

ON THE FINE STRUCTURE OF ATMOSPHERICS NEAR THEIR ORIGINS

Part II. Interpretation of pulsive waveform of leader stroke

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Synopsis—The greater part of this paper is concerned with the interpretation of pulsive waveforms emitted by cloud discharges. The fine structure of these waveforms has already been discussed in Part I. of this paper. ¹⁾ The statistical analysis of time intervals between large amplitude pulses on the waveform of violent cloud discharge, as well as of moderate cloud discharge, has shown that the minute discharge processes, each of which emits a large pulse, occur nearly at random in the course of a cloud discharge, and that the typical waveform of cloud discharge is composed of a random series of these large pulses. These results have lead the present authors to the conclusion that the minute discharges which occur in the course of a cloud discharge process and emit their respective large pulses do not correspond to each of the step streamers composing a whole of a stepped leader of violent cloud discharge, but correspond either to the exceptionally rapid step streamers, which present themselves thoroughly by chance from time to time in a train of step streamers forming up a complete stepped leader, or to the random streamers which have the characteristic of a dart leader with short channel length and occur in the course of a moderate cloud discharge. This is just the same conclusion as that has already been obtained in Part I. ¹⁾

The analysis of time intervals between small amplitude pulses on the waveform of violent cloud discharge, on the other hand, has indicated that the minute discharge processes, each of which emits a small pulse, can be inferred to correspond to the streamers having the same characteristic as the stepped leader of a ground discharge. Only one difference found between the nature of minute discharge processes emitting small pulses on the waveform of violent cloud discharge, and that of step streamer processes forming α type stepped leader of a ground discharge, is that the lower limit of the time interval between minute discharge processes is smaller than that of the time interval between step streamers. ²⁾ Generally speaking, this must mean that the stepped leader of cloud discharge can have smaller value of time of step pause than α type stepped leader of ground discharge. It can be concluded from the present results that the cloud discharges largely consist of β type stepped leaders, when the discharges are violent in a thunder cloud and the structure of them has the nature of a stepped leader.

1. Introduction.

It is a remarkable fact that the atmospheric waveform of violent cloud discharge is generally constructed of a clear train of pulses. This type of waveforms can be observed in "a" field change of the first stroke of a multiple ground discharge. ³⁾ Schonland and his collaborators inferred from their observational ground that "these electrical pulsations are due to the sudden appearance of each step streamer" in the case of ground discharge. ³⁾ As regards the cloud discharge one can similarly observe the waveforms which bear the resemblance to those of the first leader of a ground discharge, when the discharges concerned are violent; as well as the waveforms which

seem to radiate from partial discharges in thundercloud, when the discharges concerned are moderate. As Boys' camera investigation of cloud discharges recently carried out by Sourdillon ⁴⁾ has shown that the discharges in the cloud can be divided at least into three types, i.e., leader-return stroke type, multiple discharge type, and discharge which gives nothing other than streaks or obscure images on the photographic record by Boys' camera, it will be an interesting problem to interpret the pulsive atmospheric waveforms emitted by cloud discharges from the process of the stepped leader and that of the dart leader in thundercloud. It is the principal purpose of this paper to interpret the nature of the train of pulses forming up an atmospheric waveform from cloud discharge close to the observation station.

2. Pulsive waveform of cloud discharge.

In the case of cloud discharge waveform, it has been pointed out in Part I. that the frequency distribution curve of time interval between pulses can be classified at least into three cases according as the amplitude of pulses, between which the time interval is to be considered, has large, medium, or small value. ¹⁾ The correlated atmospheric waveform and electrostatic field change studies of the cloud discharge close to the observation station have made it clear that the pulses which present themselves on the waveform of cloud discharge are emitted not only by the discharge process producing a fast electrostatic field change but also during the process which produces a slow electrostatic field change, and further that the latter discharge process, being judged from its duration and progressing velocity in thundercloud, can be inferred to be a kind of "Junction streamer process" in thundercloud. ^{5 a)} Fig. 1. A represents the percentage number frequency distribution of the time interval values between large amplitude pulses on the cloud discharge waveform and fig. 2. A illustrates a typical example of the waveforms which have been used to plot fig. 1. A. The distribution of fig. 1. A is obtained by using the waveform records from lightning discharges in an

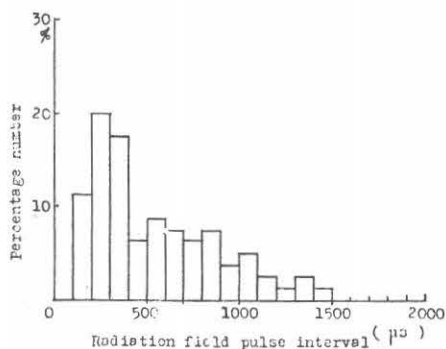


Fig. 1. A : Percentage number frequency distribution of time interval values between large amplitude pulses on the waveforms of lightning discharges in an active cumulonimbus in the sight.

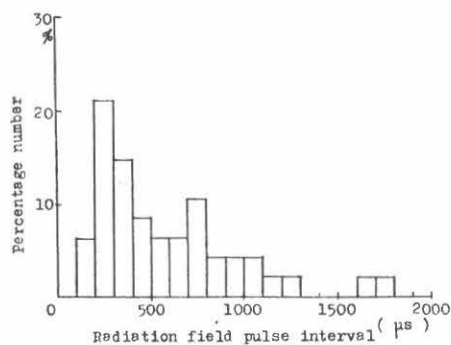


Fig. 1. B : Percentage number frequency distribution of time interval values between large amplitude pulses which occurred on the waveforms that were ascertained from the correlated electrostatic field meter record to associate with "Junction streamer processes" in thundercloud.

active cumulonimbus in the field of view without audible thunder. Therefore, it is certain that the used waveform records in this plotting can be presumed to radiate, for the most part of them, from the discharges actually occurred in that cloud. Fig. 1. B is reproduced for the purpose of comparison with fig. 1. A and represents the case, in which it is ascertained from the electrostatic field meter record that the waveforms used to plot the figure are emitted by "J" streamer processes, i.e., a slow discharge process in thundercloud. The mean distance of these cloud discharges from the station was estimated to be about 20 km. A typical example of waveform and correlated slow electrostatic field change records is illustrated in fig. 2. B, a. and b. respectively. The cloud discharge waveforms in this thunderstorm, each of which was composed of a random distribution of pulses, rather seemed to be classified into the partial discharge type waveform radiating from moderate cloud discharge.⁷⁾ Nevertheless the close investigation of these two frequency distributions, fig. 1. A, and B, which express the probability of occurrence of a time interval value between large pulses, indicates that the waveform of the latter case actually has the nature of the stepped leader type waveform radiating from violent cloud discharge,⁷⁾ so far as only large pulses are taken into account. This fact shows that the classification made in a previous paper,⁷⁾ by considering only large pulses, of the leader type waveforms of cloud discharge into partial discharge type, and stepped leader type is only a superficial one, and suggests that there are great many varieties among actual cloud discharges, from partial discharge type to stepped leader type, and any fundamental differences can not exist between the discharge mechanisms producing these two kinds of waveforms.

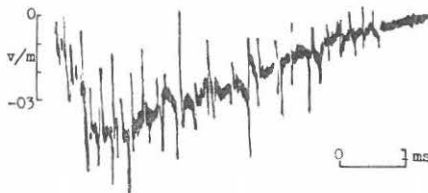
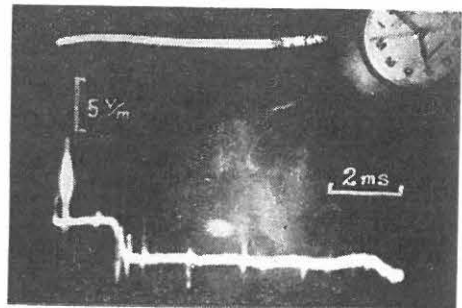
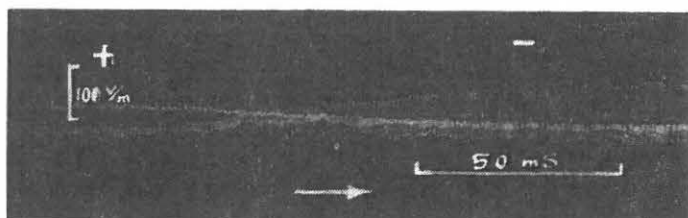


Fig. 2.A : A typical atmospheric waveform of violent cloud discharges.

Fig. 2.B : A typical correlated atmospheric and electrostatic field change records of "Junction streamer process" in thundercloud :

a. Partial discharge type waveform,





b. Slow electrostatic field change denoting a kind of "J" discharge process produced by the same cloud discharge corresponding to the waveform a.

The lightning phenomena being a kind of spark discharge, it will be plausible to consider that the discharge, which takes a form of a streamer and emits an electromagnetic pulsation composing the fine structure of cloud discharge waveform, does not always initiate itself just at the moment when the potential gradient at the discharging point has attained to the critical value necessary for the electrical breakdown, but can also start somewhat afterwards behind this moment. This delay of discharge initiation should vary from one discharge to another and accordingly the occurrence of each pulse onto the waveform must show some fluctuations which submit to the law of probability.

⁸⁾ The time interval value between successive pulses on the waveform of cloud discharge, therefore, must show corresponding fluctuation. This means that the percentage number frequency distribution curve of the time interval value between pulses can be interpreted as a problem of probability, as it is experimentally known in the case of time lag phenomena of a spark discharge initiation.

M.v. Laue ⁹⁾ interpreted the percentage number frequency distribution curve of sparking time lag as a problem of spark occurrence probability. If time t is measured from the moment, when the potential gradient at the discharging point in thundercloud has attained to the critical value necessary for discharge initiation, the probability $F(t)$ that the time lag of the discharge occurrence is larger than t is given by

$$F(t) = \int_t^{\infty} q dt, \quad (1)$$

where q is the discharge probability density and represents the probability that a discharge occurs in the moment $t, t+dt$. Here $F(t)$ must of course satisfy the normalization condition $F(0)=1$. If μdt represents the probability that the discharge which emits a pulse has not been initiated until time t and is finally initiated in the time interval $t, t+dt$, then $F\mu dt$ is equal to the probability qdt that the discharge actually occurs in the moment $t, t+dt$.

Hence

$$q = F\mu. \quad (2)$$

From equation (1) and (2) one gets

$$dF/dt = -F\mu. \quad (2')$$

Integration of (2)' gives

$$F = \exp \left(- \int \mu dt \right), \quad (3)$$

where $\int \mu dt \rightarrow 0. \quad (t \rightarrow 0)$

If the potential gradient at the starting point of another minute discharge attains instantaneously to the critical value required to initiate a new discharge, as soon as the activity of the preceeding one has ceased, and thereafter the gradient is kept constant at this critical value, then the probability of the succeeding discharge occurrence must become independent of time t , i.e., $\mu=m$ (constant).

Then $P(t)$ becomes

$$P(t) = \exp(-mt) \quad (4)$$

This means that $P(t)$ plotted on semi-logarithmic scale must be linear. If it is allowed to consider that each pulse on the waveform of cloud discharge radiates from the respectively corresponding minute discharge of the same cloud discharge, then the probability $P(t)$, that the pulse interval is larger than t , can be calculated from the percentage number frequency distribution curve of time interval value between pulses by using following equations,

$$P(t) = \sum_{\tau=t}^{\infty} N_{\tau, \Delta\tau} / N \quad \text{and} \quad N = \sum_{\tau=t}^{\infty} N_{\tau, \Delta\tau},$$

where $\Delta\tau$ must be determined adequately to calculate $P(t)$. Fig. 3. shows the curve $P(t)$ calculated from fig. 1. A, which has been obtained from as large number of cloud discharge waveforms as available.

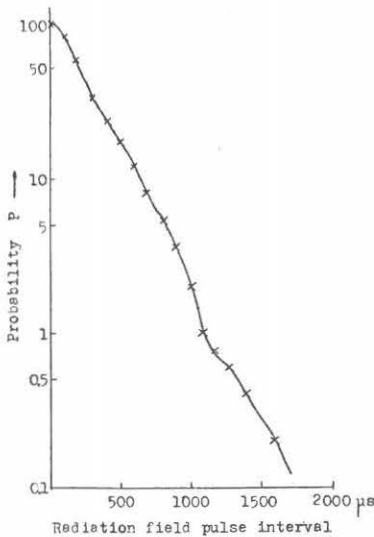


Fig. 3. Probability distribution that the time interval value between large amplitude pulses on the cloud discharge waveform is larger than t .

It is evident from the figure that $\log(P)$ is nearly linear with respect to time t except two ranges, i.e., the range of values smaller than 100 microsecs. and that of 1000 to 1300 microsecs. Hence the occurrence probability of the minute discharge which emits a pulse is seen to be kept nearly at a constant value, after the preceeding one has been completed. Although each of these small but rapid discharges emits a striking radiation field in a form of a pulse, the electrical charge quantity carried by each of them is relatively little compared with that which is transported by a slow discharge process, i.e., "J" streamer process composing the main part of a cloud discharge. The physical conditions required to start a new minute discharge which emits a pulse are recovered at most in less than 100 microsecs after the end of the preceeding minute discharge, and then this state of physical conditions is kept unchanged until the next one begins thoroughly by chance. It may be concluded from these results that, so far as the large amplitude pulses are concerned, the pulsive waveforms of cloud discharge, ir-

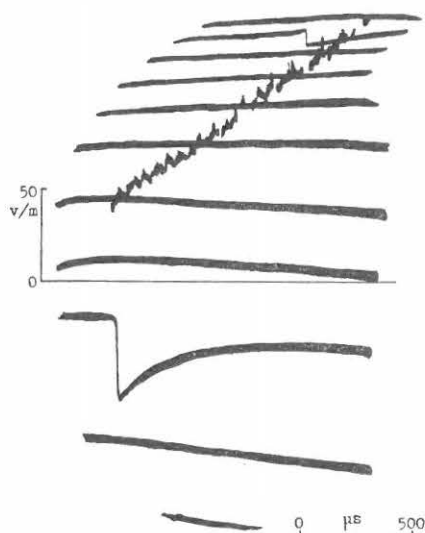
respective of the waveform being partial discharge type in moderate case or being stepped leader type in violent case, are emitted by random, minute but rapid discharge processes associated with a cloud discharge. These discharges may be random small dart leaders which construct the fine structure of moderate lightning discharge in thundercloud, or may be special violent step streamers, which present themselves thoroughly by chance

in a series of step streamers constructing a stepped leader of violent discharge in thundercloud. Fig. 3. further shows some nonlinearity in the range of values smaller than 100 microsecs. This corresponds to the existence of a maximum in the frequency distribution curve of fig. 1. and seems to mean that it takes some time to recover the physical conditions, which are necessary for initiating a new minute discharge, and which have been lost by the preceeding one. This time of recovery will not be negligibly small compared with the time interval between pulses on the cloud discharge waveform, even though only the large pulses are taken into account. This tendency can be more clearly recognized in the case of small pulses, and will be discussed in the following paragraph. In addition to this, the nonlinearity, as represented in fig. 3., in the range of values 1000 to 1300 microsecs. may result from the insufficient number of available data or from the change in probability of discharge occurrence due to the change of the mechanism of minute discharge initiation. As it will be shown in the following paragraph, the investigation of the stroke interval of multiple discharge indicates that the probability, each stroke occurring at a time interval value larger than t , varies rather abruptly from one value to the other smaller value, when the time interval is increased through a critical range of values. It will be probable, in this case to consider that the nature of minute discharge process associated with a cloud discharge is changed a little in this transitional range of values.

3. Pulsive waveform of stepped leader stroke.

The time of step pause between step streamers of α type stepped leader of ground discharge occupies rather a narrow range of values and in 90% of many leaders it lies between 50 and 90 microsecs.²⁾ It was shown by Schonland²⁾ that the time of step pause is determined, for the most part, by the mechanism of discharge which takes place, when a negative streamer proceeds into unionized air.^{10, 11)} However, the fact that it fluctuates from one step to another, rather small as it is, yet seems to indicate the existence of some factors which depend on probability. Although the atmospheric waveforms radiated from the stepped leader should be observed in many of violent discharges in thundercloud as well as in every ground discharge, it is not easy to record many waveforms which correspond clearly to stepped leaders, as far as some appropriate method of lightning observation can prove it. This seems partly to come from the fact that the recording apparatus starts its action only when the triggering circuit is excited by an atmospheric input with larger amplitude than a limiting level conveniently adjusted for observation, and accordingly the initial portion of an atmospheric waveform of stepped leader can hardly be recorded with our apparatus, and partly to come from the fact that the radiation field from each step streamer is clearly small in comparison with the radiation field from return stroke which forms the main part of a ground discharge waveform. At present there are only a few available waveforms which were obtained throughout two years thunderstorm observation and which could be identified with the stepped leader of ground discharge by the aid of visual and acoustic method of lightning observation. A typical example of these waveforms is reproduced in fig. 4. Fig. 5.A represents the frequency distribution of time interval value between pulses on these wave forms. The frequency distribution of time of step pause between step streamers, on the other hand, is reproduced in fig. 5.B, of which the data have been obtained from Boys' camera photographs illustrated in a paper of Schonland.¹²⁾

Although the two distributions of fig. 5. show fairly good coincidence in their general appearances, the one obtained from leader waveforms, however, distributes to more than 150 microsecs. in contrast to the other obtained from stepped leader photographs. At present, it is not clear by the shortage of available data, whether the time of step pause between step streamers, if observed by the electrical method, should fluctuates in the wider range of values than that obtained with photographic method. It may be possible that large time interval values between pulses not radiating from step streamers have been included in the data from which fig. 5. A has been calculated. It is remarkable that the distribution range of time interval values between successive step streamers as represented in fig. 5. clearly differs from that of time interval values between large pulses on the waveform of cloud discharge as represented in fig. 1. As to the case of step streamer interval, there are only a few available records of clear stepped leader waveform of ground discharge, the data obtained from Boys' camera photographs of Schonland ¹²⁾, are used in this case, to obtain the distribution curve representing the probability of the time of step pause between step streamers being larger than t . The result thus obtained is shown by curve A in fig. 7. As it is the purpose of this paper to interpret the pulsive waveforms radiating from the stepped leader of cloud discharge, it will have some significances to investigate the time interval values between small pulses lying between large pulses on the waveform of violent cloud discharge, as shown in fig. 2. A.



8. 12. 15h. 59m. 37s.

Fig. 4. The waveform radiating from a ground discharge at distance within 1 km. from the station.

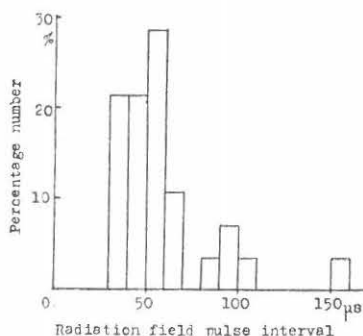


Fig. 5. A: Percentage number frequency distribution of time interval between pulses which lie on the waveforms that have been identified with the first leader of a ground discharge.

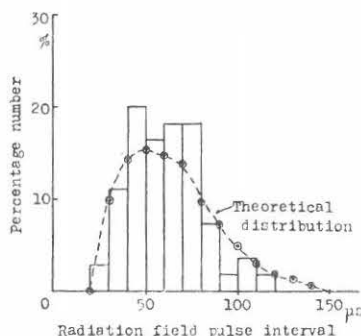


Fig. 5. B: Percentage number frequency distribution of time of step pause between step streamers obtained from Boys' camera photographs of α type stepped leaders.

The frequency distribution of fig. 6. has been obtained by measuring the time interval between small pulses on the stepped leader type waveform radiating from discharges in cumulonimbus lying in the field of view, thus it is certain that the greater part of used data to plot the figure corresponds to the violent discharge in thundercloud. The comparison of fig. 6. with fig. 5. B shows that the frequency distribution of fig.

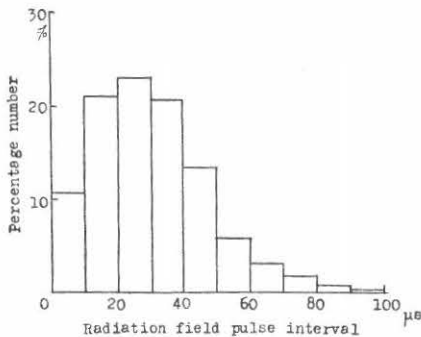


Fig. 6. Percentage number frequency distribution of time interval values between small amplitude pulses on the wave-forms of cloud discharge

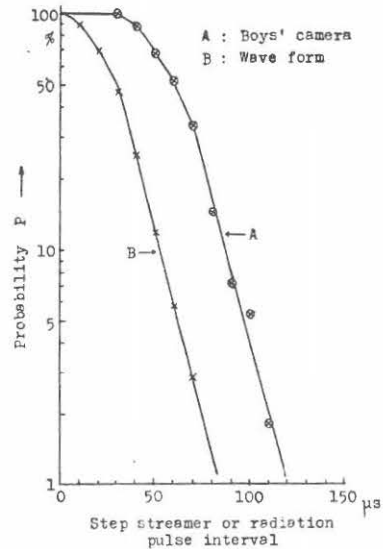


Fig. 7. The probability distribution that the time interval value is larger than t :

Curve A, the time of step pause between step streamers obtained from Boys' camera photographs illustrated in Schonland's paper,

Curve B, the time interval value between small pulses on the waveforms of lightning discharges in cumulonimbus in the sight.

6, in its general aspects, has nearly the same characteristic as fig. 5. B; however, the further investigation of their details shows that the maxima in these two curves lie at about 30 microsecs. and 50 microsecs. respectively. It is not wholly clear at present whether this difference has some definite significances or not. Nevertheless, it seems reasonable to consider that the time of step pause between step streamers of violent cloud discharge generally has the smaller value than the case of ground discharge, of which the point will be discussed in the next. Another difference between these two is that the case of cloud discharge clearly extends toward the smaller side of the distribution range of time interval values than that of ground discharge. This difference in the distribution results in the disagreement between probability distribution curves A and B of fig. 7., in which curve A has been obtained from fig. 5. B and curve B from fig. 6. It is clear from curve A that the distribution of probability that the time interval value being larger than t , between successive step streamers of α type stepped leader of ground discharge, becomes linear in semi-logarithmic plotting when the time interval value is increased beyond 70 microsecs. This tendency is also clearly recognized from curve B of fig. 7., in which only the time intervals between small pulses are taken into account. Moreover, these two curves have nearly the same characteristic and are seen to run almost parallel with each other. The amount of the parallel displacement

between these two is about 30 to 40 microsecs. Although one portion of a time interval value between step streamers must represent the time, which is necessary for the potential gradient at the discharging point of a step streamer to attain to the critical value for electrical breakdown after the gradient having been lowered by the preceeding discharge; the other portion of the same time interval corresponds, at the same time, to the time lag which is required to initiate the succeeding discharge, after the gradient at the discharging point has attained to the critical value necessary for electrical breakdown. How much time lag is required to start a streamer discharge after the least physical conditions necessary for electrical breakdown have been fulfilled, it is of course a problem of probability. Moreover even the time indispensable to the fulfilment of these least conditions seems to have sufficient reasons to show some fluctuations, for the distribution of electrical space charge around the head of a cloud discharge channel and the distribution of ions along it can not be kept in a same state of conditions at various instances, so that they must fluctuate from time to time as well as from space to space. However, the fluctuation of this kind is assumed here to be negligibly small in comparison with that of the former kind, and the fluctuation is assumed to depend, for the most part, on the probability of step streamer discharge occurrence after the fulfilment of the necessary conditions for discharge initiation. The flat portion of

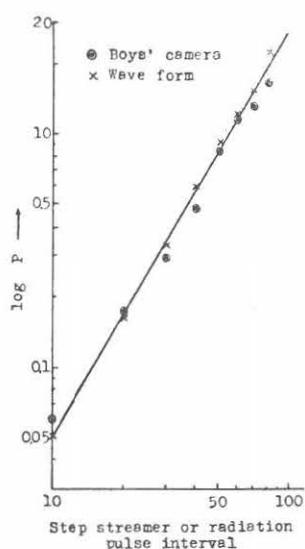


Fig. 8. Probability distribution of the time interval being larger than t ;

● — the time of step pause between step streamers obtained from Boys' camera photographs of ground discharge.

× — the time interval between small pulses on the waveform of discharge in cumulonimbus floating in the sight.

the curve *A* in fig. 7., which lies in the range of values 0 to 30 microsecs., then represents the average time necessary for the fulfilment of physical conditions to initiate the succeeding discharge after the end of the preceeding one. The curved portion of curve *A*, which lies in the range of values larger than 30 microsecs., is to be considered to indicate the intrinsic probability distribution of the time lag of streamer discharge initiation, whilst the case of curve *B* indicates no appreciable flat portion throughout the whole range of values.

This seems to mean that the case of ground discharge requires more time to fulfil the physical conditions necessary for a new streamer discharge initiation after the end of the preceeding one, than the case of cloud discharge. It will be reasonable to consider that with the aid of the author's recording apparatus, the definite portion of a time interval which is determined by the mechanism of cloud discharge can hardly be separated from the other indefinite portion of the same time interval which depends on the probability of discharge occurrence. Hence it can be concluded from these distributions that the time interval value between small pulses, which present themselves on the waveform of violent cloud discharge, is determined, for the most part, by the probability of discharge occurrence as far as the apparatus can resolve it. To confirm this point of view $\log(P)$ curve in the range of values 20 to 120 microsecs.,

in case of curve *A*, the range smaller than 20 microsecs. being omitted, and the curve in the range of step interval values 0 to 80 microsecs. in case of curve *B* are plotted in log-log scale as shown in fig. 8., which clearly indicates that curve *A* and *B* of fig. 7. can be represented by the same straight line. This seems to mean that the minute discharges associated with a violent cloud discharge have nearly the same characteristic as those of α type stepped leader of ground discharge. If use is made of value 1.7 obtained by measuring the mean inclination of the curve of fig. 8., the linear curve of the same figure can be prerepresented by

$$P(t) = \exp(-mt^{1.7}) \quad (5)$$

Here one must consider the case in which the potential gradient at the discharging point grows up continuously in proportion to the power function of t , i.e., t^n , after it has reached to the critical value necessary for the initiation of minute discharge process. In this case over potential gradient v at the discharging point can be represented by

$$v = at^n.$$

It is known from the experiment of spark discharge that the average value of the spark discharge time lag is inversely proportional to the amount of over voltage, when the over voltage is applied between a sparking gap. If this relation can be applied to the case of stepped leader processes, the following relation can be concluded

$$v\bar{t} = k,$$

where \bar{t} is the mean value of the discharge time lag, or the mean value of time interval between pulses on the waveform in this case. If it is allowed to consider that the probability density μ — the probability of the succeeding step streamer to start in the time interval \bar{t} , $\bar{t}+d\bar{t}$, after the end of the previous one — is inversely proportional to the time \bar{t} , where \bar{t} is measured from the moment, when the physical conditions necessary for starting a new discharge are fulfilled after the end of the preceeding one, one gets

$$\mu = \frac{1}{\bar{t}} = \frac{a}{k} \bar{t}^n.$$

Substituting μ in the equation (2)' with this relation and integrating it, one can derive the following equations

$$P = \exp\left(-\frac{a}{k} \frac{\bar{t}^{n+1}}{n+1}\right), \quad (6)$$

$$q = \frac{a}{k} \bar{t}^n \exp\left(-\frac{a}{k} \frac{\bar{t}^{n+1}}{n+1}\right). \quad (7)$$

Comparing the equation (5) and (6), one can determine the numerical value of n , and this gives $n=0.7$. This meaning is that the potential gradient v at the discharging point of a step streamer increases with time t in proportion to $t^{0.7}$ into a over potential gradient state, after it has attained to the critical value required to start the succeeding discharge. These processes of the lightning discharge should, therefore, be considered to present themselves not only in the course of violent discharge in cumulonimbus but also in the course of ground discharge. This point of view can be clearly recognized in fig. 8. In addition the frequency distribution reproduced in fig. 5.B must be necessarily represented by equation (7). As it is difficult to normalize the equation and to determine the constant a/k , the value a/k is determined for convenience, so that the maximum point of the curve lies at the value of time $t=50$ microsecs. The calculation gives

$$q=272 \cdot t^{0.7} \cdot \exp(-160 \cdot t^{0.7}).$$

As the time t in this equation must be measured from the moment, when the necessary conditions for the succeeding discharge initiation have been fulfilled; the

coordinate transformation $t = (\tau - 2 \times 10^{-5})$ must be made in order to plot this equation onto fig. 5.B. The transformed $q-\tau$ relation is represented by the curve drawn with broken line in the figure and gives fairly good coincidences with the observed values. As the observed values are obtained by measuring only two clear stepped leader photographs illustrated in a Schonland's paper ¹²⁾, the interpretation of the minor differences between theory and observation can hardly be made at present.

The above investigation of pulse intervals seems to make it clear that the leader stroke of the violent discharge in cumulonimbus has nearly the same structure and emits nearly the same pulsive waveform as α type stepped leader of ground discharge. Only one difference found between them is that the time necessary for the fulfilment of physical conditions indispensable for the succeeding discharge initiation is clearly smaller in the former case than in the latter. In case of cloud discharge the waveform recorder is not sufficient to separate the definite portion of a time interval value which is determined by the discharge mechanism, and which is estimated to be less than several microsecs., from the other indefinite portion of the same time interval value which is determined by the probability of minute discharge occurrence. Moreover, if one considers the construction of the waveform recorder, of which the recording action is triggered by an input of a discharge pulse, it is reasonable to think that the initial portion of a waveform can be inevitably very hardly recorded. The recorded leader discharge type waveforms, even if they radiate actually from stepped leaders, should usually correspond to the rear part of them. This seems to lead one to the conclusion that the rear portion of the stepped leader process of violent cloud discharge, generally speaking, must have the small values of step interval in comparison with the ground discharge, and hence that the rear portion of many of the stepped leaders of cloud discharges must be constructed from β type stepped leaders. In other words, the violent discharges in the cloud, when they have the nature of the stepped leader, must be constructed, for the greater part, from β type stepped leaders.

4. Multiple stroke of lightning

It is reported by Schonland ¹³⁾ that the time interval between strokes of a multiple ground discharge is determined by the time required for "Junction streamer" to proceed from the top of a discharge channel to the next upper discharge centre during the interval between component strokes, and further that the distance between successive discharge centers, each of which produces the respective component stroke, generally reduces with the height of the centre. The time interval between successive strokes, therefore, must reduce from one stroke to another in succession, if the velocity of "J" streamer advance is kept constant in thundercloud. In actual time interval, however, it fluctuates remarkably, as it is reported by Schonland in a paper of Boys' camera investigation of lightning. ¹²⁾ These inconsistent facts seem to suggest that the time interval between strokes is largely determined by the probability of discharge occurrence. Fig. 9 represents the probability distribution of the time interval between successive strokes, and is obtained from the data of Boys' camera photographs reported by Schonland ¹²⁾. It is seen from the figure that the curve is roughly composed of two linear portions, and the transitional range between them lies at about 120 millisecs. In the case of multiple discharge it takes only a very small fraction of a whole time interval value between strokes to fulfil the physical conditions required to start the succeeding stroke after the end of the preceeding one; in other words, the necessary

conditions for a new stroke occurrence which has been lost by the preceding one are fulfilled almost instantaneously, and thereafter it becomes thoroughly a problem of probability, at what moment the succeeding stroke is initiated, that is, the strokes occur entirely at random. In addition the curve of fig. 9. indicates that the probability μ reduces from one value to other smaller value as the time interval value increases through the transitional range of values lying at about 120 milliseconds. This seems to mean that the discharge process taking place in the time interval between successive strokes change its character and the velocity of "J" streamer advance reduces rather suddenly from one value to the other smaller value, as the life of a "J" streamer increases

through this transitional range of values, provided the distribution density of distances between successive discharge centers being kept uniform; or to mean that the distribution density of distances between successive discharge centers reduces rather abruptly from one value to the other smaller value, as the distance increases through a transitional range of values corresponding to that of time interval between successive strokes, provided the velocity of "J" streamer advance is kept constant in thundercloud. It is, however, not clear at present which of these can interpret the actual distribution of time interval value between successive strokes. According to Boys' camera investigation¹²⁾, it is reported that the long time interval can be observed in the initial part of a multiple discharge in one case and likewise in the rear part of it in another case, therefore one can not expect which part in the time interval series of a multiple discharge should generally have larger values. However, it seems to be reasonable to infer that the long time interval corresponds to an exceptional stroke occurring from time to time in a series of multiple strokes and accordingly that the probability μ of long time interval differs clearly from that of short one.

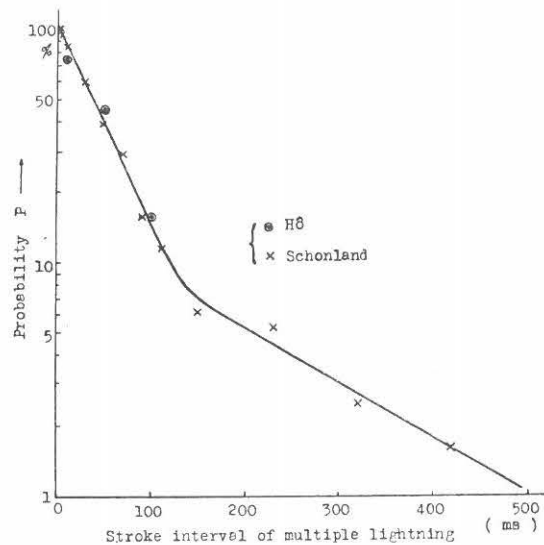


Fig. 9. Probability distribution that the time interval value between successive strokes of multiple discharge is larger than t .

5. Conclusion.

Authors have discussed for the greater part of this paper the fine structure of the cloud discharge waveforms and inferred the structure of discharge in thundercloud. It is concluded from the above discussions that:

(1) The minute discharge processes, each of which emits a clear radiation field in a form of a pulse with large amplitude and which occurs in the course of a cloud discharge, do not correspond to each of the step streamers forming up a whole of a stepped leader of violent cloud discharge, but correspond to the minute intermittent

discharges occurring nearly at random in association with a cloud discharge. Accordingly, they may be either exceptional step streamers occurring at random from time to time in a series of step streamers forming up a whole of a stepped leader in one case, or random dart leaders appearing in association with a cloud discharge in another case.

(2) The potential gradient at the starting point of a step streamer discharge requires some time to recover the critical value for electrical breakdown after the completion of the preceeding one, and the rough estimation of it gives the values 20 to 30 microsecs. in case of α type stepped leaders. The potential gradient at the starting point of a step streamer discharge increases into a over potential gradient state with time in proportion to $t^{0.7}$, even after it has reached to this critical value. It is thoroughly a problem of probability at what moment the step streamer is initiated, after the physical conditions necessary for initiating the succeeding discharge has been fulfilled at the starting point.

(3) Percentage number frequency distribution of the time of step pause between α type step streamers, obtained from the data of Boys' camera photograph, is seen to coincide roughly with that of the time interval between small pulses obtained from the data of waveform records that correspond to the stepped leader of ground discharge. However, there are some differences in details between these two, which are considered to depend, for the most part, upon the shortage of the available, exact data.

(4) Generally speaking, the occurrence probability of the time interval value between small pulses on the waveform of violent cloud discharge has the same character as that of time of step pause between step streamers in α type stepped leaders, of which the data obtained from Boys' camera photographs. Only one difference found between them is that in the former, one can not separate any measurable portion of a time interval value between pulses, which corresponds to the time required to fulfil the physical conditions indispensable for starting a new streamer discharge after the completion of the preceeding one, from the other portion of the same time interval value, which is determined thoroughly by the probability of discharge occurrence; whilst in the latter, the appreciable portion of a step interval is determined by the mechanism of stepped leader discharge. This seems to indicate that many of the lightning discharges in thunder cloud can be classified into β type stepped leaders, if the discharges are violent and emit the stepped leader type waveforms.

(5) In the case of time interval between strokes of multiple discharge it has been made clear that the time, which is required to fulfil the physical conditions necessary for the starting of succeeding stroke, is negligibly small compared with the time interval between them, and further that this state of physical conditions is kept unchanged after the fulfilment of them, therefore at what moment the succeeding stroke will occur, it is thoroughly a problem of probability. This probability value is seen to be kept roughly constant within the range of time interval values up to 500 microsecs except for a transitional range which lies roughly at about 120 millisecs. and in which the probability reduces rather suddenly from one value to another smaller value as the time interval value increases. It is not possible at present to interpret this transition of probability by some definite mechanism of discharge occurring in thundercloud.

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