

PHYSICS OF OUR DAY

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The mechanism of lightning attraction and the problem of lightning initiation by lasers

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Contents

Abstract. **Physical processes determining the ability of lightning to change its trajectory by choosing high constructions to strike are discussed. The leader mechanism of lightning propagation is explained. The criterion for a viable ascending (upward) leader to originate from a construction is established. The mechanism of the weak long-distance interaction between the ascending counter leader originating from a grounded construction and the descending (downward) leader from a cloud is analyzed. Current problems concerning lightning protection and lightning triggering by a laser spark are discussed, the latter being of special interest owing to a recent successful experiment along this line.**

1. Introduction

Experiments to initiate a high-voltage discharge employing a laser-produced plasma and to direct the discharge along the channel of a long laser spark [1 – 12] as well as the advent of lasers appropriate for this purpose have lent impetus to attempts to control lightning with lasers. Research in this field, which is being pursued in the USA, Japan, Canada, and Russia [13 –31], until recently did not go beyond the scope of laboratory investigations, though goal-seeking. In recent years, however, a start was made on natural experiments in Japan. As a result of repeated attempts, two events of successful lightning triggering with the aid of a laser plasma produced near the summit of a tall tower were recorded in 1997 [17, 18, 21]. These undeniably impressive results raised the expectations of many that the dawn of an era of laser techniques in lightning protection is near. Of prime importance in this connection is a clear understanding of the lightning processes and a statement of what is definitely known about the basic lightning mechanisms and what invites elucidation or comprehensive investigation. This will facilitate the search for efficient ways of controlling lightning by laser action in an effort to promote both research and lightning protection. At the same time, this will guard against excessively optimistic expectations, especially where engineering practice is involved.

Below we will consider some key physical mechanisms of the lightning process, discuss the potential of laser triggering of lightning and the requirements on the control laser spark, and highlight the currently topical problems of lightning and lightning protection physics that might be solved with the aid of lasers.

2. How the lightning leader works

Of prime interest for both lightning physics and practical lightning protection is descending lightning which originates in a cloud and propagates towards the ground. In consequence of the lightning – ground contact, the cloud or part of it (a charged cell) eventually discharge. Usually, a lightning flash consists of several sequential components spaced at tens of milliseconds, which travel through a common channel (and

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sometimes through different ones). The overall flash duration may be as long as a second; sometimes the 'component' flicker of a channel is discernible to the human eye. The first component, which makes its way through the unperturbed air, is similar in nature to the laboratory spark leader which breaks down the long gap, say, between a high-voltage rod and a grounded plane.

The electric field in this gap is strongly nonuniform. It focuses near the small-radius rod tip. The air in this region begins to ionize, which requires a field $E > E_{\mathrm{i}} \approx 30$ kV cm^{-1}, with the effect that under specific conditions there arises a thin plasma channel growing towards the plane. Despite the fact that the channel soon enters the domain of a very weak external field not nearly strong enough to ionize air, it continues to grow. Due to the still high conduction of the channel, the high electrode potential U is transferred without significant losses to the front end of the channel — the tip of small radius r. The tip is a source of a strong field $E_{\mathrm{m}} \sim U/r$, and the adjacent air ionizes. As soon as the new volume of air acquires a high conduction, the high potential is transferred to it, and this volume becomes the new tip. The length of the plasma channel therewith increases. The ionization process in the vicinity of the tip is inherently the propagation of an ionization wave. The structureless plasma channel thereby produced is referred to as a streamer (Fig. 1).

The theory of streamers is in an advanced stage of development and permits estimation of the main parameters in agreement with experiment [32]. In air, for a voltage of 10 – 1000 kV, the streamer travels at a speed $v_{\mathrm{s}} \sim 10^7 - 10^9$ cm s^{-1} and produces, immediately behind the tip, a plasma with an electron density up to 10^{14} cm^{-3} in a channel of radius $r \sim 0.1 - 1$ cm. But in cool air electrons attach themselves to oxygen molecules in 10^{-7} s and also recombine rapidly with the resultant complex O_4^+ ions. That is why a cool plasma channel does not live long and does not grow to very great lengths. As shown by experiments, in cool normal-density air, a positive (moving towards the cathode) streamer grows for as long as the average external field over its length exceeds $E_{\mathrm{cr}} \approx 4.5 - 5$ kV cm^{-1}, while $E_{\mathrm{cr}} \approx 10 - 12$ kV cm^{-1} for a negative streamer. Hence, for $U = 5$ MV — a nearly limiting voltage for laboratory experiments — a negative streamer can grow no longer than $U/E_{\mathrm{cr}} \approx 5$ m. Meanwhile, spark discharges longer than 100 m have been obtained at this voltage in the laboratory (to be more specific, at outdoor high-voltage test benches), whereas lightning ranges into kilometers for an average external field of only 100 – 200 V cm^{-1}.

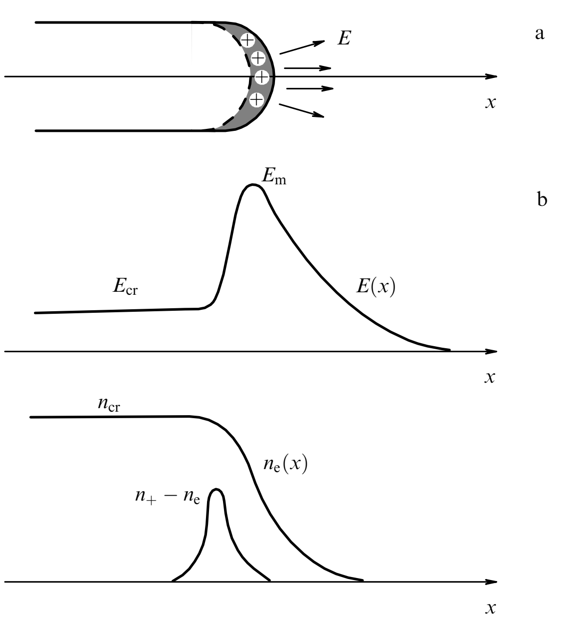

Figure 1. Schematic of the front part of a positive streamer (a), and qualitative distributions of the electron density n_{e}, the difference between the densities of positive ions and electrons, $n_+ - n_{\mathrm{e}}$, which determines the space charge density, and of the field E along the axis in the vicinity of the tip (b).

The only way to prevent an air plasma from decaying in so weak a field is to heat the gas to a high temperature. For $T \geqslant 5000$ K, the electron losses due to their attachment are virtually nonexistent, the electron recombination is moderated owing to the decay of complex ions, and the electron loss is compensated for by associative ionization involving O and N atoms, which does not require an electric field. But the radius of the channel which may be heated is sharply limited, for only a limited amount of energy can be expended for this purpose. As is well known, in charging a capacitor with capacitance C to a voltage U, an energy $CU^2/2$ dissipates, which is equal to the electric energy to be stored. About the same is the case with a growing long line with distributed parameters, typified by the channel [32]. The capacitance of a unit length of the channel of radius r and length $L \gg r$ is approximately equal to

$$C_1 \approx \frac{2\pi\varepsilon_0}{\ln(L/r)} = \frac{0.555}{\ln(L/r)} \ \mathrm{pF\,cm^{-1}}\,. \tag{1}$$

The capacitance of a unit length of its tip, if it is taken to be a hemisphere, $C_{1\mathrm{t}} \sim 2\pi\varepsilon_0 r/r = 2\pi_0\varepsilon_0$ is $\ln(L/r)$ times larger and does not depend on the radius at all. No more energy than $C_{1\mathrm{t}}U^2/2 = \pi\varepsilon_0 U^2$ can be spent to form a unit length of the channel, including its heating. For instance, 28 kJ cm^{-1} if $U = 10$ MV, which is typical of weak lightning. This energy can heat an air column of radius $r \sim 1$ cm to 5000 K (at a pressure of 1 atm, the specific enthalpy is equal to 12 kJ g^{-1}). In laboratory conditions for $U \sim 1$ MV, $r \sim 1$ mm.

However, a prodigious field $U/r \sim 10^6 - 10^7$ V cm^{-1} would have been induced near the channel tip for so small a radius. The electric field around the cylindrical channel, $E \approx U[r \ln(L/r)]^{-1}$, would also be very strong ($\ln(L/r) \sim 10$). An extremely strong ionization wave would travel through the air surrounding the tip and the channel, which would immediately increase their radius. But in this case the amount of energy would fall short of the gas heating. Being cool, the channel would rapidly lose conductivity and the electrical link to the voltage source. It would cease to grow. We arrive at a vicious circle. The voltage should be augmented to increase the energy deposited into the channel, but simultaneously the volume of the conducting (and therefore heated) gas increases owing to the ionization expansion, with the effect that the specific energy deposition does not rise. This is precisely the reason why a long laboratory spark and lightning cannot constitute a structureless plasma channel akin to a streamer. They propagate employing the leader mechanism.

The leader is structurally much more complex. The thin plasma channel of a leader is embedded in a shell of space charge (termed a cover) of the same sign as the channel potential U. The cover radius $R_{\mathrm{L}} \gg r$. The potential U now falls off at a radial distance of the order of R_{L} rather than r, as was the case with a streamer. That is why the electric fields at the channel surface and near the leader tip prove to be moderate even for a very high voltage — ranging into tens of megavolts, as for lightning. Nevertheless, the field around the tip is high enough to initiate streamers, $E_t \sim 30-50$ kV cm^{-1}. The tip serves as a source of a diverging bundle of numerous streamers which make up a continuous sequence starting from the tip as from a high-voltage electrode. On travelling a distance of the order of $R_s \sim U/E_{cr}$, the streamers come to a halt. For a negative leader for $U \sim 10$ MV, $R_s \sim 10$ m. A streamer zone is thereby formed in front of the leader tip (Fig. 2). It is occupied with moving streamers and those already dead. The charge introduced by the streamers becomes the cover charge. Penetrating into the streamer zone preformed, the growing leader channel pulls on a cover of radius $R_L \sim R_s$.

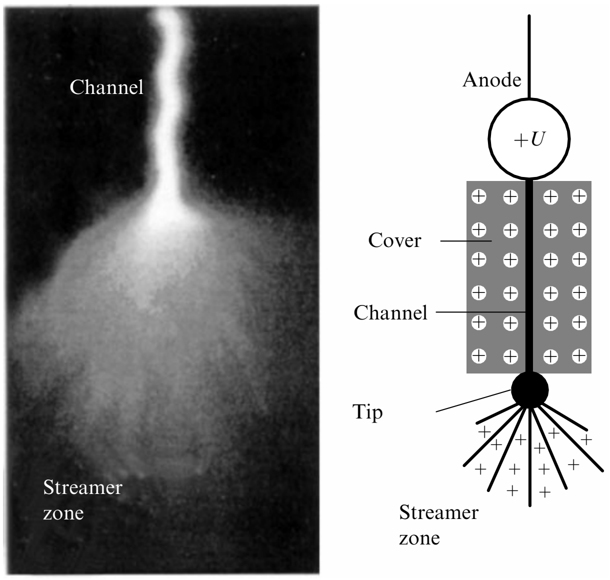

Figure 2. Photograph (made in a laboratory) and schematic representation of a positive leader.

The channel tip moves to a new position, adding a new portion to the channel, when the current of many 'young', just emitted and still well conducting streamers is concentrated in a thin column to heat it to a high temperature providing retention of the conductivity. This is the most important phase of the leader process — the current contraction to a thin filament is akin to the effect of constriction in a glow discharge and is associated with the action of an ionization-overheating (thermal) instability [33]. The scale for the leader velocity v_L is supposedly the ratio between the length of the streamers that retain a good conductivity, $l \sim v_s/\nu_a$ (v_s is the velocity of streamers in the immediate neighborhood of the leader tip, and ν_a is the electron attachment frequency), and the characteristic instability build-up time τ_{ins}. The bundle of conducting streamers nearly in contact with each other, in which the electron density is still relatively high, supposedly forms what appears in the photographs as a bright leader tip. The tip radius r is therefore about the same as l. For the values $v_s \sim 10^7$ cm s^{-1} and $\nu_a \sim 10^7$ s^{-1} typical of the streamer zone of laboratory leaders, one finds $l \sim 1$ cm. The instability build-up time in this case is, according to calculations [32], of the order of $\tau_{ins} \sim 10^{-6}$ s. Hence it follows that $v_L \sim l/\tau_{ins} \sim 10^6$ cm s^{-1}. Estimated values of r and l agree, in order of magnitude, with those given by experiments. The lightning leader velocity v_L is higher by an order of magnitude, since the tip voltage is $1-2$ orders of magnitude higher and all the processes are more intense. The effects and the processes in the leader tip and in the streamer region are so complicated that the dependence of the leader velocity on external factors is hard to represent in the form of a reliable and physically transparent formula. Neither an adequate theory, nor adequate numerical calculations exist at present. The understanding of the phenomena which determine the leader velocity does not, even qualitatively, go far beyond the scope of what was just stated. This issue is discussed somewhat more fully in Ref. [32]. One can find there a numerical simulation of the instability development that is responsible for the contraction of the current in the leader tip to a thin filament, thus allowing the plasma heating up to a high temperature.

In a leader, the ionization-overheating instability builds up in a somewhat different manner than in the contraction of a glow discharge. In the latter, the process proceeds for a fixed voltage, while in a leader for a fixed current. The source of this current is the streamer zone which possesses an extremely high resistance. It is as if this region served as a current generator, and no processes in the leader tip (including contraction of the currents of many streamers to a thin pinch) can alter this current.

Progress toward understanding lightning processes is impossible without prescribing some reasonable dependence of the leader velocity on external parameters. Having no theoretical dependence at our disposal, subsequently (see Section 4) we will invoke an empirical relationship and, naturally, provide a physical substantiation of which of the external parameters is the controlling one as regards the velocity. We note that constructing a good leader theory is a topical problem for the future, if we are seriously interested in the processes underlying the development of long sparks and lightning. Determination of the leader velocity should be one of the outcomes of this theory.

The situation with the theory of a leader channel is little better (from the quantitative standpoint). Without this theory, it is also hard to make advances in the description of the lightning processes. The voltage drop across the channel and, hence, the potential of the leader tip responsible for the leader movement depend on the intensity of the longitudinal field in the leader channel. The leader channel resembles the channel of an arc. The quasi-stationary state with a non-decaying quasi-equilibrium plasma with an electron density $n_e \sim 10^{14}$ cm^{-3} is sustained in a leader channel and an arc by a relatively weak field. The state in an arc channel is determined by the current flowing through the arc. The plasma temperature and the longitudinal field depend on the current. For a relatively high current $i \sim 100$ A, the plasma is quasi-equilibrium in the sense that the temperature of the electron gas T_e and that of the gas of heavy particles T, including ions, are close to each other ($T_e \approx T \approx 10,000$ K), and the degree of ionization corresponds to this temperature according to the laws of thermodynamic equilibrium. For $i \sim 100$ A, the plasma of an arc channel is sustained by electric fields of several volts per centimeter. Indeed, such are the leader currents in lightning. In a laboratory leader, the current is lower, $i \sim 1$ A, and the electric field in the channel is stronger — according to different estimates, several hundred volts per centimeter ($\sim 1-5$ kV cm^{-1} immediately after the initiation of a new portion of the channel). In an air arc at atmospheric pressure for so low a current, the field is weaker though also close to 100 V cm^{-1}. In low-current arcs, the gas temperature is distinctly lower than 10^4 K and the temperatures are appreciably different, viz. $T_e > T$. It seems likely that the situation is also the same in the leader channel of a laboratory spark. Since the theory of the leader channel is also far from completion — and knowing the electric field in the channel and its dependence on the leader current is indispensable to an understanding of many lightning processes — in the subsequent discussion we will take advantage of the following approximation formula

$$i \approx \frac{b}{E}, \quad b \approx 300 \text{ V A cm}^{-1}, \tag{2}$$

which describes in a crude way the calculated and experimental results relating to the volt–ampere characteristic of an air arc at atmospheric pressure for moderate currents $i \sim 1-100$ A [33]. The leader and arc channels are compared more fully elsewhere [32].

3. Initiation of descending lightning in a cloud

On the average, about 90% of descending lightning carries a negative charge to the ground, the start being made from the lower, negatively charged part of the cloud dipole (Fig. 3). The initiation of descending lightning in a cloud is literally shrouded in mist. Nobody ever saw or recorded it. One may conjecture the initiation mechanism, but one thing is clear. A cloud is not a conductor and cannot be likened to an electrode of large radius connected to a high-voltage generator. The negative charge of the cloud resides in hydrometeors (droplets, snow flakes) — small low-mobile macroscopic particles separated by a dielectric air medium. In the short time it takes the lightning leader to propagate to the ground and the cloud to discharge, the carriers of the cloud charge have no time, so to say, to move out of the positions.

The average electric field in the cloud cell (of the order of several kV cm^{-1}) is not nearly strong enough to ionize the air, which requires at least 20 kV cm^{-1} at an altitude of 3 km. The initial ionization, without which a leader cannot originate, occurs owing to a chance field strengthening in a small volume. It is conceivable that a local accumulation (a vortex) of charged hydrometeors is responsible for this. By the way, even near uncharged hydrometeors the maximum field is at least three times stronger than the average, because a water droplet with a relative permittivity $\varepsilon_1 = 80$ polarizes almost like a metal conductor. For a spherical droplet, the polarization charge suffices to triple the electric field; for droplets elongated along the field, the effect is even stronger. It was hypothesized that the initial track of ionization is produced by a high-energy particle being a constituent of cosmic rays. Nobody knows this with certainty. It is beyond question that the lightning leader should originate from some ionized conducting plasma object extended along the vector of the cloud field E_0. Owing to the polarization of a conductor of length $l \gg r$ (Fig. 4), the field at its ends strengthens as

$$E_m \approx E_0 + \frac{\Delta U}{r} \approx E_0\left(1 + \frac{l}{2r}\right). \tag{3}$$

The tip of the initiator conductor serves as the source of streamers in the bundle of which there originates a leader [32]. In this respect, both ends are equivalent, and therefore two leaders emerge. The twin leaders move in opposite directions. One, being negative, moves primarily down to the ground (if the leaders originated in a negatively charged cloud cell, as is shown in Fig. 5) while the other, the positive one, moves upwards. The leaders are electrically linked to each other and are therefore interdependent: as they grow, the charge flows from one to the other. In this case, the charge cloud remains in place. During their development, the leaders can bypass the charged regions altogether if they originated outside the charged cell. As the descending leader grows, it is supplied

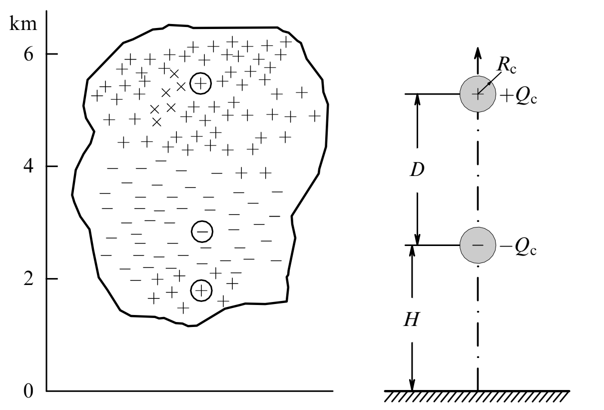

Figure 3. Charge distribution in a cloud and model of the equivalent cloud dipole. Sometimes beneath the negative-charge domain there resides a small positive charge, which is disregarded by the dipole model. Typical geometric and electric scales are: $H \approx D \approx 3$ km; $R_c \approx 0.5$ km; $Q_c \approx 10$ C. Taking into account the mirror charge reflection by the perfectly conducting ground, the potential at the center of the negatively charged cell is $U \approx -290$ MV relative to the ground; the potential at the lower edge of the negatively charged sphere is –180 MV.

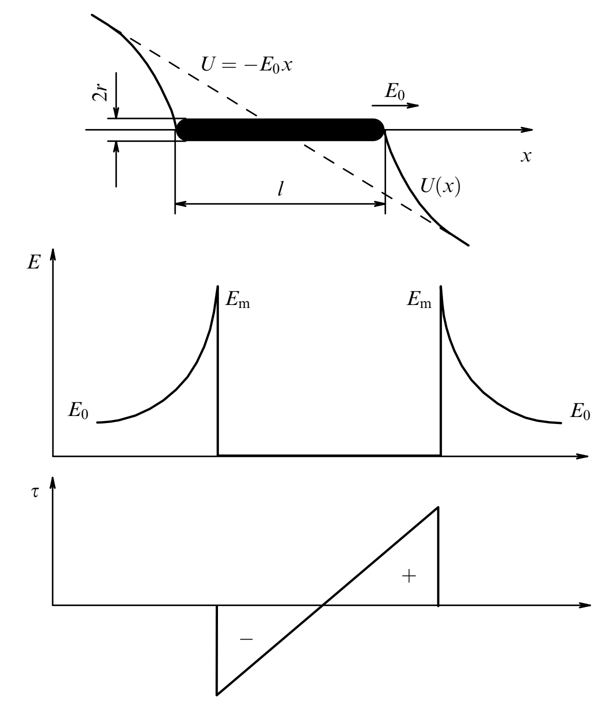

Figure 4. Cause of the field multiplication at the ends of a conducting rod embedded in and aligned with a uniform electric field E_0. The diagram shows the distributions of the potential U (the dashed line corresponds to the absence of the rod), the field E, and the charge τ of a unit length of the rod. The potential changes at the rod ends with respect to the external one are $\Delta U \approx \pm E_0 l/2$.

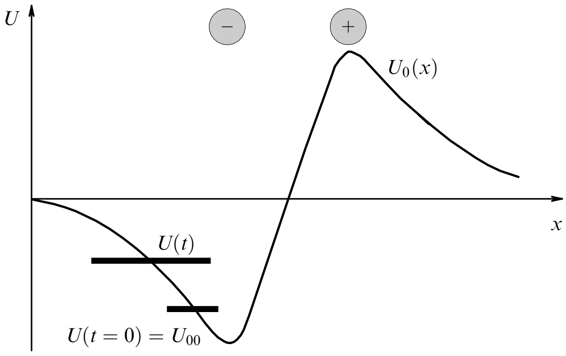

Figure 5. Schematic of the initiation and the propagation of twin leaders which started near the lower edge of the lower cloud charge at the instant of time $t = 0$. The potential distribution of the cloud dipole $U_0(x)$ (taking into account the mirror reflection) along the x-coordinate is measured from the ground upwards. The leader channel is assumed to be perfectly conducting, so that its potential U is everywhere the same but changes with time.

with negative charge not from the cloud. It takes the charge away from its twin, leaving it positive. The role of the cloud charge reduces exclusively to inducing the electric field which initiates and drives the leader process by supplying it with its electric energy.

Naturally, the leaders are more likely to originate where the average cloud field is strongest. When we are dealing with a negative descending leader, this is the lower edge of the negatively charged cloud cell. At the center of the cell, the field is close to zero; outside the charged region, it falls off as we recede from this region. It is pertinent to note that the origination of twin leaders is observed in laboratory conditions by placing a polarizable metallic rod in the electric field, for instance, between plane electrodes (Fig. 6). Concerning lightning, this idea was apparently first stated by Kazemir [34]. We came across his forgotten, uncited, and inherently qualitative paper when we were quantitatively developing a similar notion in our monograph on lightning [35].

In a similar manner, the twin leaders originate at and grow from the ends of an extended metallic body insulated from the ground when its long dimension is aligned with the electric field vector of a thundercloud, even though it may not be fully mature. This is the main reason why large-sized aircraft and rockets are struck by lightning. They suffer from lightning which they induce themselves rather than from accidental encounters with descending or intercloud leaders. Running tip, we note that it is possible, in principle, to provoke the origination of lightning in exactly the same way with a long laser spark. It is desirable to produce its conducting channel as close as possible to the lower cloud edge but within visibility range and, so far as possible, parallel to the vector of the local external field. It would then be possible to observe, with preparations made in advance, the origination and the subsequent growth of the descending leader. It is precisely this type of experiment that would hold greatest interest for lightning science.

4. Build up of the leader of descending lightning and potential delivered to the ground

The leader velocity v_L is determined ultimately by the excess of the leader tip potential U_t over the external potential $U_0(x)$ at the point of tip location x, $\Delta U_t = U_t - U_0$. The quantity v_L

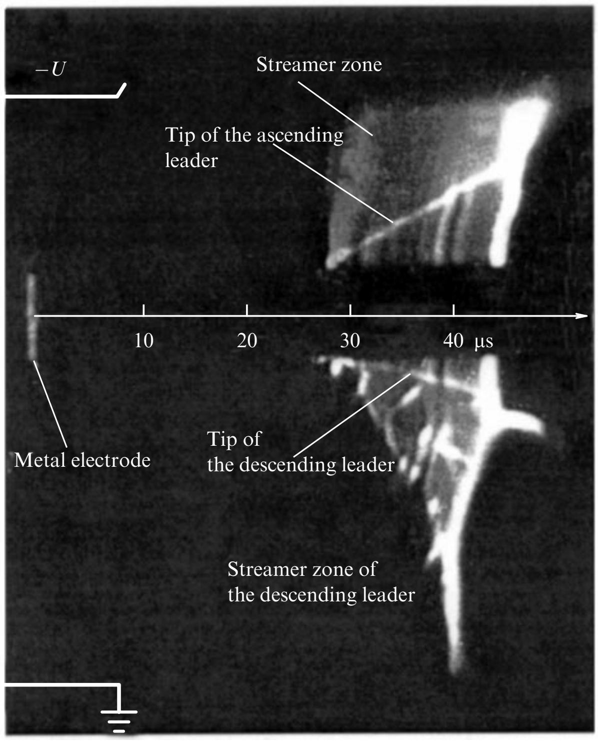

Figure 6. Time scan of the twin leaders which started from a 0.5-m long metal rod embedded in a uniform field in a 3-m long gap. The interdependence of their development is evident.

may equally be thought of as being dependent on the current i_L which flows to the leader tip and feeds it:

$$i_L = \tau v_L, \quad \tau = C_1(U_t - U_0), \quad C_1 = \frac{2\pi\varepsilon_0}{\ln(L/R_L)}, \qquad (4)$$

where τ is the charge, and C_1 the capacitance of a unit length of the leader. The latter obeys the above formula (1), with the reservation that the channel radius r should be replaced with the effective cover radius R_L that harbors the bulk of the leader charge. The velocity cannot depend directly on the external field $\mathbf{E}_0(x) = -\nabla U_0$ at the point of tip location. The mechanism of leader advance is indeed associated with the action of overwhelmingly stronger inherent fields induced by intrinsic charges. In the streamer region of a negative leader, $E_s \approx 10$ kV cm^{-1}. This field determines the radius of the region and, hence, the radius of the charge cover around the channel: $R_L \sim \Delta U_t / E_s$. In the proximity of the leader tip, the field is even stronger ($E_i \approx 50$ kV cm^{-1}) to initiate streamers. In the region of current contraction during the action of the instability, the field was calculated to be as high as 20 kV cm^{-1} [32]. Meanwhile, the leader quite often propagates in the external field $E_0 \sim 100$ V cm^{-1}, which is weaker even than random variations of the intrinsic one.

Not engaging in speculations as to the $v_L(\Delta U_t)$ dependence, we take advantage of the empirical relationship $v_L \sim (\Delta U_t)^{1/2}$ established in laboratory experiments with positive leaders. Unlike a positive leader which moves in a near-continuous manner, a negative one propagates (both in a laboratory and with lightning) in a clearly defined intermittent, jump-like manner. A leader of this kind is termed stepped. The nature of the stepping is not completely understood; it is discussed in Refs [32, 35]. However, experiments with sparks hundred meters long exhibited no fundamental differences between the average velocities of the positive and negative leaders. The same is also true of positive (continuous) and negative (stepped) lightning leaders. In the consideration of the growth of leaders of either sign, in what follows it is therefore assumed that

$$v_{\mathrm{L}} = a\sqrt{|U_{\mathrm{t}} - U_0|}, \quad a = 1500\ \mathrm{cm\,s^{-1}\,V^{-1/2}}. \tag{5}$$

Generally speaking, the potential distribution along the leader should be calculated in the context of the theory of a distributed-parameter long line. However, for a typical current of the lightning leader $i \sim 100$ A and the field in the channel estimated using formula (2), the voltage drop across the channel is found to be relatively low in comparison with ΔU_{t}. Hence, the entire channel formed by twin leaders (the descending and ascending ones) in the first approximation may be thought of as carrying a common potential U at every point in time, like a perfect conductor. Then, the growth of the leaders is described by the elementary equations

$$\frac{\mathrm{d}x_1}{\mathrm{d}t} = -a\sqrt{|U - U_0(x_1)|}, \quad \frac{\mathrm{d}x_2}{\mathrm{d}t} = a\sqrt{|U - U_0(x_2)|}, \tag{6}$$

where x_1 and x_2 are the tip coordinates of the descending and ascending leaders (the leader axis is measured from the ground upwards). In this case, the instantaneous value of the channel potential $U(t)$ is determined by the condition that the total charge distributed along the combined channel of the leaders with a linear capacitance C_1 is equal to zero:

$$\int_{x_1}^{x_2} \tau\,\mathrm{d}x = 0, \quad \tau \approx C_1(U - U_0(x)),$$
$$U = \frac{1}{x_2 - x_1}\int_{x_1}^{x_2} U_0\,\mathrm{d}x. \tag{7}$$

The calculation of the growth of a lightning leader is exemplified in Fig. 7. The leading role is played by the descending leader which hardly decelerates as it travels in the direction of the electric force of the external field and which feeds the ascending one with its current. Before long, the latter (leader) begins to decelerate, for it finds itself in the domain of a steeply rising cloud potential. In this case, the ascending leader travels in the direction opposite to the electric force (see Fig. 5) and grows so far as the charge is delivered to it from the considerably faster descending one. When the descending leader reaches the ground and stops, the charge ceases to be delivered to the channel for a moment. The ascending leader also comes to a halt. Immediately after this, a wave travels upwards through the channel to carry the zero ground potential and the highest lightning current, the wave velocity being only a few times lower than the speed of light. However, this is an entirely different stage of the lightning process. This stage is termed the principal, or return stroke, and we will not enlarge on this subject (it is considered in detail in the monograph [35]). Formally, according to Eqns (6), the ascending leader comes to a halt when the voltage change on a tip $U - U_0(x_2) = 0$ but actually when this difference falls off to a relatively low value $\Delta U_{\mathrm{t\,min}} \approx 0.4$ MV $\ll U,\ U_0(x_2)$. Such is the limit below which the leader cannot grow at all, as shown by laboratory experiments and calculations [32]. Therefore, the potential U_{i} which the descending leader delivers to the ground can be estimated even without considering the evolution of the leaders, employing only equalities (7) and putting simultaneously $U \equiv U_{\mathrm{i}} \approx U_0(x_2)$ and $x_1 = 0$, which corresponds to cessation of motion of both leaders. Geometrically, this

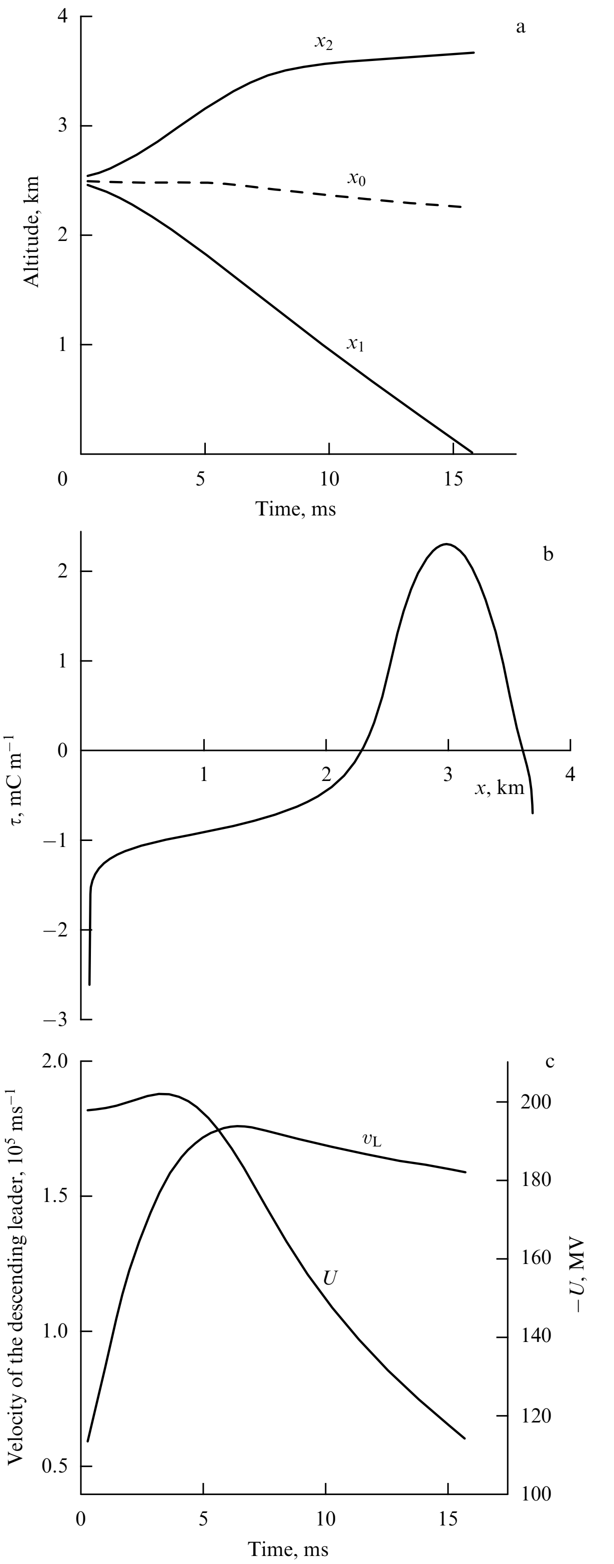

Figure 7. Simulation of the development of a pair of leaders that start from the lower boundary of the negative charge of a cloud dipole ($H \approx D \approx 3$ km, $R_{\mathrm{c}} \approx 0.5$ km, $Q_{\mathrm{c}} \approx 12.5$ C): (a) positions of the tips of the negative descending (x_1) and twin positive ascending (x_2) leaders, and also of the point of zero potential difference $U - U_0(x_0) = 0$; (b) distribution of the linear charge along the leader axis at $t = 16$ ms (calculated using an advanced model); (c) potential and velocity of a descending leader.

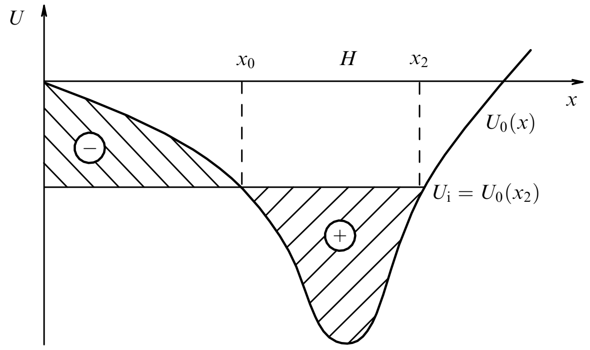

Figure 8. Employing the area equality condition to determine the electric potential delivered to the ground by a negative leader.

corresponds to equality of the two figure areas enclosed by the $U_0(x)$ curve and the $U =$ const straight line in Fig. 8. [1]

The potential U_i which the descending leader delivers to the ground is far lower in magnitude than the cloud potential U_{00} at its point of origin. Despite the widespread belief, this is not owing to the voltage drop across the channel, which is neglected in the above calculation altogether. The potential of a perfectly conducting channel which had its origin in a nonconducting space with an electric field need not necessarily coincide all the time with the potential of this field at the point of origin. This would be the case if the channel were connected to a voltage source having zero internal resistance or with a plate of a charged capacitor of unlimited capacitance. In the case under consideration, the potential assumes a value obtained by averaging the $U_0(x)$ function over a length $x_2 - x_1$, strongly asymmetric relative to the point of the channel origin. As the channel grows, $|U|$ becomes progressively lower in comparison with $|U_{00}|$. The reason is that the $U_0(x)$ curve is strongly extended towards the ground from the point of leader origin, whereas it has the shape of a narrow deep well in the opposite direction (see Fig. 8). In the case of an unbranched vertical channel, as in Figs 7 and 8, about half the potential is delivered to the ground ($U_i = -105$ MV instead of $U_{00} = -185$ MV at the starting point of the lightning). The numerous branchings and path curvature usually inherent in lightning significantly reduce U_i, actually several-fold further.

The magnitude of the potential delivered to the ground is the most important lightning parameter. The destructive lightning current upon leader–ground contact is proportional to the delivered potential: $I = U_i/Z$, where $Z \approx 500\ \Omega$ is the wave impedance of a long line formed by the leader channel. It is not inconceivable that record-high lightning currents of ~ 200 kA correspond to those rare occasions when the descending leader develops nearly along a vertical line and without branching rather than to record-high charged thunderclouds. The magnitude of the potential delivered to the ground is significant in one more respect. The 'force of attraction' of lightning for a tall grounded object depends on this potential, as discussed immediately below. The higher $|U_t|$, the earlier the lightning sets off for the object and the greater the range of attraction.

[1] Curiously, a similar condition for the equality of areas in the corresponding coordinates describes the static equilibrium (co-existence) of a great diversity of states in physics, e.g., the current and currentless regions in discharges, the burned and initial mixtures at the moment of a combustion flame stopping, and many others [36].

5. Attraction of lightning. Ascending counter leader

It has been known for a long time that lightning exhibits selectivity, striking primarily tall objects. It is as if the tall grounded conductors attract it. This underlies the operation of lightning rods. As a rule, a cloud-to-grounded-object strike is preceded by the excitation of a counter leader from its summit. The descending and counter leaders grow, attracting each other. Their joining connects the descending lightning to the ground via the conducting object. There may be several counter leaders in a group of grounded objects (for instance, they can start from the summits of the lightning rod and the object under its protection). The earlier the counter leader originates and the more intense its development, the better the chance that it intercepts the lightning. The ascending leader may also originate in the absence of descending lightning, under the action of the field of the thundercloud alone (if the object is tall enough and the cloud field is strong). This is the way so-called triggered lightning is organized artificially: a small rocket is launched into a cloud, pulling a thin (0.2–0.3 mm in diameter) grounded wire behind it [37]. The ascending lightning starts when the rocket reaches an altitude of about 200 m. In experiments [17, 18] on laser triggering of lightning, the leader was also excited to ascend from a tall tower.

The cause of the origination of the ascending leader is simple. If the charges of the descending lightning and (or) the cloud induce a vertical field E_0 in the region of a grounded conductor of height h, the difference between the zero potential of the conductor summit and the potential of the external field at the point of its location is $\Delta U = E_0 h$. This gives rise to a region of local field strengthening near the summit. This field and ΔU may turn out to be sufficient to ionize the air and generate the leader ($\Delta U > \Delta U_{t\,\min} \approx 0.4$ MV). However, the lightning is affected only by that counter leader which is capable of travelling a distance L at least comparable with the object height, i.e. several tens to a hundred meters. Only then will the 'gain' in an object height owing to the conducting leader channel become significant. For this to happen, the potential change near the tip of the counter leader $\Delta U_t = (E_0 - E_L)L + \Delta U_0$, where E_L is the field strength in its channel, should not lessen in comparison with ΔU_0 (Fig. 9). The condition for viability of the counter leader, $E_0 > E_L$, proves to be more rigorous than its origination condition, $E_0 > \Delta U_{t\,\min}/h$.

According to formula (2), the current in the channel of a viable leader exceeds $i_{\min} \approx b/E_0$, where the current is given by expression (4). The requirement $i > i_{\min}$ imposes conditions on the initial potential change $\Delta U = E_0 h$ at the object summit and its height for a given external field or on the minimal intensity of the external field for an object of a given height:

$$\Delta U_{\min} = \left(\frac{b \ln(L/R_L)}{2\pi\varepsilon_0 a} \right)^{2/3} \frac{1}{E_0^{2/3}} \,, \tag{8}$$

$$h_{\min} = \left(\frac{b \ln(L/R_L)}{2\pi\varepsilon_0 a} \right)^{2/3} \frac{1}{E_0^{5/3}} \,.$$

Taking the values of b and a from formulas (2) and (5), and putting $L/R_L \sim 10$ (the dependence on this not-too-well determined parameter is very weak), we find for $E_0 = 150$ V cm^{-1} that $\Delta U_{\min} \approx 3.2$ MV and $h_{\min} \approx 210$ m. Much

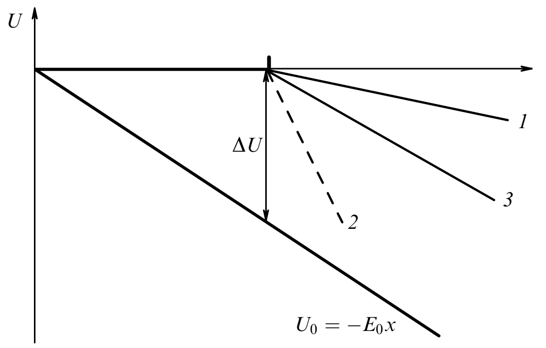

Figure 9. Viability criterion for the leader ascending from a grounded structure of height h in an external field E_0: *1* leader is capable of developing and accelerating; *2* decelerating nonviable leader; *3* leader on the verge of viability.

the same field at the ground is produced by a cloud dipole with a lower charge $|Q_c| = 10$ C at an altitude $H = 3$ km. These parameter values are quite moderate for thunderclouds, and the triggering of lightning for a 200-m elevation of a rocket with a wire is a wholly realistic situation. From buildings of typical height, say, $h = 50$ m, the counter leader is, according to formula (8), excited for an external field $E_0 \approx 350$ V cm^{-1}. Over plains, the thunderstorm field from a cloud charge is rarely, if ever, that strong (in the mountains, sometimes it is). The leader of the descending lightning should add about 200 V cm^{-1} by its charge. This may happen, for instance, when a leader carrying a potential $U = 37$ MV to the ground descends along a vertical path to an altitude $H_0 = 5h = 250$ m at a horizontal distance $R = 3h = 150$ m from the object. The main contribution to the leader field at the ground is made by the charge localized in the portion of the leader of length H_0 immediately behind the tip. Here, the linear charge density is $\tau \approx C_1 U \approx 4.4$ μC cm^{-1} for $U = 37$ MV. It may be said that the lightning trajectory deviates 'purposefully' from the vertical at a point with coordinates H_0 and R and rushes to the object instead of striking the ground a distance R away. The calculated figures given above are in reasonable accord with observations.

6. Physical mechanism for the attraction of lightning

Clearly the attraction of lightning for a tall building and most often for its extension — a counter leader — is attributable to the electric field produced by the charges induced in these bodies by the charges of the cloud and the developing lightning. But this commonplace statement is void of content unless what this field acts upon is specified and unless the specific physical mechanism of the interaction of two leaders is elucidated. For, while the leader tips are hundreds of meters apart, each of them is subject to the field of the other leader, which is little stronger than the cloud field. It is as weak as hundreds of volts per centimeter and they do not exert a noticeable effect on the magnitude of the leader velocity. This was explained in Section 4 and is inherent in formula (5). What is the mechanism of mutual attraction of the leaders?

We allow ourselves to propose a hypothesis. The weak external field E_0, which has no effect on the leader velocity v_L determined by the magnitude of the potential change $|\Delta U_t|$ at its tip, affects the leader acceleration:

$$\frac{\mathrm{d}v_L}{\mathrm{d}t} = \mp\left(\frac{\mathrm{d}v_L}{\mathrm{d}|\Delta U_t|}\right)\left[\frac{\mathrm{d}U}{\mathrm{d}t} - \nabla U_0 \frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t}\right]$$
$$= \mp\left(\frac{\mathrm{d}v_L}{\mathrm{d}|\Delta U_t|}\right)\left[\frac{\mathrm{d}U}{\mathrm{d}t} + (\mathbf{E}_0\mathbf{v}_L)\right]. \qquad (9)$$

Here, the upper sign refers to the negative leader, and the lower sign to the positive one. The first factor in Eqn (9) is independent of E_0 and is always positive, the second consists of two terms comparable in absolute value. The term $\mathrm{d}U/\mathrm{d}t$ related to the charge redistribution along the growing lightning channel is most often favorable to the moderation of the growth of the descending leader. The term $(\mathbf{E}_0\mathbf{v}_L)$ characterizes the direct dependence of the leader acceleration on the external field. The higher E_0 and the smaller the angle between the vectors of the leader velocity and the 'electric force' $\mp\mathbf{E}_0$, the higher the acceleration, all other factors being equal. Hence, the leader will get to the ground or a grounded conductor sooner if it moves in the direction of the vector of the electric force.

In reality, the growth of the descending leader involves inherently statistical factors. As revealed by frame-by-frame photography of a laboratory leader with an exposure time of the order of 10^{-7} s, a growing leader always exhibits several leader tips. They are connected to the main channel by short, randomly oriented leader 'branches' (Fig. 10). Of all these tips, the one whose branch grows closest to the direction of the external electric force has the highest probability of survival. More often than not the remaining tips soon die off, because the tip which grows along the $\mp\mathbf{E}_0$ vector and thereby keeps ahead of them hinders the growth of those lagging behind through the repulsive action of the intrinsic charge. The infrequent survival of two tips initiates a

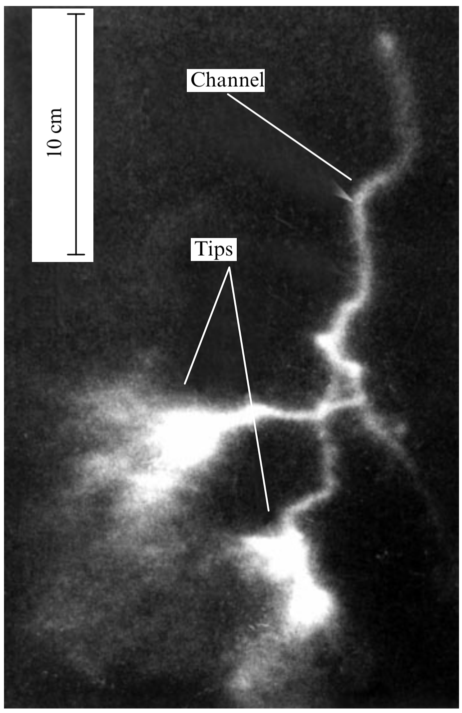

Figure 10. Photograph of a leader with several tips; the exposure time is 0.3 μs.

'macroscopic' leader branching clearly visible in photographs of lightning and sometimes of long sparks. The chance survival of a tip deflected from the direction of the external field causes the lightning trajectory to bend. However, the latter event becomes a rarity when the external field builds up in magnitude along some of the directions of the descending leader growth. The route to the counter leader is precisely the one.

An assumption can be made as to the cause of the random origination of new tips. The surface of the equipotential plasma channel conductor is unstable. An accidental sharp spike induces a field enhanced along the spike direction. Under its action, the spike begins to grow. Growth is possible in any direction, including that at a significant angle to the weak external field.

All of the aforesaid, we believe, provides a qualitative explanation why the leader on the average adheres in its motion to the external field line but does not necessarily follow it rigorously. By and large the descending leader is headed to the ground. But it is more likely to deviate from its principal direction as the cloud field is combined with a differently directed field of comparable intensity induced by some other source, for instance, by the charge carried by the counter leader. Naturally, the qualitative reasoning outlined above calls for a more rigorous theoretical substantiation and, which is desirable, numerical simulations employing, e.g., the Monte Carlo technique.

7. Adverse effect of the corona on the initiation of ascending and counter leaders and the possibilities to overcome it

It is well known, all other factors being the same, that the ascending leader is far less frequently excited from a stationary building than from a rocket with a grounded wire moving fast upwards. The reason lies with accumulation of the corona space charge nearby the summit of a grounded building, whereas this charge does not have time to form in front of a rocket flying with a velocity of 100 m s^{-1}. The electric field near the summit of the building becomes weaker owing to the space charge, with the effect that a stronger external field E_0, which is induced by the thundercloud alone or in combination with the leader of the descending lightning, is required to excite the ascending or counter leaders. We are dealing now with a 'quiet' stationary corona, which is sometimes termed an ultracorona. It develops for a relatively slow rise of the voltage across the discharge gap. In the case under consideration, the field builds up with repeated accumulation of the charge of the cloud cell after each lightning discharge or as the thundery front approaches the location of the grounded building. Hence, times of no shorter than a second are the case in point.

In a thin layer near the surface of the structure's summit, where the field is maximum [2], ionization of the air occurs. If the thundercloud is negative, as is the case in 90% of instances, the grounded electrode (the grounded structure) is positively charged. The electrons being produced enter it and the positive ions drift from the summit to the cloud. In an ultracorona, the electric field near the summit of the electrode is sustained close to what is defined by the condition for discharge self-maintenance, $E_{\rm cor}$ [33]. For a summit radius of several centimeters, the latter is nearly coincident with the ionization threshold, $E_{\rm cor} \approx E_{\rm i} \approx 30$ kV $\rm cm^{-1}$. The field is controlled automatically. If for some reason it is enhanced, the ionization speeds up and more positive charge is introduced into the space, which induces a negative charge at the summit to attenuate the field. If the field becomes weaker than $E_{\rm cor}$, the corona is extinguished for some short time, the previously produced positive ions recede from the electrode, their action becomes weaker, and the field at the summit builds up to resume the ionization. Such is the case only for relatively slow voltage variations, because the controlling mechanism is based on the ion motion whose mobility is low. For a sharp rise of the voltage at the summit of the electrode, the space charge required for the stabilization has no time to form and the field rises there significantly to generate ionization waves — streamers. A streamer flash (it is referred to as a pulsed corona) may trigger the leader process. This is precisely how the counter leader originates, when the channel of descending lightning approaches the object with a velocity of $\sim 10^7$ cm s^{-1}. Figure 11 gives the results of numerical simulation of the ultracorona at the summit of a grounded rod embedded in the external field. The model, elaborated in cooperation with N L Aleksandrov, takes full account of the effect of all the charges on the corona field distribution, including those induced over the whole length of the rod.

While the corona protects buildings from lightning to some extent by hindering the origination of a counter leader, it is detrimental to efficient operation of the lightning rod, for its task is the opposite — to emit the counter leader as early as possible and to intercept the descending lightning by itself. In principle, the performance of this function could be promoted by shooting, in due time, a 'harpoon' with a metallic marline tied to the summit of the lightning rod in order to transport the conductor tip beyond the ion cloud. It is not improbable that the main role of a laser-produced spark in the experiment to trigger the ascending leader from a tower (reported in Refs [17, 18]) reduced precisely to the transfer of the conductor outside the corona cloud nearby the tower summit (see Section 9).

We will consider the simplest corona model to gain an idea of how far and with what velocity the 'extender' of the lightning rod should be ejected upwards. Let a corona be displayed by an immobile spherical electrode of radius r_0 to which a voltage $U(t)$ is applied (r_0 corresponds to the radius of the summit of a lightning rod of height h, and $U = E_0(t)h$ is the potential difference of the summit and the growing external field $E_0(t)$ at the point of summit location). Let us assume, and there are grounds for doing so, that the state of the ultracorona formed is quasi-stationary in the sense that the radial distributions of the field $E(r)$ and the space charge $\rho(r)$ closely follow the corona current $i(t)$ which varies relatively slowly in time. At every point in time, they correspond to the instantaneous value of $i(t)$ as if the current were invariable. In this case, the current through all the spherical sections of the charge cloud at a given moment is the same, i.e. a new portion of charge $i\,{\rm d}t$ introduced into the corona goes exclusively to expand the ion cloud, into an increment ${\rm d}R_{\rm f}$ of its front radius $R_{\rm f}(t)$. Under this assumption, the electrostatic and charge conservation equations

$$\frac{1}{r^2}\frac{{\rm d}}{{\rm d}r}r^2E = \frac{\rho}{\varepsilon_0}\,, \quad \frac{\rho}{\varepsilon_0} = \frac{i}{4\pi r^2\varepsilon_0\mu_{\rm i}E} \tag{10}$$

with a typical boundary condition for an ultracorona, $E(r_0) = E_{\rm cor} = {\rm const}$, are easily integrated ($\mu_{\rm i}$ is the ion

[2] In the absence of a corona, it may be estimated by formula (3).

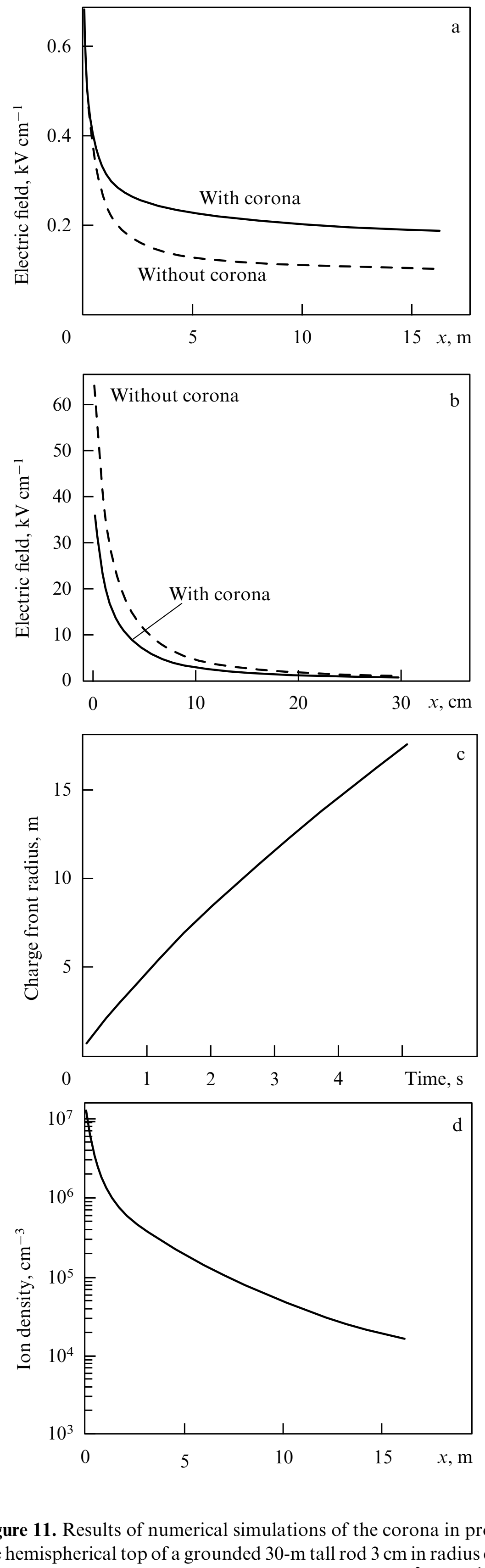

Figure 11. Results of numerical simulations of the corona in proximity to the hemispherical top of a grounded 30-m tall rod 3 cm in radius embedded in the external field; the average ion mobility is 1.5 cm^2 (V s)$^{-1}$. The field builds up linearly with time up to 100 V cm^{-1} for $t = 1$ s and is thereafter held constant. (a) Field distributions along the x-axis, reckoned from the rod upwards, for the instant of time $t = 5$ s with and without the corona. (b) The same on an enlarged scale in proximity to the top. (c) Radius of the front of the ion cloud. (d) Ion density distribution at the moment $t = 5$ s.

mobility). Not writing out the somewhat unwieldy complete formulas, we give only the compact asymptotic expressions valid away from the electrode in the stage when the cloud has strongly expanded and $R_{\mathrm{f}} \gg r_0$, while the space charge in the gap, $Q \approx 4\pi\varepsilon_0 R_{\mathrm{f}}^2 E(R_{\mathrm{f}})$, is much larger than the electrode charge $q_{\mathrm{cor}} = 4\pi\varepsilon_0 r_0^2 E_{\mathrm{cor}}$ which does not vary during the corona discharge:

$$E(r) \approx \sqrt{\frac{i}{6\pi\varepsilon_0 \mu_{\mathrm{i}} r}}, \qquad \rho(r) \approx \frac{1}{r}\sqrt{\frac{3\varepsilon_0 i}{8\pi\mu_{\mathrm{i}}}}. \tag{11}$$

More precisely, these formulas are appropriate where the electric field of the space charge exceeds the field of the electrode charge, $E_{\mathrm{cor}}(r_0/r)^2$.

The electrode potential is calculated employing one of the equivalent expressions

$$U = \int_{r_0}^{R_{\mathrm{f}}} E\,\mathrm{d}r + E_{\mathrm{f}} R_{\mathrm{f}} = E_{\mathrm{cor}} r_0 + \int_{r_0}^{R_{\mathrm{f}}} \frac{\rho r\,\mathrm{d}r}{\varepsilon_0} \approx 3E_{\mathrm{f}} R_{\mathrm{f}}\,, \tag{12}$$

where $E_{\mathrm{f}} \equiv E(R_{\mathrm{f}})$. The radius of the ion cloud and the current are found by integrating the equation $v_{\mathrm{f}} \equiv \dot{R}_{\mathrm{f}} = \mu_{\mathrm{i}} E_{\mathrm{f}}$ with expression (12) and a given function $U(t)$. The latter is governed by the external conditions — for an atmospheric field, by the charge accumulation rate in the thundercloud. In particular, for $U = at$, one finds

$$R_{\mathrm{f}} = t\sqrt{\frac{\mu_{\mathrm{i}} a}{3}}, \qquad v_{\mathrm{f}} = \sqrt{\frac{\mu_{\mathrm{i}} a}{3}}, \qquad i = 2\pi\varepsilon_0 a t\sqrt{\frac{\mu_{\mathrm{i}} a}{3}}. \tag{13}$$

For instance, let the cloud field attain a value $E_0 = 100$ V cm^{-1} one second after the commencement of growth, $h = 100$ m, and $\mu_{\mathrm{i}} = 1.5$ cm^2 (V s)$^{-1}$. Then, $a = 10^6$ V s^{-1}, and at the point in time $t = 1$ s we have $U = 1$ MV, $i = 390$ μA, $R_{\mathrm{f}} = 7.1$ m, $E_{\mathrm{f}} = 470$ V cm^{-1}, and $v_{\mathrm{f}} = 7.1$ m s^{-1}. These estimative figures are in reasonable agreement with numerical calculations.

If the corona-displaying electrode could move fast to travel through the preformed ion cloud with a velocity v far higher than v_{f}, in a short time it would be ahead of the previously produced peripheral ions and the new peripheral part of the ion cloud formed in the course of motion would now be unable to be ahead of the electrode. In other words, the corona charge would cease to accumulate in front of the electrode. In the radial distribution of ion velocities $v_{\mathrm{i}} = \mu_{\mathrm{i}} E(r)$ given by the first of equalities (11), there exists a section r_{c} such that $v_{\mathrm{i}} < v$ for $r > r_{\mathrm{c}}$, and $v_{\mathrm{i}} > v$ for $r < r_{\mathrm{c}}$. Roughly speaking, the region from r_{c} to R_{f} is nonexistent in the new cloud. The contribution of the charge corresponding to this region to the U potential also vanishes. Since U remains unchanged, being given by an external source, this loss should be cancelled out by an increase in the electrode charge $q = 4\pi\varepsilon_0 r_0^2 E(r_0)$ and the corresponding enhancement of the field $E(r_0)$ at its surface. Formulating these qualitative notions in the context of the spherical model, we can write a conditional equality which replaces the second of expressions (12):

$$U = E(r_0) r_0 + \int_{r_0}^{r_{\mathrm{c}}} \frac{\rho r\,\mathrm{d}r}{\varepsilon_0}\,. \tag{14}$$

Let the electrode velocity ensure the field strengthening from the previous value E_{cor} to half the maximum, $E_{\mathrm{m}} = U/r_0$, which would take place in the absence of the corona. In the numerical example given above for $r_0 = 3$ cm, $E_m = 333$ kV cm^{-1} and a field half as strong would suffice to excite the leader. Bearing in mind that $E(r_0) = E_m/2 \gg E_{cor}$ and $U \gg E_{cor} r_0$, we estimate r_c from the condition which follows from expression (14):

$$\int_{r_0}^{r_c} \frac{\rho r}{\varepsilon_0} \, dr \approx \frac{U}{2} \approx \frac{1}{2} \int_{r_0}^{R_f} \frac{\rho r}{\varepsilon_0} \, dr \, . \tag{15}$$

Employing formulas (11), we find that $r_c/R_f \approx 1/4$, $r_c \approx 1.8$ m, and $v_c \equiv v_i(r_c) = 2v_f \approx 14.2$ m s^{-1}. These figures give an idea of the scale of the quantities. To eliminate the action of the corona, a conductor connected to the lightning rod is to be fired upwards from its top to a distance l of several meters ($l > r_c$) with a velocity of several tens of meters per second ($v > v_c$). Solving the two-dimensional axially symmetric problem of the field and space-charge-density distributions in the discharge of a spherical electrode in a gas flow would aid to refine these results. For a flow velocity v exceeding some value v_c, the solution with $E_{cor} = \text{const}$ would cease to exist. The flow with a velocity $v = \mu_i E_{cor} \approx 450$ m s^{-1} would indeed blow away all the ions completely. In this case, the potential $U \gg E_{cor} r_0$ is to be induced only by the increased electrode charge. The critical value v_c arrived at will indicate the lower velocity bound for firing the extender of the lightning rod. Also note that the numerical solution of the problem on corona discharge of a rapidly growing electrode encounters no difficulties.

8. Demands for, capabilities of, and modern trends in lightning protection

Half a century ago, the main goal of lightning protection was to eliminate fire arising from the contact of the lightning channel with combustible materials and to guard power transmission lines against storm overvoltages induced by the current and the strong electromagnetic field of lightning. Lightning rods cope with this 'coarse task' easily. To solve this problem, it will suffice to divert lightning from a fire hazardous or dangerously explosive area. Power transmission lines are safely protected by lightning protection wires. Suspended above the lines, they serve the function of an extended lightning rod by intercepting the lightning channel. So-called induced overvoltages turned out to be the first truly serious indication that the lightning protection is inadequate. Induced by the lightning current from a distance of several hundred meters, they bring a threat to relatively low-voltage power distribution networks (up to 10 kV). It was recognized that the lightning hazard becomes more severe as the operating voltage in electric devices is lowered. Regrettably, this prediction was amply borne out with the advent of the microelectronic era, when electronic devices with operating voltages of tens-to-several volts came into being and became indispensable. Aeroplanes, space vehicles, communication and information processing facilities are literally stuffed with microelectronics. Here, the 'long-range action' of lightning reveals itself in full measure. Damage may be caused not only by a direct lightning strike to an object, but also by quite remote discharges. Their electromagnetic fields may be extremely strong, for the lightning current build-up rate may exceed 10^{11} A s^{-1}. We are forced to provide screening devices, quite often heavy and bulky, or to protect the object from any lightning, including remote lightning.

No better is the situation concerning highly inflammable fuels, explosives, and gaseous exhaust into the atmosphere, produced in the operation of some technical facilities. All of these are an integral part of many present-day devices. Explosives have long ceased to be exclusively a means of destruction. Many compact one-time actuating mechanisms employ explosives. The explosion does not destroy but performs a specific, previously planned action. Lightning-induced actuation of such a pyrotechnic device cannot be tolerated, which it can well do by remotely exciting current in the electric ignition circuit. Nor need the lightning channel necessarily strike an inflammable gas mixture to set it on fire. Counter discharges discussed in the foregoing and all kinds of sparking due to electromagnetic noise can easily do the job. A home piezoelectric igniter sets fire to the gas in the kitchen with an incommensurably weaker electric spark.

Experts in lightning protection have never abandoned the dream of diverting lightning to a safe place, far from the critical object. Nor have they abandoned the idea of finding a means for provoking lightning to discharge thunderclouds in uninhabited vacant areas, where the lightning would cause no damage. There is no question that this is basically possible. But when the question is raised as to the use of new means in lightning protection, issues of technical substantiation, reliability, and cost come to the forefront. These factors are intimately related. For instance, it is beyond reason to increase the power or the energy capacity of a complex and therefore expensive device in an attempt to attain a 100% efficiency of lightning interception with the use of this device if the device itself cannot ensure the controlling action with a reliability of over 0.9. A primitive and inexpensive metal lightning rod would easily ensure at least one more nine after the decimal point in a reliability index.

Of course, there may be circumstances in which traditional lightning rods are basically incompatible with the technological functions of an object. A lightning rod cannot be mounted within the field of vision of a large-scale radar antenna. A lightning rod of many meters high should not tower on the launching site of a space vehicle. It constitutes a real life hazard in the actuation of the astronauts rescue system, for an ejected capsule may collide with the metal frame of the lightning rod. Present-day technology rapidly multiplies the list of these examples, sending us in search for unconventional protection devices.

It is not always possible to devise an electronic unit capable of withstanding the electromagnetic field of lightning by the application of metal screens or pulsed overvoltage limiters. For the most critical and easily vulnerable objects, it is desirable to arrange protection in such a way as to prevent the lightning discharges from occurring anywhere near the object whatsoever. But it is hardly realistic to construct a fencing of lightning rods at the distant approaches to the object, the more so as this does not ensure that lightning will not break through. In principle, the problem could be solved by a mobile laser facility capable of discharging a thundercloud in a safe place. To do this, the laser should 'shoot' kilometers upwards to provoke descending lightning by a plasma trace appropriate in length and other characteristics (see below). This would be an inestimable aid to investigators pursuing descending-lightning research. They would not have to set hopes upon good fortune and wait for a successful discharge within the field of sight of the short-run recording instruments. During a thunderstorm, it would be possible to excite lightning in the required place and ensure timing down to a microsecond. In the same way it would be possible to solve the problem of modelling situations characteristic for the initiation of lightning from bulky aircraft. This would hold the great interest for both lightning science and practical lightning protection.

The laser technique of exciting ascending lightning is much simpler but less expedient from the practical standpoint. First, a tall structure ('extended' by a laser) is required, because producing a very long laser spark (of the order of 200 m, for the electric field at the ground is too weak) with appropriate conductive properties would require prodigious laser energy and power. Second, this technique nevertheless does not ensure perfect protection. Ascending leaders are quite often excited from the summit of the 540-m high Ostankino television tower in Moscow. However, they do not discharge the clouds completely. Though the density of descending lightning in the neighborhood of the tower is lower than usual, it is far from zero, and not all of the lightning strikes the tower. Furthermore, it is well known that subsequent lightning components do not always follow the same path. Nearly half of them do not take the path of the primary channel [38]. Hence, there persists a real danger that one of the components of the lightning provoked would strike the nearby protected object rather than the construction intended for the purpose. Of course, this does not diminish the significance of the experiment performed, which is the first real step toward laser control over lightning.

It should be admitted that alternate, non-laser-based techniques of initiating and controlling lightning are also possible, some of them being technically simpler. The excitation of artificially triggered ascending lightning referred to in the foregoing text has been practiced since the 70s, though for the purposes of research. A well-heated gas jet ejected from the top of a stationary lightning rod can be used to 'extend' it and improve its efficiency. The lowering of gas density arising from the heating lowers the counter-discharge ionization and excitation thresholds. It is well known that the long wake of hot gas jets from aircraft and rocket engines facilitates the initiation of lightning from them. It is not unusual that combustion products are partly ionized; there also exist special techniques to produce plasma jets, which may, in principle, have an effect similar to that of a laser-produced spark.

Controlling lightning is also possible by applying a high voltage to an object. In this case, there are several options. With a voltage of the same polarity as the descending lightning, the latter should be repelled from the object (in principle, this is a way to protect a structure). For an opposite polarity, the lightning is attracted, and this is a way to improve the efficiency of a lightning rod. However, from the technical standpoint it is clear that applying megavolt voltages at the necessary times with the required repetition rate is a complicated task. Lower voltages are out of the question, which was shown in the estimation of the excitation conditions for counter and ascending leaders. The problem of action of high voltage on lightning arose inevitably in the construction a 1150-kV power transmission line. The amplitude of the alternating voltage at its conductors relative to the ground is close to 1 MV, which is commensurable with the potential of the lightning leader. This gives rise to quite tangible difficulties in the design of a reliable lightning protection for the power transmission line. The feasibility of overcoming the action of the corona was discussed in Section 7. The same effect may be attained if a voltage of polarity opposite to that of the cloud is applied to the electrode. The case in point are quite moderate voltages of the order of $E_0 h$, where h is the electrode height, and $E_0 \sim 100$ V cm^{-1}.

There is no question that the above-listed methods of affecting lightning and similar methods are the right subject of discussion from the viewpoint of investigations, but they do not attract considerable attention when it comes to practical lightning protection. Pragmatic considerations underlie the skepticism of engineers — is the game worth the candle? We repeat: the reliability of lightning protection is primarily determined by the reliability of actuation of the entire sequence of complex technical devices that form the controlling action on the lightning rather than by the efficiency of the controlling action itself. One is forced to take into account the possibility of interruption of the power supply to the controlling devices caused by a thunderstorm, the operational lifetime, maintenance expenditure, etc. The use of conventional lightning rods is not associated with these problems, and therefore dilettante inventors, and sometimes even solid companies, address themselves to precisely these rods, proposing inexpensive and allegedly efficient means to improve the reliability and extend the protection radius. As an example we refer to radioactive and piezoelectric attachments. In the view of their manufacturers, both ionize the air to prepare the easiest route for the lightning channel. In reality their effect is akin to the action of an ultracorona. The effect, if any, is the opposite of that expected. But even that is in fact nonexistent. A weak radioactive source, the more so a piezoelectric cell, cannot compete with a corona. The action of radioactive sources of safe intensity has been repeatedly verified in the laboratories. They have no effect on the origination and development of a long spark.

9. Laser triggering of lightning

Two schemes of producing a laser plasma for controlling lightning are now under development. One of them has roots stretching back 30 years, when a long laser spark was produced [7, 39–43]. It is produced employing neodymium or CO_2 lasers, in record-breaking versions with an energy of 2 kJ or even 5 kJ [31] and a duration of the main part of the pulse of 50 ns. The respective threshold intensities for the breakdown of the pure and aerosol-containing air are 10^9 W cm^{-2} and $10^7 - 10^8$ W cm^{-2}, respectively. The virtue of this scheme involving a CO_2 laser is that the channel can be heated to several thousands of degrees. Reducing the gas density N by an order of magnitude promotes the collisional ionization by electrons, whose rate constant is determined by the reduced field E/N. For a temperature above 4000 K, the associative ionization $\mathrm{N} + \mathrm{O} \to \mathrm{e} + \mathrm{NO}^+$, which does not depend on the field at all, becomes appreciable. Heating also strongly suppresses the electron losses due to their attachment and recombination. But the laser spark proves to be continuous only when it is not too long, no longer than several meters for the energy specified above. When the radiation is focused to a distance of tens or hundreds of meters, spark production does occur, but the resultant spark consists of separate plasma centers. The longer the focal distance, the greater their spacing. The discontinuity of the conductor hinders its polarization as of an entity in the external field and does not permit using it as an efficient 'extender' of the lightning rod or for the triggering of lightning in the open atmosphere.

The other scheme pursued in Refs [14, 16, 20, 22] is free from this drawback. It is suggested that a short and extremely intense pulse of ultraviolet radiation be employed to accomplish the three-photon ionization of the O_2 molecules and the four-photon ionization of N_2. A longer pulse of visible radiation complements the short one to release the electrons from negative ions. In this case, far less energy goes to ionize the air as compared with the breakdown by a CO_2 laser, because the energy is in fact not expended on anything else. The objective is to produce a long thin ionized channel in the open atmosphere. It will be polarized under the cloud field, and leaders will be excited from its ends.

In laboratory experiments involving these laser pulses, the gap exhibited a lowering of the breakdown voltage and the spark discharge was observed to make its way through the laser-produced channel [14, 20]. A multistage laser system produced ultraviolet radiation with a wavelength $\lambda = 248$ nm starting from the fourth harmonic of a neodymium laser, with final amplification by an excimer KrF laser. The output was a 10-ps long pulse with an energy of 10 mJ (1 GW in power). This pulse was superimposed on an alexandrite-laser pulse with a wavelength $\lambda = 750$ nm, an energy of 0.21 J, and a length of 2 μs. The authors are designing a system to provide a $\lambda = 248$-nm pulse with an energy of 50 mJ and a length of 200 fs (250 GW in power), and also a $\lambda = 750$-nm pulse several joules in energy and tens of microseconds in length. They carried out a numerical simulation of the initial stage of the evolution of a thin channel several tens of meters long ionized by the laser radiation at a small altitude in the open atmosphere. A gradual field multiplication was seen at the ends (the calculations indicated a two-fold multiplication). However, the controlling parameter — the external field $E_0 = 6.5$ kV cm^{-1} — adopted in the calculations seems to be unrealistically overrated. This supposedly led the authors to make an unjustifiably optimistic prediction that low-energy laser pulses would be sufficient. Real storm fields at the ground are weaker by a factor of several tens; even at an altitude of 2 km they are still 2–3 times weaker than those adopted in the model.

Experiments [17, 18] were carried out to model lightning with a laser on the shore of the Sea of Japan in the period of intense winter low-cloudage thunderstorms typical of this region (Fig. 12). In this case, the electric field at sea level is usually close to 100 V cm^{-1}. To trigger the ascending leader, a tower with a height $h = 50$ m (the authors do not give the magnitude of the h parameter most critical for the analysis; the figure was borrowed from an entirely different source [23]) was constructed on a 200-m high hill. Data on the electric field profile in the neighborhood of the tower are not given, either. However, there are grounds to believe that the field was significantly more intense (in the classical problem of a conductive hemisphere on a grounded plane in a uniform field cited in textbooks of physics, the maximum field at the top of the hemisphere is three times stronger than the external one).

Stationed on the ground were two CO_2 lasers delivering 50-ns pulses with an energy of 1 kJ. One laser beam was focused with a mirror on a dielectric target at the tower summit to produce the initial plasma. The other beam, also focused with a mirror, produced a two-meter-long laser spark from the tower summit. In addition, an ultraviolet laser was employed (like in the second scheme outlined above) for producing a weakly ionized channel to direct the leader to the cloud, which was slightly offset from the tower.

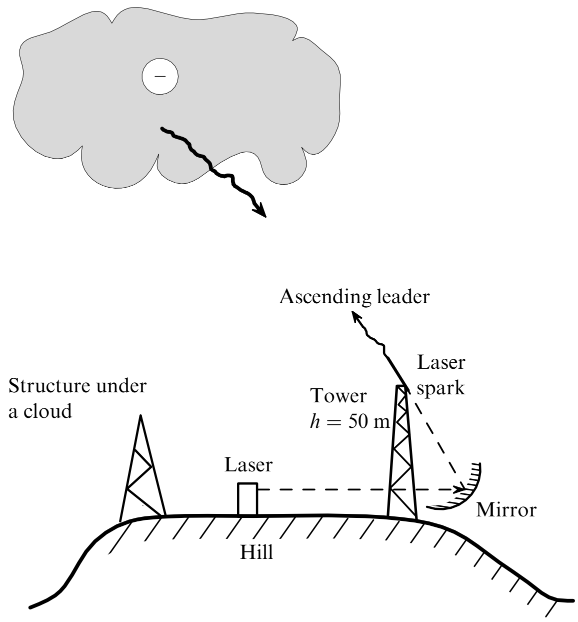

Figure 12. Schematic diagram of the experiment on the laser triggering of lightning [17, 18].

The experimenters believed that the selection of the instant of laser actuation was one of the most critical elements of the operation. Should it be done too early, nothing would be accomplished owing to the smallness of E_0. Should it be done too late, spontaneous descending lightning might originate in the cloud to strike the structure beneath. Special-purpose microwave instrumentation traced the state of the cloud, and the lasers were actuated at the instant of the onset of the cloud discharge, which may be considered as the precursor of the descending lightning. In the authors' opinion, among the many attempts made two were successful; the lightning thus provoked was synchronized with the laser pulses. The authors state that an ascending leader went off the tower upwards. As a consequence, the nearby cloud region measuring about 2 km discharged 3 C into the tower with a current of 35 kA typical of lightning.

It is safe to assume that the cloud field E_0 near the tower was so strong that the natural potential change $\Delta U = E_0 h$ was on the verge of provoking an ascending leader, were it not for the screening corona action. Of course, we cannot expect the numerical value of ΔU to literally satisfy the estimative formula (8), which relies on the not-too-dependable relationships (2) and (5). Furthermore, it is highly improbable that condition (8) was not satisfied without a laser spark and came to be satisfied when the 50-m high tower became two meters longer. The entire experience of experimental investigation of long spark discharges suggests that the statistical scatter of their threshold values is much larger. It may well be that the function of the lasers was as follows: a moderately long and therefore continuous laser spark 'shot through' (perforated) the corona to instantly bring the conductor summit beyond some portion of the ion cloud, which was responsible for the origination of the ascending leader. Upon its penetration into the thundercloud or in consequence of the interception of a travelling descending leader, there followed a completion of the lightning discharge. It is conceivable that the discharge was multicomponent and comprised its return strokes, for which the current with an amplitude of 35 kA measured is quite typical. As regards the interpretation of the experimental results, there are some indications that preference should be given to the interception of the descending leader. Be it as it may, the current oscilloscope trace given in the paper does not exhibit a long-duration build-up of the current pulse up to several hundreds of amperes typical for ascending lightning.

10. Requirements on a laser-produced channel

In our opinion, the capability of triggering lightning high in the sky would hold the greatest interest for lightning science and lightning protection, in particular, for modelling the origination of lightning from aircraft. Let us see what the parameters of a channel between the cloud and the ground should be to permit the excitation of viable leaders from its ends. The channel should work as a good conductor. Hence, the electric field should be largely suppressed inside it but multiplied at the ends. Given this, a unit length will harbor a charge $\tau \approx 2\pi\varepsilon_0 E_0 x/\ln(L/r)$, where E_0 is the external field parallel to the channel, L is its length, r its radius, and x the coordinate reckoned from the middle. This is explained by Fig. 4 and formula (1). The potential difference $\Delta U = E_0 L/2$ originating at the ends of the initial conductor should ensure viability of the leaders. The requisite length L is defined by formula (8):

$$L_{\min} \approx 2\left(\frac{b\ln(L/R_{\mathrm{L}})}{2\pi\varepsilon_0 a}\right)^{2/3}\frac{1}{E_0^{5/3}}\,.$$

For instance, in order to excite lightning for $E_0 = 1$ kV cm^{-1} (say, at an altitude of 2 km, 1 km below the center of a cloud charge of 10 C), a length $L_{\min} = 20$ m ($\Delta U = 1$ MV) is required. To polarize the plasma conductor, a charge

$$Q \approx \pi\varepsilon_0\frac{E_0 L^2}{4\ln(L/r)} \approx 90\ \mu\mathrm{C}$$

should flow from its one half to the other. On the verge of possibility, it is afforded by a length-averaged ionization $N_{\mathrm{e\,min}} = 2Q/(eL) = 5.5\times10^{11}$ electrons cm^{-1}. For the electrons to flow from one half of the conductor to the other before they recombine, the current i should be provided with a sufficiently large section. The magnitude of the electron density $n_{\mathrm{e}} = N_{\mathrm{e}}/(\pi r^2)$ has only a small effect on this, because the charge transfer time $t_{\mathrm{p}} \approx Q/i \sim n_{\mathrm{e}}^{-1}$ and the characteristic recombination time $t_{\mathrm{rec}} = (\beta n_{\mathrm{e}})^{-1}$ vary similarly in proportion to n_{e}^{-1} (β is the recombination coefficient). The time of charge transfer and significant attenuation of the electric field inside the plasma conductor is approximately

$$t_{\mathrm{p}} \approx \frac{Q}{\pi r^2 e\mu_{\mathrm{e}} n_{\mathrm{e}} E_0} \approx \frac{1}{\ln(L/r)}\left(\frac{L}{2r}\right)^2\tau_{\mathrm{M}}\,,$$

where $\tau_{\mathrm{M}} = \varepsilon_0/(e\mu_{\mathrm{e}} n_{\mathrm{e}})$ is the Maxwellian time, and $\mu_{\mathrm{e}} \approx 600$ cm^2 (V s)$^{-1}$ the electron mobility. Unlike a plasma volume equally extended in all directions ($L/2r \sim 1$) where the times of space-charge relaxation and field attenuation are close ($t_{\mathrm{p}} \approx \tau_{\mathrm{M}}$), for an extended thin conductor $t_{\mathrm{p}} \gg \tau_{\mathrm{M}}$.

The requirement $t_{\mathrm{p}} < t_{\mathrm{rec}}$ defines the lower permissible bound for the radius of the initial plasma channel

$$r_{\min} \approx \frac{L}{2}\sqrt{\frac{\varepsilon_0\beta}{e\mu_{\mathrm{e}}\ln(L/r)}} \approx 3.8\ \mathrm{cm}\,.$$

The numerical value of $r_{\min}$ corresponds to the value $\beta = 10^{-7}$ cm^3 s^{-1} inherent in cold air. It is impossible to get by with a smaller radius in a scheme involving multiphoton ionization. However, it may be that a longer channel will prove to be hard to produce as far as radiation focusing is concerned, but this is quite a different matter. A long CO_2-laser-produced spark, if it is continuous, usually proves to be heated. This circumstance is beneficial because a high temperature significantly suppresses both electron recombination and attachment. However, considerably higher expenditures of laser energy are the price that has to be paid.

We revert to the scheme involving multiphoton ionization. To induce the needed voltage change ΔU provided by the transfer of a charge Q, a very low ionization would suffice: $n_{\mathrm{e\,min}} = N_{\mathrm{e\,min}}/(\pi r_{\min}^2) \approx 1.2\times10^{10}$ cm^{-3}. But for so low an electron density the current would be too weak, $i \approx 0.1$ A (even for an electric field still retaining the initial level, ~ 1 kV cm^{-1}), and the charge transfer time would be $t_{\mathrm{p}} \approx 1000$ μs. For at least this time, electrons would have to be released from negative ions with the aid of a laser. The case in point now is a real laser with a pulse length $t \approx 10$ μs. For the charge transfer to be accomplished during this time, a current $i \approx 10$ A and an initial electron density $n_{\mathrm{e}} \approx 10^{12}$ cm^{-3} are required (for a field of the order of the initial one). There is little point in producing orders of magnitude higher electron densities employing an ultraviolet laser, because the density will inevitably lower to the 10^{12} cm^{-3} level owing to recombination during the same period of time $t_{\mathrm{rec}} = (10^{-7} n_{\mathrm{e}})^{-1} \approx 10$ μs. To ionize a column of air of length $L = 20$ m and radius $r = 3.8$ cm to a level $n_{\mathrm{e}} = 10^{12}$ cm^{-3} takes an ultraviolet radiation energy $W \approx \pi r^2 L n_{\mathrm{e}} I \approx 200$ mJ ($I \approx 15$ eV is the ionization potential).

However, the above list of difficulties is not exhaustive. Until now, we have been dealing with the preparation of conditions for forming a potential change and a strong field multiplication at the ends of a long artificial conductor. However, it also takes time for the leaders to develop. This time is hard to estimate but, according to laboratory experiments, it runs into the tens of microseconds. Hence, negative ions will have to be destroyed for a longer period of time, though this will not exclude recombination. But most important of all, the leader process, namely, the propagation of two leaders in opposite directions, will require an uninterrupted charge transfer from one channel to the other, i.e. characteristic leader currents of 1 – 100 A flowing through a conductor initially produced by artificial means. For the leader to commence unimpeded propagation and provoke real lightning, the laser-produced channel should acquire the properties of a true leader channel, i.e. become thin and strongly heated, like an arc, and additional ionization should proceed in it. In the leader tip, all this takes place through the action of the ionization-overheating instability. However, this process in the leader tip begins with a far thinner channel in a stronger electric field and for a higher electron density $n_{\mathrm{e}} \sim 10^{14}$ cm^{-3}, which cannot persist in our case without heating for more than $t_{\mathrm{rec}} \sim 10^{-7}$ s. In essence, the question which we now are dealing with is the same as the glow-to-arc discharge transformation, the question of contraction or arcing in a weakly ionized cold plasma (the terms are many), which is still a long way from being solved [33].

An alternate scenario for the course of events is also possible. If the conductivity in the cold laser-produced channel is somehow maintained for a time period such that the leader develops and travels a distance L, at least one (if the leaders of opposite polarity behave in a different way) viable conductor of the same length L will result. Subsequently, if the laser-produced channel decays, this new conductor will be polarized in the external field and the development of leaders from its ends will continue. For a leader velocity $v_L \approx 2 \times 10^6$ cm s^{-1} and $L = 20$ m, the time taken for this is about $L/v_L = 100$ μs. The time it takes the contraction to develop also runs into the tens of microseconds (according to our calculations [32] referring to the formation of the leader channel in the leader tip, where the conditions are, we repeat, more favorable, this proceeds faster — in a time $t \sim 1$ μs). That is why the ionized state of the cold laser-produced channel will have to be artificially maintained for at least tens of microseconds. Which of the scenarios outlined above will be realized, if at all, will be revealed by a close theoretical treatment and numerical computations probably supported by a dedicated experiment — which presents a real challenge.

It is conceivable that it will not be possible to dispense with the initial artificial heating of the primary channel altogether, and then preference will be given to the long laser spark produced by a CO_2 laser. This will require a higher laser energy because the same 20-m long channel (for an external field of 1 kV cm^{-1}) is to be made continuous. To make it clear what kind of energy expenditure will be dealt with, we point out that a 20-m long column of cool air 1 cm in diameter harbors, when heated to 4000 K at pressure 1 atm (to which there corresponds an equilibrium electron density $n_e \approx 7 \times 10^{12}$ cm^{-3}), 16 kJ of energy. At present, CO_2-laser pulses with an energy of 2–5 kJ have been realized.

In brief, it seems likely that the problem of lightning triggering at high altitudes is still a long way from receiving a final solution, despite the fact that there appear to be no fundamental obstacles. The reason is that the natural source for the origination of lightning is, we believe, the same kind of cool plasma object that we are dealing with. Here, we do not discuss the problem of focusing and transportation of high-power laser radiation to a high altitude provided that it does not induce air breakdown and is not absorbed on its path. When it comes to moderate altitudes, this problem does not generate skepticism among enthusiasts of laser triggering of lightning [16]. But, as the altitude decreases, the requirements on the length of the initial channel L and the laser energy become more stringent owing to weakening of the cloud field: $L \sim E_0^{-5/3}$. Conversely, the difficulties associated with transportation and focusing of the radiation become more severe with increasing altitude. One can see that the conditions for selecting the appropriate altitude are contradictory. Therefore, future work should proceed not only on the development of laser pulses of higher energy and power. It should search for ways of unimpeded transportation of the radiation to as high an altitude as possible.

We emphasize once again that the very possibility of exciting twin leaders from an isolated conductor embedded in an external field is beyond question. This is precisely how lightning originates from airplanes, and experiments of this kind on metal rods of moderate length have been repeatedly staged in laboratories (see Fig. 6). The question arises of how to gain the 'right' behavior of a plasma conductor, which possesses a far lower initial conductivity and is prone to lose it. This issue may and should be purposefully studied in a laboratory, as applied to the problem of triggering lightning. In doing this, emphasis should not be placed on lowering the breakdown voltage in a long gap or the use of a laser spark to direct the high-voltage spark, as have primarily been done until now. For simplicity, solid rods with a conduction well below that of metals are perhaps worth trying as the initiators.

We point to the experimental fact which may be pertinent to the behavior of a discontinuous (broken) long spark. It is well known that a high-voltage discharge can propagate along a path in which small metal rods are placed at intervals. As the leader approaches, each of the small rods is polarized in the enhanced external field supposedly to emit a pair of leaders: one toward and the other in the same direction as the principal leader, and that is the way the spark propagates. It is significant that only a negative spark, and not a positive one, propagates in this way, which is clearly associated with the fact that the leader process is inherently stepwise in the former and void of steps in the latter.

11. Conclusions

So, in the foregoing we showed how and why lightning that propagates from a cloud to the earth opts to strike a tall structure, even though it may have to depart from its initial path. Under the action of the electric field induced by the charges of the lightning leader, electric charges are induced on the grounded structure and the electric field is multiplied at its summit; and the higher the structure, the greater the multiplication. This is responsible for the origination of a leader ascending from the summit, the leader behaving like a high-voltage electrode. The criterion for viability of the counter leader imposes a constraint on the minimal structure height or the combined field of the charges of the lightning and the cloud acting on the structure. The mutual attraction of the descending and counter leaders, when they are widely separated (by over a hundred meters) and interact via weak fields, is determined by a subtle nontrivial mechanism which affects the acceleration. In this case, the absolute values of the leader velocities, which are determined by intrinsic fields in the proximity of the tips that are several orders of magnitude stronger, are virtually invariable.

The joining of the leaders attracted to one another results in the closing of the electric cloud – ground circuit. During the subsequent (not discussed in this paper) return stroke, the plasma channel between the structure summit and the cloud recharges acquiring the potential of the ground, with the result that an extremely high current flows through the structure. To protect buildings, recourse is made to lightning rods which are raised in the neighborhood of the object under protection but are made even higher in order for the counter leader to be excited from the lightning rod rather than from the object.

In the quest to improve the reliability of protection of especially vulnerable and critical objects, different approaches to controlling lightning are basically possible. Attempts are being made to use lasers for this purpose as well. The laser triggering of lightning involves the production of an ionized air channel by employing laser radiation. Two major schemes are conceivable on this route. In one of them, the plasma channel is produced by a laser at the summit of a tall tower to promote the earlier excitation of an ascending leader, which intercepts the lightning. It is precisely this effect that was recently observed in Japan as a result of extensive preparatory work and after many unsuccessful attempts. It is conceivable that the role of the laser-produced plasma reduced to the extension of the top of the grounded conductor beyond the corona charge layer which was prohibitive to leader excitation.

The other scheme under development involves laser-assisted production of a plasma channel in the open atmosphere so as to have lightning-provoking leaders excited at its ends, much as large airplanes do. The condition for the excitation of viable leaders from a plasma conductor is the same as for a grounded structure. It also defines the minimal conductor length. This approach to laser triggering of lightning is much more complicated but is of greater interest for both lightning science and, potentially, lightning protection. That would be the way to excite descending lightning in the required place and time, timing the recording instruments to a fraction of a millisecond and, on the other hand, to discharge the cloud in a safe place. Many basic and practical difficulties will be encountered in reaching this goal, but a start has been made on this research and the scope of work will most likely expand. One of the major problems is to focus the laser radiation at as high an altitude as possible and in doing this to eliminate the breakdown of air over the path of radiation transportation. The higher the altitude of the plasma channel produced to excite the leaders, the shorter it may be, because the cloud field at a high altitude is stronger. A shorter laser-produced spark would require less laser energy. The laser radiation is easier to focus near to the earth, but in this case the requisite length of the initial laser-produced channel and the laser energy rise steeply.

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