The Mechanism of the Lightning Discharge

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The leader stroke mechanism for the lightning discharge is explained on the basis of ion recombination in the discharge channel. It is assumed that a pilot streamer advances continuously from cloud to ground at a speed of 2×10^7 cm per sec. The current which flows into the tip of the pilot streamer is calculated as 0.1 amp., and it is considered that this current must be maintained at an approximately constant value for the pilot streamer to propagate. The resistance of the channel which joins the pilot streamer to the cloud is then calculated in terms of the ion density, and it is shown that the voltage gradient increases sufficiently to cause successive breakdown of the channel to occur at intervals of some 50 microseconds, i.e., the stepped leader stroke. The high speed of step and dart leaders is explained by the fact that the ion density ahead of their tips is about 10^{10} and 10^7 per cm^3, respectively.

INTRODUCTION

A TENTATIVE theory of the lightning discharge has been developed by Schonland[1] on the basis of his Boys camera studies.[2, 3] The latter show that individual strokes consist of a discharge process, or leader stroke, which develops from a negative cloud to ground and is followed by a return, or main, stroke which develops from ground to cloud along the preionized channel. The initial leader stroke usually proceeds as a series of steps separated by time intervals of some 50 microseconds; each step extends the ionized channel by about 10 meters. The leader process as a whole advances towards ground with a velocity of 2×10^7 cm/sec., while the velocity of propagation of the individual step leaders lies between 1×10^9 and 5×10^9 cm/sec. In order to account for this stepped development Schonland assumed that the leader mechanism is preceded by a pilot streamer, which travels in virgin air at the speed of 2×10^7 cm/sec. This speed is shown by Schonland to be in close agreement with the electron drift velocity v_c, which is given by $v_c=(2E_ce\lambda/\pi m)^{\frac{1}{2}}$, on the assumption that the collisions between electrons and molecules are inelastic. Schonland was not able to account for the remarkable uniformity of the stepped process. However, on plausible assumptions, he indicated that the high velocity of the step leaders could be accounted for on the basis of the Cravath-Loeb mechanism[4] if a fairly uniform density of residual ionization of 10^3 ions per cm^3 is present.

His theory does not explain the exact character of stepping and its uniformity, nor does it describe the exact mechanism of the leader stroke.

A study of the rate of ion recombination in both the pilot streamer and in the step leader has been made in terms of the roughly known conditions in the lightning discharge. It is found that the resistance of the leader channel after 50 microseconds is such that for the estimated current which must be maintained in the pilot streamer the potential gradient increases sufficiently to cause the channel to break down again; the breakdown occurs from the cloud end of the channel. On this basis a fairly clear and complete picture of the lightning discharge can be presented in quantitative agreement with experimental observation.

THE PILOT STREAMER

For simplicity we may consider the discharge path to consist of a cylindrical channel of ions and electrons with a hemispherical tip. Ahead of the tip the high field causes ionization by collision of existing electrons or of photoelectrons produced by the ultraviolet light emitted from the streamer tip, as indicated by Loeb.[5] A current

* Commonwealth Fellow.
[1] B. F. J. Schonland, Proc. Roy. Soc. **A164**, 132 (1938).
[2] B. F. J. Schonland and H. Collens, Proc. Roy. Soc. **A143**, 654 (1934).
[3] B. F. J. Schonland, D. J. Malan and H. Collens, Proc. Roy. Soc. **A152**, 595 (1935).
[4] A. Cravath and L. B. Loeb, Physics **6**, 125 (1935).
[5] L. B. Loeb, Rev. Mod. Phys. **8**, 267 (1936).

then flows up the channel from the advancing tip. Rudenberg[6] has estimated this current in relation to the velocity of propagation v, the field strength E and the radius r. Schonland uses the resulting equation in his calculations and Jehle[7] has deduced a similar expression. Unfortunately, because of a confusion in the interpretation of symbols, the equation given by Rudenberg is dimensionally incorrect. In this paper we will use the expression as it is given by Schonland, *viz.*, $i=\frac{1}{2}Evr$ e.s.u., where E is the electric field at the tip in e.s.u., v is the speed of advance of the streamer and r is the radius of the tip.

The field strength is considered as 30,000 volts per cm. This is the generally accepted breakdown strength of air, and it has been shown by Loeb and Kip[8] to be the field at which streamer propagation is important in the breakdown process. The average speed v of the pilot streamer is known from the observations of Schonland to be 2×10^7 cm per sec. This is about the velocity of electron avalanches observed by White[9] and Raether[10] in fields of 30,000 volts per cm.

We still require to know the value of r before the current can be determined. Some measure of its value can be obtained from the experiments of Raether,[10] who has shown that an electron avalanche spreads laterally to a radius $r=(2Dt)^{\frac{1}{2}}$ where t sec. is the time of travel and D is the coefficient of diffusion. For $X/p=40$ the value of D is 500 and thus $r=(1000t)^{\frac{1}{2}}$. The average time-interval between step leaders has been observed by Schonland to be 50 microseconds and for this value of t the radius $r=0.23$ cm. In our calculations we will take $r=0.3$ cm, for which the current in the pilot streamer is 0.1 amp. by the equation given above. The value so chosen for r is not unreasonable since observations indicate the diameter of the main channel to lie between 1 and 10 cm.[11]

The number of electrons which flow into the tip of the pilot streamer per second may be obtained by dividing the current by the electronic charge and is therefore i/e. Whence the number of electrons per cm is i/ev and the density of electrons is $i/\pi r^2 ev$ per cm³. For the values assumed for i and r the density is 1.1×10^{11} ions per cm³. The value seems a reasonable one, as it is known from the experimental work of Loeb and Kip[8] that streamers of ion densities of 10^{12} ions per cm³ can barely be detected photographically. Thus the fact that the pilot streamer has not been photographed for the lightning discharge is simply accounted for. The density calculated is that at the advancing tip of the pilot streamer. Because of recombination the density in the channel decreases with distance from the advancing tip, and by the time the tip has progressed 50 microseconds the density is $N=N_0/(1+N_0\alpha t)=10^{10}$ ions per cm³ (where the recombination coefficient α is taken as 2×10^{-6} from the data given by Sayers[12]).

The Stepped Leader

The tip of an individual step leader, as it travels down the pre-ionized path, is only weakly recorded on the photographs given by Schonland. Experiments by Loeb and Kip[8] show that a cluster of 50 streamers one cm long can be photographed when the total number of ions produced per streamer is 10^9; the streamer diameter is given to be about 0.01 cm and so

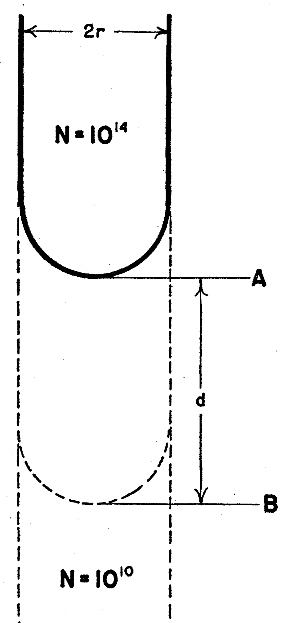

Fig. 1. Diagram to illustrate step leader development.

[6] R. Rudenberg, Wiss. Veröff Siemens-Konz. 9, part 1 (1930).
[7] H. Jehle, Zeits. f. Physik **82**, 784 (1933).
[8] L. B. Loeb and A. F. Kip, J. App. Phys. **10**, 142 (1939).
[9] H. J. White, Phys. Rev. **46**, 99 (1934).
[10] H. Raether, Zeits. f. Physik **107**, 91 (1937).
[11] B. F. J. Schonland, Phil. Mag. **23**, 503 (1937).
[12] J. Sayers, Proc. Roy. Soc. **A169**, 83 (1938).

the ion density is of the order of 10^{14}. We will thus consider that the ion density in the tip of the step leader is 10^{14} ions per cm^3, though the calculations are not materially affected if a value of 10^{13} or 10^{15} is adopted. The ionization decays rapidly with time, and after 50 microseconds, when the subsequent step leader occurs, its value is only 10^{10} ions per cm^3. This is the ion density ahead of the tip of the step leader. As the step leader progresses it eventually encounters a maximum density of 10^{11} ions per cm^3, when it catches up with the pilot streamer. It will later be shown that when the value of ion density of 10^{10} per cm^3 is reached the resistance of the path is so great that the potential gradient is sufficient to cause further breakdown of the channel.

The high velocity of the step leader can now be explained in terms of the ion densities given on the basis of the Cravath-Loeb mechanism as modified by Schonland. Consider the densely ionized tip of the streamer to have reached the position A, as shown in Fig. 1, and that the field strength at B, a distance d ahead of the tip, is 30,000 volts/cm. The distance x moved by the electron originally at B in the direction of the field must be such that by the time it is enveloped by A it must have produced the necessary 10^4 additional electrons to increase N from 10^{10} to 10^{14}, i.e., $e^{\alpha x}=10^4$, or $\alpha x=9.2$, where α is the Townsend primary ionization coefficient. Now the distance moved by the electron is $x=vt$ where v is its mean velocity in the direction of the field and t is the time during which it is subjected to this field. This latter time t is given by $t=d/u$, where u is the speed of the advancing tip and is large compared to v. We then have a condition necessary for the tip to propagate, *viz.* $\alpha vd/u=9.2$. Since the velocity v is approximately 2×10^7 cm/sec., and the average velocity u is 2×10^9 cm/sec., the condition reduces to $\alpha d=920$.

In order to calculate what value of d is required to satisfy this relationship, it is necessary to consider the field distribution. We will consider a hemispherical tip to the step streamer, as was the case for the pilot streamer, and that the field at a distance x from the center of the tip is given by $X=rV/x^2$, where V is the tip potential. We have already stated that the field strength is 30,000 volts per cm when $x=d+r$, and so we may write $X=3\times 10^4(d+r)^2/x^2$, or $X/p=39.5(d+r)^2/x^2$. If we plot such a field for $r=0.3$ cm and different values of d, and then plot the corresponding values of α, we find that $\alpha d=920$ for $d=0.8$ cm. The potential at the tip A of the step leader is then 400 kilovolts with reference to B. Thus the high speed of the step leader can be explained without the introduction of an excessively high potential gradient at the tip.

The necessity of stepped leaders can be explained by the fact that the current flowing into the pilot streamer must be maintained at an approximately constant value in order that it may advance in its evidently continuous manner. It is thus reasonable to suppose that a second step streamer will be initiated when the voltage gradient along the channel is sufficient to cause it to break down. Now the specific resistance of a gas which contains N ions per cm^3 is given from the well-known mobility equation as $R=2mc/Ne^2\lambda$ e.s.u.$=(1.3\times 10^{15})/N$ ohms per cm^3, where e is the electronic charge, m the electronic mass, λ the mean free path (5.4×10^{-5} cm) and c is the average thermal velocity (10^7 cm/sec.). The resistance of the channel is then $(1.3\times 10^{15})/\pi r^2 N=(4.6\times 10^{15})/N$ ohms per cm. After a time interval of 50 microseconds since the previous step leader we have shown that the ion density in the channel decays to 10^{10} ions per cm^3 and thus the resistance is 4.6×10^5 ohms/cm. The voltage gradient is then 46,000 volts per cm if we consider the pilot streamer current to be maintained at its value of 0.1 amp. This gradient is more than sufficient to cause breakdown; the usually considered breakdown voltage of 30,000 volts per cm would be reached after a time interval of 33 microseconds since the previous step, which is consistent with observed values.

On this basis we can present the following picture of the stepped leader process. The latter is initiated in the form of a pilot streamer by a suddenly occurring local voltage gradient of about 30,000 volts per cm. The possibility of such intense local gradients is most likely in view of the experiments of Simpson and Scrase,[13] who have shown that local concentration of

[13] G. C. Simpson and F. J. Scrase, Proc. Roy. Soc. **A161**, 309 (1937).

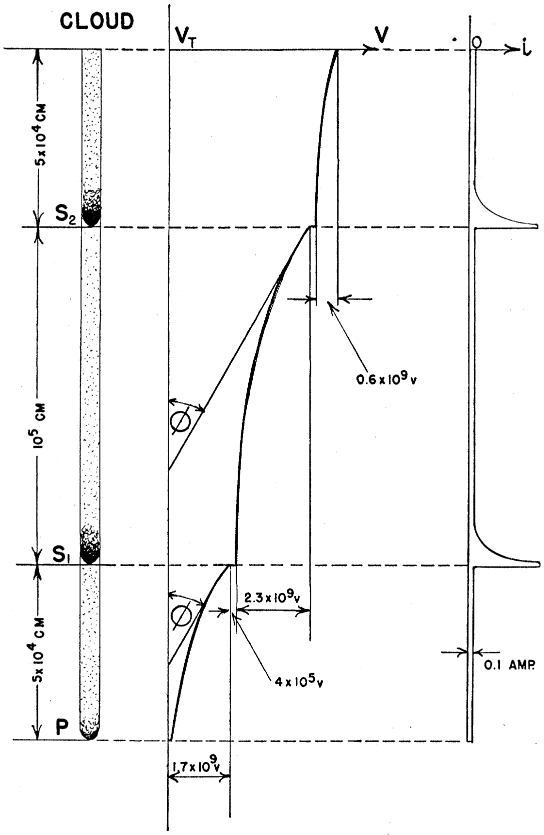

FIG. 2. Voltage and current curves for a stepped leader stroke of length 2 km, when the first step leader S_1 is 5×10^4 cm from the pilot streamer P. The voltage gradient 30,000 volts per cm is given by tan ϕ.

positive charge frequently occurs in the otherwise negatively charged cloud base. When the pilot streamer has traveled for a time of 50 microseconds or so the voltage gradient of the ionized channel at the cloud end increases to such a value that a further breakdown of the channel is initiated, the breakdown proceeding from the cloud end. This breakdown procedure is the step leader observed by Schonland. Since the density of ions ahead of its tip is 10^{10} ions per cm^3, its high speed of 2×10^9 cm per sec. or so can simply be explained. The current which flows in the tip of the step is about 2000 amp., if we consider a tip density of 10^{14} ions per cm^3 and the speed 2×10^9 cm per sec. Thus a high current flows in the cloud end of the channel when a step leader develops. This high current causes the potential of the cloud in the vicinity of the cloud end of the channel to drop immediately, and thus the current is not maintained at its high value, i.e., we can consider an attenuated current pulse to travel down the pre-ionized channel. When the step leader overtakes the advancing tip of the pilot streamer the latter is re-energized and proceeds to advance.

The procedure of successive breakdown, or stepping, is illustrated in the schematic diagram given in Fig. 2. Two step leaders S_1 and S_2 are shown to travel down the pre-ionized channel at the same instant; this occurs when the total length of the path traced out by the pilot streamer P is in excess of the distance traveled by a step leader in 50 microseconds, *viz.* 10^5 cm. The fall in potential from V_c at the cloud to V_T at the tip, and also the current pulses, are represented.

THE MAIN STROKE

When the stepped leader stroke approaches within a few meters of the ground the field intensity is sufficient to cause an upward-developing positive streamer to occur. This positive streamer, which forms the main stroke, travels up the pre-ionized path at a speed of 10^9–10^{10} cm per sec. The speed is observed to decrease as the main stroke develops. Such a decrease in speed can be explained by the fact that the density of ions ahead of the tip falls off as it advances.

The reason why the main stroke does not develop from the cloud is that the latter has such a high internal resistance (it consists of pure water vapor) that a large current flow along the channel from the cloud end immediately causes a decrease in potential in that vicinity. However, the ground is of comparatively low resistance, and the development of the positive streamer is accompanied by no appreciable change in potential. We can thus liken the cloud-ground system to a large condenser only one of whose electrodes can be considered as conducting, and the discharge of the condenser takes place from this electrode. When the main stroke reaches the cloud end of the ionized channel the current does not cease immediately when the charge in the vicinity of the channel has been drained. The main stroke continues to develop as a positive leader stroke to remove further charge from other regions of the cloud.

Malan and Collens[14] have investigated the fine structure of the main stroke and show that steps occur from the ground, in particular when the main stroke reaches a branching point. The stepping may be accounted for in a similar fashion to that described for the leader stroke development, i.e., that breakdown occurs successively from the ground end of the channel due to the increase of voltage gradient. When the main stroke reaches a branching point the current increases suddenly, to maybe double its previous value, and thus it is reasonable to suppose that a step will be initiated.

The Dart Leader

After the first main stroke of the discharge as many as forty further strokes may take place along the same ionized path; the average time interval between such strokes is given by Schonland as 0.03 sec. These subsequent strokes are not preceded by a stepped leader but by what Schonland has termed a dart leader. This dart leader usually travels continuously from cloud to ground at an average speed of 2×10^8 cm per sec.; occasionally, when the time interval since the previous stroke is exceptionally long, the dart leader is stepped as it approaches the ground. Dart leaders and the corresponding main strokes are found to follow the path of the original main stroke in detail.

The initiation of dart leaders is different to that of step leaders. We can consider that no current is flowing in the ionized channel for some time before the dart leader occurs; thus the ionized channel now forms an extended point of potential approximately that of the ground. When the cloud voltage has built up sufficiently in the region of this point breakdown will occur to the point and a dart leader will then develop down the channel from cloud to ground and will be followed by a main stroke in the reverse direction.

The speed of the dart leader can be explained in the same manner as that for the step leader, since it travels down a pre-ionized channel. The ion density ahead of the tip of the dart leader is given by $1/\alpha t$, since N_0 the original ion density in the previous main stroke is high. For the usually observed time interval of 0.03 sec. this density is then 1.7×10^7 ions per cm^3, in comparison with the 10^{10} ions per cm^3 ahead of the tip of the step leader.

[14] D. J. Malan and H. Collens, Proc. Roy. Soc. **A162**, 175 (1937).

The Upward Stepped Leader Stroke

As a result of recent investigations of lightning discharges to the Empire State Building, McEachron[15] has shown that the discharge in general starts from the top of the building in an upward-developing positive stepped leader process, the inverse of the downward-developing process observed by Schonland. The same physical picture which we have given above applies equally well to both processes. However, McEachron was able to obtain oscillograms of the current which flows to the leader stroke, and it is interesting to compare this measured current with the calculated value. The current is seen to fluctuate in correspondence with the outset of stepped leaders, but the resolving power of the oscillograph used is not sufficient to enable the current fluctuations to be accurately determined. However, the peak value of the currents is observed to increase from about 50 to 650 amperes. Since the average speed of an individual step leader is given by McEachron as 6×10^9 cm per sec., the current which flows into its tip is $i=N\pi r^2ev$ e.s.u. $=2.7\times10^{-10}N$ amp., where N is the ion density in the tip and $r=0.3$ cm is the channel radius. Now the minimum value of N is set by the ion density in the tip of the pilot streamer, or else stepped propagation would not occur. We have calculated this ion density as 1.1×10^{11} ions per cm^3, and from this we obtain a minimum current of 30 amp. The higher value of 650 amp. for the leader current, as given by McEachron, can be accounted for if $N=2.4\times10^{12}$ ions per cm^3, which seems a reasonable value in view of the fact that the step leaders are so weakly recorded in the photographs.

The upward-developing stepped leader is not followed by a return stroke from the cloud, for reasons given in the section on the main stroke.

The succeeding strokes of a discharge are of the same type as observed by Schonland for discharges to open country, i.e., downward-developing dart leader strokes followed by main

[15] K. B. McEachron, J. Frank. Inst. **227**, 149 (1939).

strokes which travel from ground to cloud. Occasionally a positive charge was lowered to ground by one of these succeeding strokes; no change in the direction of development of the dart leader was observed. All these facts are in agreement with the interpretation of the dart leader as given earlier in the paper.

Cloud to Cloud Discharges

Discharges which occur between clouds consist of a stepped leader stroke but no return stroke.[3] A similar development is observed for the discharge which starts out from the cloud towards ground, but which terminates in mid-gap.

This is in full agreement with the statements on the main stroke in the section of that title. The termination of a discharge in mid-gap is probably due to the fact that it proceeds from a source which is of sufficient voltage to initiate the discharge but of too low an energy to maintain it.

The Potential of the Cloud

The potential of the tip of the leader stroke when it is close to the ground may be neglected in comparison with that of the cloud. Thus an estimate of the potential of the latter may be obtained by integrating the potential gradient along the leader stroke channel.

Reference to Fig. 2 will show that when the distance between cloud and ground exceeds 10^5 cm two step leaders can be traveling along the channel simultaneously. Now the usually estimated height of a cloud is 2 km, i.e., 2×10^5 cm. Hence the total potential gradient along a channel of such length is

$$2\int_0^{10^5} R_x i\, dx,$$

where R_x is the resistance per cm at a section of the channel distant x from the tip of the step leader. The time interval since the tip passed x is $t=x/u$, where $u=2\times10^9$ cm per sec., the average speed of the step leader. Now the resistance of the channel has been given earlier in the paper as $(4.6\times10^{15})/N$ ohms per cm, so that $R_x=(4.6\times10^{15})(1+N_0\alpha x/u)/N_0$ ohms per cm. The current in the leader channel is 0.1 amp. and therefore the potential V_c of the cloud is given by

$$V_c=2\times0.1\int_0^{10^5}\frac{4.6\times10^{15}}{N_0}\left(1+N_0\alpha\frac{x}{u}\right)dx$$
$$=9.2\times10^{14}(10^5/N_0+5\times10^{-6})\text{ volt.}$$

In our calculations for the step leader mechanism we have considered $N_0=10^{14}$, so that the potential of the cloud is 4.6×10^9 volts.* This value is only changed by one percent if we take $N_0=10^{12}$.

The Spark Discharge in the Laboratory

The leader/main stroke sequence has been observed by Allibone and Meek[16, 17] for sparks between different types of electrodes separated by gap lengths between 25 and 200 cm. It is found that the development of the leader stroke is slowed down by the inclusion of resistance between the voltage source and the discharge gap, and that stepping can be produced if the resistance is sufficiently high. The fact that series resistance has such a marked effect on the development of the leader stroke to a spark substantiates the theory which has been put forward for the lightning discharge, where the high resistance is provided by the leader channel itself.

Preliminary calculations indicate that many of the phenomena of spark breakdown can be accounted for on the basis of ion recombination, and the results of these calculations will be published shortly. It is considered that stepped development of the spark will be observed when the latter occurs over gap lengths greater than ten meters or so, even though there is low resistance between the discharge gap and the voltage source.

In conclusion the author wishes to thank Professor L. B. Loeb for his continual interest and valuable suggestions in the development of the theory, and in particular for his most helpful criticism.

* *Note added in proof.*—Further calculations, based on an oscillographic study of the voltage required to break down a pre-ionized gap in the laboratory, now indicate that propagation of a lightning discharge can occur for an average voltage gradient between cloud and ground of only 600 volts/centimeter. Details of these calculations will be given in an article on the electric spark which will shortly be published.

[16] T. E. Allibone and J. M. Meek, Proc. Roy. Soc. **A166**, 97 (1938).

[17] T. E. Allibone and J. M. Meek, Proc. Roy. Soc. **A169**, 246 (1938).