are limited by the power of the energy source, of which more will be said later on. The electric fields of a unified capacitance and the breakdown front are combined to intensify the field beyond the limits of the charged dielectric surface (the instant of time t_1, Fig. 2c). The approximate distribution of the potential along the length of the DG at the instant of time t_1, with consideration given to the polarization of the dielectric, is shown in Fig. 2d.

The process involved in the formation of the leader channel essentially involves a series of secondary breakdowns along the lines of the maximum gradient of the potential, along which these streamers develop in the gaseous medium above the surface of the dielectric, heating the leader channel. The automatic record shown in Fig. 3a was produced in the same manner as in Fig. 2b, but not at the breakdown front, but in the leader channel; the automatic record shown in Fig. 3b involves utilization of filters to shield against emission from the leader channel. The utilization of filters raises some doubt connected with the discharges in the air gaps, but in the radial direction from the leader it is possible to observe an analogous pattern (Fig. 3c). Since the surface of the dielectric is already positively charged, the leader channel is formed in the gaseous medium above the surface. Figure 3d shows a photographic scanning of the discharge channel, accomplished in the ultraviolet portion of the spectrum with the photographic recording aperture positioned perpendicular to the discharge axis. The recording spot along the length of the DG is the region at which the breakdown characteristic bends [19], i.e., the region of unstable staged leader formation. A cylindrical plasma shell [20] is formed on the linear portion of the breakdown characteristic. It should be noted that the concepts developed here pertain only to the linear portion of the breakdown characteristic of the SS [19], where the breakdown proceeds with formation of the staged leader. The plasma shell at the beginning of the high-current stage in the SS represents a semicircle with a diameter of

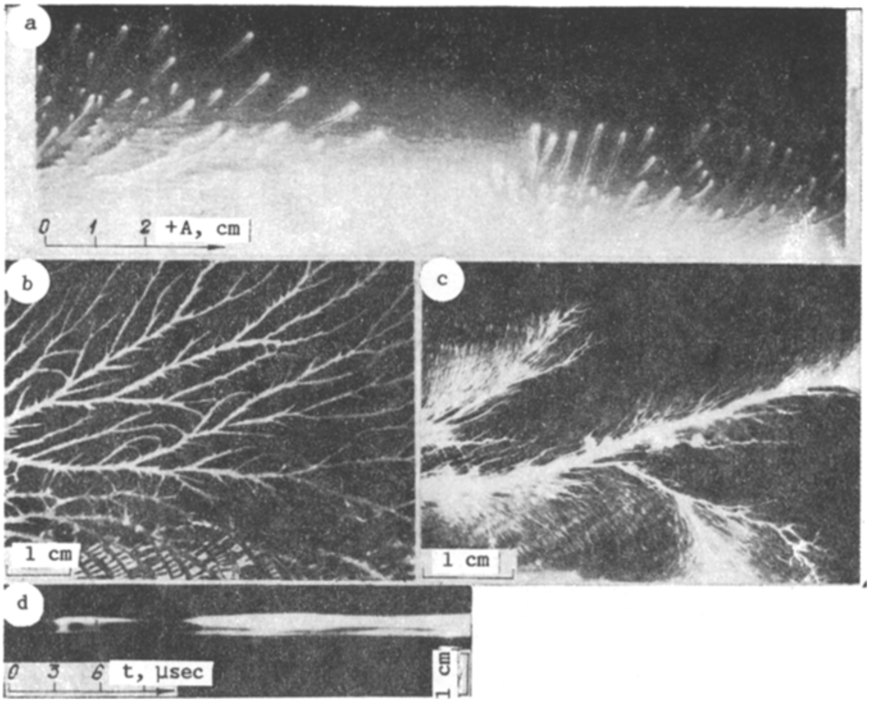

Fig. 3

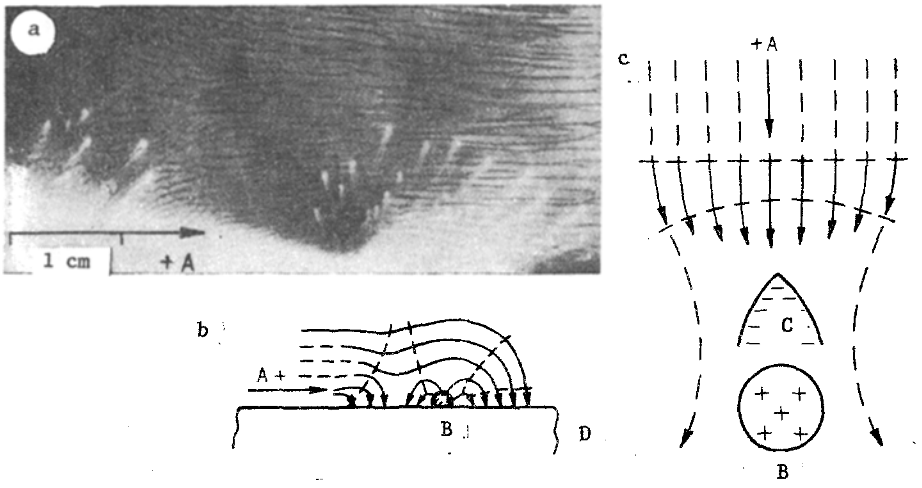

Fig. 4

3-10 mm, which is preserved to the end of the discharge as a consequence of the limited specific energy in the discharge [20]. In lightning the discharge channel prior to the onset of the high-current stage is a circle with a diameter of ~1 m [10].

The trajectory of the leader is determined by the current channel of initial conductivity, positioned on the surface of the dielectric. This channel will subsequently serve as the channel to offset the positive charge of the dielectric (Fig. 3d). However, the time within which this current channel of initial conductivity exists exceeds the time for the existence of the discharge current from the current source and it exists in the plasma disintegration stage (see Fig. 1b). It is clear that prior to the onset of the leader stage significant changes occur within the channel. Figure 4a shows self-recorded pictures of the breakdown front, corresponding approximately to the instant of time t_1 (see Fig. 2), and from these we can draw the conclusion that the positive space charge left behind by the electron cascade is localized within a small zone. The process of localization remains unclear at the present time. The recording of several simultaneously appearing luminescence zones allows us to make the assumption that the process of positive-charge localization begins in the fast wave stages of the breakdown in the region through which the breakdown wave is propagated.

The local positive charge alters the distribution of the electric field in the DG (Fig. 4b). The dashed lines show the directions of the gradient of the field, along which the streamers develop. These apparently lead to partial recombination of the local charge B, thanks to which it becomes possible to record the glow of this charge. Partial shielding of this charge by negative ions is also possible in air, and as a result the initial current channel retains an excess (relative to the quasineutral plasma) positive charge which gradually recombines. It is difficult to explain the prolonged existence of this current channel in any other way.

The self-recording method is in good agreement with the charge recording method which involves the use of electronic recording, such as that used to evaluate the streamer charge in a long laboratory spark [21, 22]. If the pattern of SS development is employed for the long spark and the lightning, then the distribution of electric fields for that segment of lightning with the leader A in the general direction of the field from the cloud to the ground at the instant of time corresponding to Fig. 4b for the SS, and in analogy with the latter, will have the appearance approximately of that shown in Fig. 4c. Primarily on the scale of these phenomena, the differences lie in the fact that the trajectory of the lightning discharge is situated in three-dimensional space, rather than on a plane. Moreover, zone C with a predominantly negative charge is formed not as a consequence of the polarization of the dielectric, as is the case in the SS, but as a consequence of the high (10^8 V) potential of the lightning, as a result of which the process of charge separation is more effective.

We can see from Fig. 4 that charge B generates the oppositely directed field of leader A, to which our attention was drawn by V. S. Komel'kov [23]. He also criticized the attempts by M. Tepler to transfer the pattern of the sliding discharge to the lightning. The oppositely directed field leads to two consequences: 1) a staged development of leader A, since an increase in the potential is needed to overcome it; 2) to a bending of the leader trajectory. This latter circumstance explains why the trajectory of both the lightning [10] and of the SS is always sinuous. This property of being sinuous in the SS increases as the leader approaches the opposite electrode, and the angle formed by the leader and the direction of breakdown development may reach 45°. The angle of leader deflection depends on E on the given segment of the DG. In Fig. 1a the right-hand channel which develops later on, i.e., with smaller E, is more sinuous than the left-hand channel. It is probable that the same quantitative relationships apply in lightning, provided that $U_0 \simeq U_{br}$.

A shell of low-mobility ions [23] is of considerable significance from the standpoint of stability in the leader channel. The question of streamer stability is examined in [2]. The ion shell is formed by streamers (see Fig. 3a) propagating in the radial direction. Thus, the breakdown process of the long DG must be regarded not only as a charging process and the breakdown of the longitudinal (linear) capacitance. Virtually the same processes occur in the radial direction. The process of charge separation is considerably more effective in the zone of maximum E, i.e., at the breakdown front. In the radial direction the process of breakdown is significantly retarded by the shell of low-mobility ions generated by this oppositely directed field. It is probable that this primary charge and the breakdown of the radial capacitances with an increase in the potential at the channel serve to explain the electromagnetic radiation of the lightning at frequencies from tens of kilohertz to hundreds of megahertz [10]. When we take into consideration the expenditures of energy on the breakdown processes we must also take into consideration the expenditures on the radial expansion of the channel, i.e., the charge of the radial capacitances. For the moment it is difficult to achieve any quantitative estimates, for the SS the energy required for the development of breakdown amounts to several Joules per meter of channel length, and at the same time the movement of the leader to the front of the breakdown is limited primarily by the strength of the power supply. With infinite power the pattern of SS discharge will be somewhat different, but such a regime is unattainable in lightning, owing to the great resistance of the discharge channel. Nevertheless, much SS work has been done in this regime, and drawing an analogy to lightning must be done with great care.

The diameter of the semicylindrical volume within which these secondary breakdown processes take place in the SS is ~15 cm. An experimental estimate was achieved with the self-recording method and is slightly undervalued. In lightning this diameter is probably greater by 2-3 orders of magnitude. The estimate for the spark length in [23] is clearly undervalued.

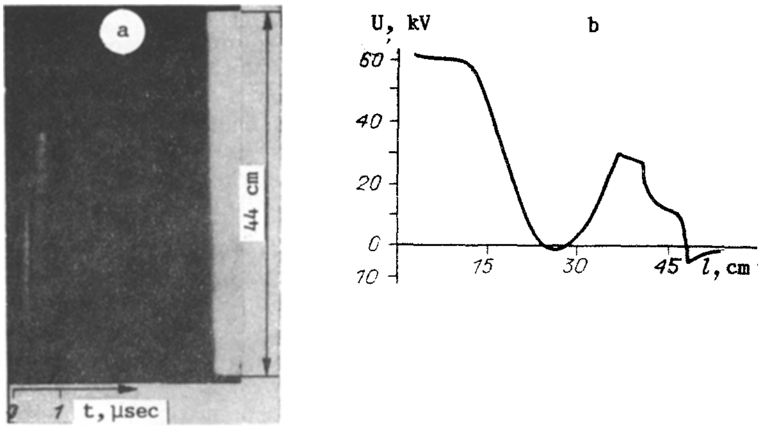

Fig. 5

The streamers forming the ion shell can be classified as primary and secondary. The fundamentally different models of streamer propagation discussed in the literature [24] (quasiwave displacement of the charged head, trailing no conducting channel; the formation of a channel of rather high conductivity) with the given approach, may prove to be entirely compatible, under the assumption that the streamers developing in the direction of the maximum potential gradient do not leave a conducting channel behind. This is a virtually unavoidable condition for the existence of a shell around the leader, as well as for a plane breakdown front at a distance of about 5 cm from the leader in the case of an SS (see Fig. 2b). The streamers developing after passage of the breakdown waves and forming the trajectory of the leader may exhibit sufficiently high conductivity.

In the case of negative polarity in the applied voltage the analysis of the processes taking place here becomes more complex and calls for a detailed examination. The complexity lies in the fact that the developing leader has an excess charge of one sign, with the lifetimes of the negative and positive excess charges different. For example, Fig. 1a shows the incomplete discharge of the SS in each half-period of the sign-changing voltage develops along one of the branches, which can be explained by the differences in the process of excess-charge compensation. In a qualitative analysis of the breakdown processes we can neglect these differences and for the sake of simplicity of comprehension we can retard the breakdown process which occurs with positive polarity in the applied voltage.

The process of forming a staged leader involves the following. The propagation of the breakdown wave along some segment of the DG and the initial conductivity current, on the trajectory of the leaders, produce a chain of local charges of the same sign as at the high-voltage electrodes (see Fig. 4a). Any further propagation of the breakdown front and in the radial processes leads to neutralization (recombination and shielding) of local charges. which leads to an increase in E in this segment of the DG. The growth in E will continue until the secondary breakdown of the DG segment takes place, this being the segment at which the chain of local charges was formed and where the leader processes of channel formation occurred. The breakdown will occur along the outside boundary of the cylindrical shell of the leader, since the axial channel (see Fig. 3d) exhibits high resistance. The ion shell blocks breakdown along any other trajectory and maintains the continuously active electric field of the breakdown front. The jump in potential in the secondary breakdown leads to a redistribution of the electric fields of the shell, and from the end of the staged leader it is , therefore, frequently possible to observe side branches. Figure 5a shows a photographic scan of the staged SS leader (see also Fig. 3a) and the approximate distribution of potential along the length of the DG prior to the onset of the second leader stage (Fig. 5b).

For determination of the long DG it was assumed in [25] that during the basic time for the development of the breakdown processes there is no transfer of current through the cathode surface, the current in the external circuit interpreted as a displacement current. Another determination of the long DG may be associated with the average E between electrodes, where it is possible in the long DG to neglect this energy, and the breakdown process of the long DG in this case occurring with formation of the staged leader, self-propagated with a linear breakdown characteristic. This was experimentally obtained in the SS [19], and with a great degree of assurance it can be assumed in lightning.

A long DG when $U_0 \approx U_{br}$ contains a breakdown segment in which E between the electrodes cannot be neglected (a short DG). It can be assumed that a substantial portion of the voltage is applied to the short DG. The long laboratory spark is modeled precisely by the short DG of lightning. The mechanisms of breakdown for long and short DG are different. The short DG breakdown process when $U_0 = U_{br}$ exhibits a comparatively prolonged channel heating phase where the heating is accomplished by a through current which is directed toward the offsetting of the excess charge of the leader and its shell, as a consequence of which the formation of the leader is made difficult. When $U_0 = 1.1\text{-}1.2U_{br}$ it may turn out that the time for the formation of the leader is smaller than the time for the heating (by the through current) of the breakdown channel. The discharge trajectory is then changed. This may serve to explain the damage due to lightning to the Ostankino TV Tower [26]: the lightning discharge does not damage the top of the tower, but rather its midsection. Analogously, in SS, in the case of a grounded rod electrode at the surface of the dielectric, the discharge trajectory ends at the midsection of the dielectric.

The length of the short DG in the SS is easily determined when $U_0 = U_{br}$ from the bend in the breakdown characteristic [19]. In the case of lightning, estimate of length is of no great significance because of the fundamental indeterminacy of the energy source parameters, nor is there great sense in estimating the length of the lightning bolt itself, i.e., the discharge develops both downward, toward the earth, as well as into the depth of the cloud [10]. Moreover, the condition $U_0 = U_{br}$ for lightning also makes little sense. At the same time, the practical significance of predicting a lightning strike in the design of lightning shields is very great. The SS may serve as a convenient model in this case. Some estimates as to the length of a short DG in lightning can be obtained on the basis of the orientational height of the lightning leader [27]. Apparently, this length is no less than 50 m.

For purposes of analyzing the breakdown processes which take place here, the transition from the long to the short DG represents some difficulty, since it is necessary to take into consideration both breakdown mechanisms, and their changing relationship. However, the overwhelming majority of studies involving the long laboratory spark in SS has been conducted under precisely such conditions. The experimental data in the region of transition from one breakdown mechanism to another turn out to be of low reliability, since they depend strongly on the conditions of the experiment. For example, even under identical conditions breakdown voltages in the areas where the breakdown characteristics bend [19] show scattering. Therefore, in order to study the breakdown of long DG the condition for the formation of the staged leader is essential, and an investigation into the structure of the SS discharge channel acquires primary significance to ascertain the mechanisms by which charges are localized in the DG.

The structure of the SS discharge channel is governed not only by the processes of closing the interelectrode distance by the open current channel. Of significant value is also the process of neutralizing the excess charge both in the leader channel, and in its shell, by the discharge processes of radial capacitances, and in the SS, by the discharge process of the surface capacitance. In lightning, probably, the most prolonged breakdown phase is the time between the closure of the DG and the high-current stage, on the average approximately 0.2 sec [10].

Thus, in the opinion of the authors, the SS is similar to lightning primarily in terms of the distribution of electric fields in the DG, which is what governs the similarity between the subsequent phases and breakdown stages, so that the SS can therefore serve as an experimental model of lightning in the breakdown stage. When we take into consideration the multiplicity of processes taking place in the breakdown of long DG, regardless of the number of quantitative estimates, the available experimental data are so far clearly inadequate.

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