N91-32696

THE PHYSICS OF THE OSCILLATING LIGHTNING

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ABSTRACT

The lightning is proposed to start in a limited region of electric break-down field. A growing charge pool in a cumulonimbus cloud is likely to produce such a field in its outer layers. When the field is not aligned with the potential surfaces, the electric force pushes positive charge in one direction and negative in the opposite. Self-inductance develops and an embryo open electric circuit is born. Oscillations swiftly grow in strength when potential energy of the cloud is released. The channel extends in steps during those cycle-stages where charge is crammed into the channel terminals.

Electro-static consequences of a narrow conductor among the cloud charges are computed. The conductor is charged by influence to such a degree that the charge is bound to leak out to the ambient air and appear as a charge sheath some distance off the channel. Ample energy is released to sustain the oscillations. The period increases with channel length and agrees well with observed time between steps.

A ground strike leads to a shock-pulse travelling up the channel.

INTRODUCTION

The start location of a lightning event is within a cumulonimbus cloud and therefore out of sight. The highly visible event, particularly during the night, is the final stage. That stage has been intensely studied by various photographic means. Electrostatic and electrodynamical instruments observe the lightning as an entity from some distance. The total description gathered lacks some detail and is felt to be puzzling in many respects.

A model for the phenomenon should obviously lead to lightning characteristics identical to those observed. The more important characteristics are the following:

- Before the lightning event the electric charges are on cloud droplets or in the air, i. e. on isolators. The lightning collects charge in a fraction of a second.

- The channel extends in steps of the order of 50 m over about 1 μs. It apparently "rests" for some 50 μs inbetween. The whole channel is visible when a new step takes place. It seems to become extinct inbetween.

- The return stroke shows up as a light pulse travelling upwards along the channel. Later strokes are light pulses as well, going down and then up the channel.

- The electric current is more pronounced in the return stroke than in the stepped leader. Electric field changes associated with the lightning last longer than the visible lightning.

It is the purpose of this paper to point out that the characteristics above are those of a progressing aerial conductor undergoing free electric oscillations. Some electro-static consequences of such a conductor among the cloud charges must first be considered.

ELECTROSTATIC CONSIDERATIONS

The cumulonimbus cloud is highly charged. Tens of coulombs of positive charge are present in the upper part and tens of coulombs of negative charge in the lower part, where a smaller amount of positive charge may also be found. If a vertical rod-shaped conductor is introduced in such a cloud, a radical redistribution of the rod charge takes place.

The fundamental requirement for a conductor is a common potential all over its surface. The common potential is achieved by a distribution of charge over the surface. Ambient potential deviations are locally balanced by the surface charge.

Charge and potential are connected. Let the mean ground potential be zero and the relative potential be called voltage. If the ground is considered to be a perfect conductor, a charge element ΔQ causes a voltage increment ΔU at a point in space

$$\Delta U = \Delta Q \cdot (1/\varrho_1 - 1/\varrho_2)/\epsilon \qquad (1)$$

The equation is based on the model of a charge combined with a negative mirror charge below the ground, where ϱ_1 and ϱ_2 are the distances between the point and the two charge elements in question, while ϵ is the permittivity of air. In order to find the voltage at a given point, the increments may be added for the whole charge distribution.

In a computer model the cloud electricity has been replaced by two charge pools shaped as cylinders. The charge in a pool has even density. A lower pool between 3 and 5.5 km height has radius 2.5 km and charge -20 C. An upper one between 8.5 and 11 km has radius 1.5 km and charge +10 C. The conductor is represented by surface-charges on a tube with radius 200 m; the height of the charge-terminals may be chosen at will. The tube has no net charge, but whenever it intersects the charge pools, the core charge is moved radially out to its surface. The cylinders and the tube have a common axis. The horizontal resolution is variable, but less than 250 m. The vertical one is 100 m.

The charge on the conductor surface cannot be found analytically, but it may be approximated by iteration. The iteration requirement is a common voltage for the tube axis. It is achieved by shifting charge along the tube. The total amount of positive charge must be equal to the total amount of negative charge; this demand is sufficient to establish the value of the common axis voltage.

The voltage along the system axis is shown in figure 1 for different tube configurations. Wherever it is positioned, the tube-shaped charges have a pronounced effect on the voltage distribution. The common voltage established along the axis appears to be close to the mean value of the original distribution between the terminals.

When charge distribution and voltage distribution are known, the potential energy may be computed. If a charge on the ground is given zero energy, the potential energy W of the system is

$$W = \Sigma(0.5 \cdot \Delta Q \cdot U) \tag{2}$$

For the tubes with an upper terminal at 8.5 km, the system energy is plotted in figure 2 as a function of height of the lower terminal. When the tube charges are introduced, the energy is reduced from that represented by the cloud charges. This is also true for the tubes 3-5.5 and 8.5-11 km, where energies are 19.7 and 19.9 GJ respectively. The reduction increases with increased length of the tube, although the increment appears to be marginal for tube extensions outside the cloud charges.

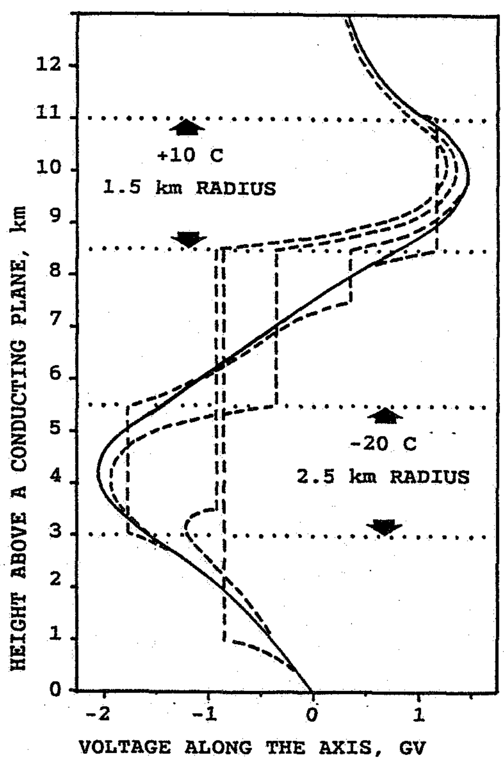

Fig. 1. Voltages in the Model
The solid curve is the voltage for the cloud charges only, the dashed curves when additional tube-shaped charges are present. Radius 200 m. Various end points.

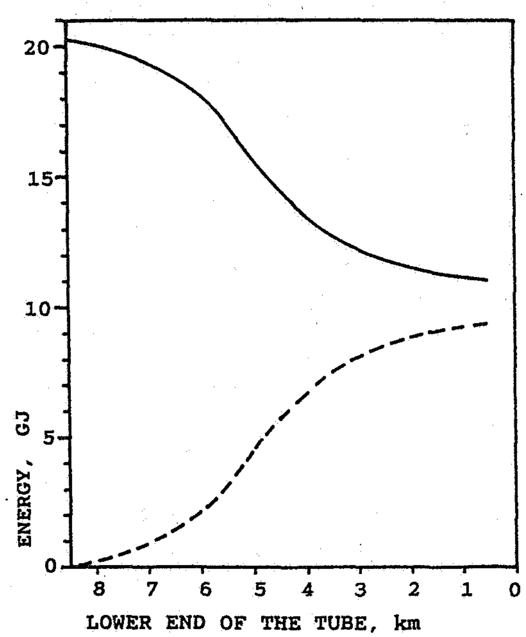

Fig. 2. Energy of the Configurations
Upper tube end 8.5 km.
Solid curve: Potential energy.
Dashed curve: The energy released by introducing tube charges.

The energy deficit represents an energy conversion. If the tube is envisaged as a lightning channel, the released energy is dissipated or is available for further channel progression. The converted energy is plotted in figure 2 as well.

The vertical field at the ground is another quantity of interest. In the computer model it is only available as a mean for the lowest 100 m, and it is plotted in figure 3. One curve is drawn for the base of the axis, the other close to the outer cloud limit. The field is strongest in the central part, and it is very much influenced by tube charges close to the ground.

The charge distribution along the tube is plotted in figure 4. Within the cloud the extreme sections carry very large charges compared with the next ones. It is certainly qualitatively correct, but the vertical resolution is not good enough to bring about quantitative accuracy. A better resolution would undoubtedly give higher absolute values for the charge in the terminals.

The charges are nevertheless very high. At 9 km height the break-down field of air might be about 1 MV/m. For an infinitely long cylinder with a linear charge density of 20 mC/m, the field strength drops below this value at a distance of 360 m. The computer model is consequently artificial. If the charge distribution were ever brought into existence, ions would achieve ionization energy between collisions with neutral molecules. They would multiply, and an exchange of charge between cloud and tube would take place.

The tube charges in the lower terminal are lower, and the highest positive charge density corresponds to about 200 m radius for the breakdown region.

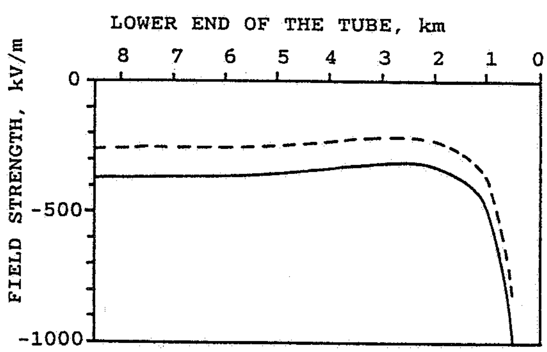

Fig. 3. Ground Voltage Gradient
Solid curve: At the axis base.
Dashed curve: 2.5 km off-base.
Upper tube end at 8.5 km.

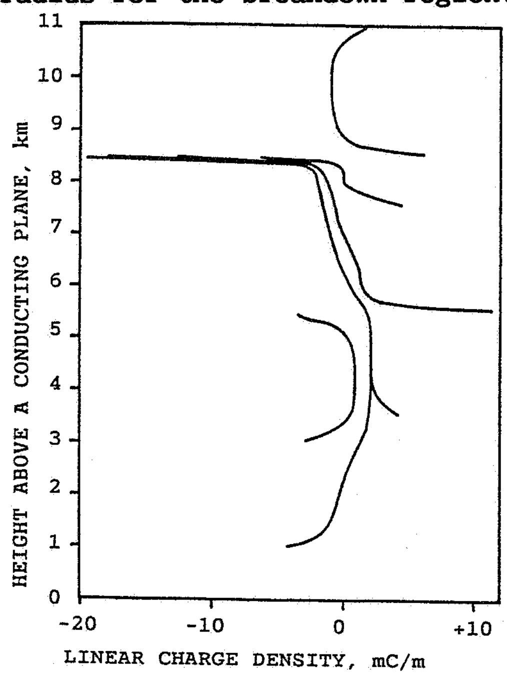

Fig. 4. Tube Charge Distribution
Distributions corresponding to all the tubes in figure 1 are shown.

In the middle part of a long tube the computed charge-densities seldom give break-down radii greater than a few tens of meters. These charges are consequently able to remain on the surface.

The general conclusions in this section are meant to be used for the lightning phenomenon, but some caution must be applied. The computer-results depend very much on the charge configuration in the cloud, both on the quantities and on the positions in space. Some runs with a more impressive positive charge pool show a positive axis voltage when the terminal approaches the ground.

INITIATION OF A LIGHTNING

The charge generation in a cumulonimbus will not be discussed here. Charge pools of the order of tens of coulombs are formed. After a lightning event the charge lost may be replenished over some 20 s in a mature cloud. The charge build-up appears to be fast.

In an isolated and symmetric spherical pool with charge Q and radius r, the field E at the surface is

$$E = Q/4\pi r^2 \epsilon \qquad (3)$$

The charge will in general build up as r^3, and the surface field should therefore increase and eventually surpass the break-down limit of some 1 MV/m. The configuration in a cloud is never ideal, and deviations from a radial field is the rule. The break-down field should therefore initially be surpassed over a limited region only, and the region is not likely to be aligned along equi-potential surfaces. A tilted electric field pushes positive charge into one end and negative charge into the other end of the region. Self-inductance leads to more separation than called for in the situation; a voltage drop develops in the opposite direction, and charge is pushed back. An embryo oscillating circuit has been brought into existence.

The air is heated to some sort of plasma. The outer plasma parts are exposed to cooling and recombinations, and the oscillating charges are likely to find a best path with low resistivity in the core part of the breakdown region: The electricity flow consequently contracts to a current in a narrow channel.

The channel is a conductor among the cloud charges. It is not the sturdy tube considered in the computer model, but the effect must be similar. The high charges formed by influence, most pronounced for the terminals, cause break-down fields exceeding by far the trigger-off field. Charge is immediately transferred to the very limit of the field, and the final result is a new configuration with charge neutralized in the cloud pool, but appearing anew, at a different place, as a charge sheath surrounding the channel. A common mean voltage for the channel is achieved by the sheath charges, not by charges in the channel proper.

The concept of a charge sheath led to the formulation of the computer model discussed in the electro-static section. The oscillations are not affected by a shift of static charge from the channel to a surrounding sheath.

THE STEPPED CHANNEL EXTENSIONS

The oscillation current is started by a potential difference between the terminals. It over-shoots because the current builds up self-inductance. And charge jammed in a terminal creates break-down field in the channel extension. The charge is then likely to proceed beyond the limit reached in the previous oscillation. The field is best aligned when the terminal charge is of the same type as that in the sheath, and those extensions should be most robust. The twisted shape of a channel may be caused by the more uncertain field of opposite charges, which occurs in every second step. Because the channel extends in a field of its own making, the direction of a new step may only be slightly affected by the original static field.

The channel lengthening is an involved electric phenomenon tied up with protuberances of an advancing tip. In this stage the current works against an increasing counter-potential, and the excess charge diminishes. The progress stops when the break-down field disappears.

A conductor extension requires a new "static" voltage pattern. It can only be established by way of the channel: In order to cope with the new configuration, a balance current shifts charge along the channel. The event is illustrated in figure 5. The charge brought into the terminal creates a general break-down field and immediately takes up a more permanent position as a charge sheath extension in the surrounding air.

The adjusted charge distribution has less potential energy than the old one, and the released energy is fed right into the channel by the balance current. The current is actually a pulse spanning over the extension time only. The sequence of pulses is synchronized with the oscillations. When the

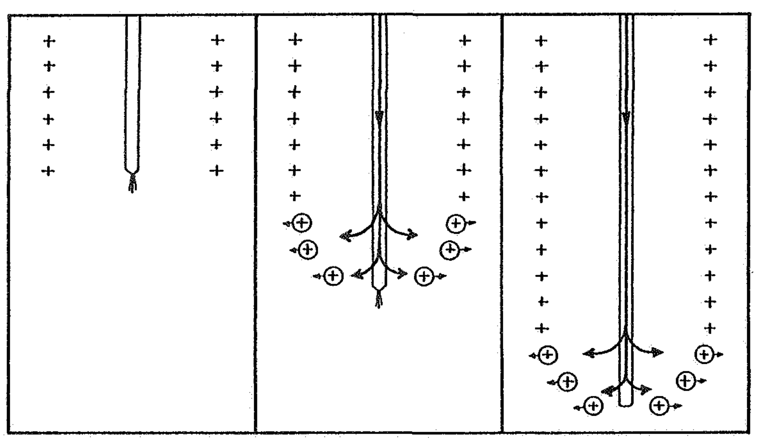

Fig. 5. The Charge Sheath Extension
The individual drawings show the initial, medium and final stages of a step. The balance current is indicated by the heavy curve with arrows. The charge elements are shown as +, those moving are inside circles. The drawing is not to scale.

balance and the oscillation charges are of the same type, oscillations are reinforced. When they are opposite, oscillations are damped. The former step type is likely to be most pronounced, and the oscillations are consequently sustained and amplified.

The balance current must be the main agent for heating the whole channel to luminosity. The charge distribution in figure 4 may be used for an estimate: The lowest terminal has a charge density of 3.5 mC/m. An extension of 50 m over 1 µs demands a current of 175 kA. The secondary oscillating current is likely to be considerably weaker. Photographs agree with this concept. According to the idealized diagram of Schonland et al [1] and the photographs of Salanave [2], the whole channel is visible at the moment of extension and becomes extinct for a much longer time inbetween.

In the furher course of events the channel apparently defies spread of the luminous molecules. In a cross-section the periphery is cooled between the current-pulses. The channel appears stable and narrow because new pulses again and again find their way along the best path in the core region and revitalizes the channel along its axis.

OSCILLATION CHARACTERISTICS

The lightning oscillations are defined by capacity and self-inductance. Standard radio formulas [3] may be used for an estimate. The electric quantities depend on the dimensions of the conductor. In the calculation a channel radius of 1 cm is assumed. Estimates in the literature range from millimeters to tens of centimeters. The results are given in table I.

Table I. Oscillation Characteristics for a Vertical Channel

Channel length, m	10	100	500	1000	4000	10000
Capacity, pF	80	604	2570	4830	16400	40000
Self-inductance, µH	15	152	1150	2441	10900	29000
Period, µs	0.2	2	11	22	84	215
Wave-length, m	65	570	3240	6470	25000	64000

The wave length is always long compared to the channel length. The whole channel will consequently oscillate without nodes. Two lightning steps should take place in a full oscillation. The oscillation period agrees well with reported stepped-leader intervals.

An estimate of the energy needed for heating and ionization is called for. Lightning temperatures above 25000 K have been measured, but are probably confined to a very narrow core. For the 1 cm channel let us assume 3000 K and a pressure of 10^6 Pa. The number of molecules per meter channel length is $7.5 \cdot 10^{21}$. If a mean ionization potential of 16 V is used, the calculated energy for singly ionized molecules is 1.2 kJ. Heating the molecules requires an other 1 kJ. These are the major energy requirements. Let us assume that a 1000 m channel is built up in 20 steps, i. e. heating and ionization must take place anew 20 times for a mean length of 500 m.

The energy need is 22 MJ. It is small compared with the 1.2 GJ, which according to figure 2 is the mean energy released.

The oscillation model seems to indicate a lightning path growing somewhat by chance. The released energy is however essential for driving the oscillation. The loss by way of heat radiation and ionization is considerable, and a path extending in the wrong direction cannot be held up for a long time. Some of the lightnings terminating in free air may simply have run out of working energy.

THE GROUND STRIKE

The electro-static computations are meant to illustrate some aspects of the lightning event. With some justification the abcissa of figure 3 may be taken as time. The rate of change for a terminal close to the ground appears to be formidable. It is questionable if the less than perfect ground is able to keep on to a zero voltage in the striking point.

A voltage turmoil is likely to appear at the moment of strike. The model lightning of figure 1 should keep on to some of its negative voltage, but the short-circuited base would immediately be raised to zero. A positive pulse is thus fed into the channel and will start its way upward as a return stroke.

It should be noticed that neither the ground strike nor the return pulse has an immediate effect on the charge sheath outside the channel proper. A comparatively slow discharge must therefore follow. The oscillation model thus leads to a two-step electric signal, an instantaneous jump followed by a slower final discharge.

The present theory establishes the stepped leader as the main lightning stroke. It releases the bulk of the available electrostatic energy. It transfers the charge. It is, however, brought about in smaller steps, the mean is a "slow" transfer. The electro-magnetic radiation may for this reason be fairly weak, and instruments based upon sensing radiation may faultily record the first ground strike as a rather insignificant event.

FURTHER MODEL POTENTIALITIES

Up to now only the lower end of a channel has been studied. The model does not imply any difference between the terminals. The other end is expected to extend out of the region where it was created.

An extension upwards could imply a lightning towards the ionosphere simultaneously with the lower flash. Such thoughts apparently have been put forward earlier, based upon observations. A discharge towards the more diffuse ionosphere is not so abrupt as that towards the ground, and the prerequisite for a following shock-pulse may not be present.

The upper terminal need not to proceed upwards at all. A horizontal or even downward growth meets the basic requirements. Some lightning terminations into free air could be "the other end" channels.

Multiple strokes following the same channel are in general observed. The subsequent strokes appear as travelling light pulses. They could be pulses reflected from the upper channel. The model is open for other explanations as well, if a semi-free upper channel is allowed to roam about. On its way it might be able to tap energy from other charge configurations and thus have the power to mend a broken section of the channel. Continuous luminosity might be new and stronger oscillations with the ground as a lower condenser plate. Salanaves photographs indicate oscillations.

CONCLUSION

If a long and narrow conductor is exposed to rapid changes of a strong electric field, electric oscillations tend to be generated. The lightning model proposed owes its characteristics to free electric oscillations. Channel extensions are triggered off when oscillating charge is crammed into the channel terminals.

Many characteristics can be tested against observations published on the lightning phenomenon, and they seem to agree well. Other characteristics are not explicitly mentioned in the literature and may be looked on as predictions. It is the hope of the author that these predictions will be tested.

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