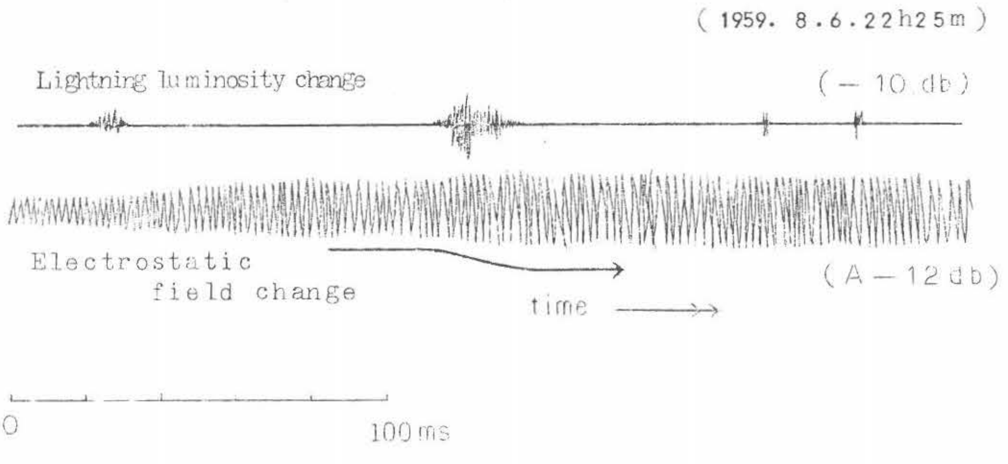
Chapter IV Cloud Discharge

1. Introduction

As we have already investigated in Section 1, Chapter II, the statistical measurement of the record of electromagnetic field changes due to a lightning discharge shows the fact that about 76% of all the recorded lightning discharges are occupied by cloud discharges, which can be divided into three categories, i.e., the intracloud discharge which developes completely inside of a thundercloud, the inter-cloud discharge, in which the middle part of the lightning channel travels through the transparent air outside a thundercloud and both ends of the channel are hidden in the cloud, and the air discharge, which developes from the inside portion of a thundercloud toward the outside of it, hence one end of the lightning channel is included in the cloud while the other end of it terminates in the clear air. Of these three categories, the intercloud discharge and the air discharge have, at least, a part of their lightning channels being recordable with a photographic camera, therefore these discharges are suitec, to a certain extent, for analyzing the structure of the lightning flash. As to the intracloud discharge, in which all parts of the lightning channel are hidden in a opaque thundercloud body, it can be noticed optically only as a curtain lightning.
In this case, there is no way to photograph any part of a lightning channel, and the only one possible optical way is, though indirectly, to know the character of light emissions form the discharge by investigatining the record of flash luminosity changes (see Fig. 1).

Fig. 1



For this reason our knowledge about the mechanisms of a intracloud discharge, so far obtained, are very rough and usually assume the discharge of a vertical dipole. So that we have only a least knowledge especially concerning the fine structure of the discharge which directly relates to the radiation of an atmospheric pulse at present. Concening this point, the development of an observation method which enable us to measure the intracloud discharge more directly, e.g., the radar method of lightning measurement, will promote our knowledges about the discharge mechanism very much.

2. Intercloud discharge and air discharge

The photographs of intercloud discharges and air discharges obtained with our flash resolving camera through thunderstorm observations in several summers have made it possible to measure the progressive velocities of the discharge streamers. Table 1 shows the results of these measurements, which indicates three velocity values of cloud discharge streamers,

Table 1.

lightning flashes		Progressive volcities*	Number of data
Multiple intercloud discharge	First stroke	3.7×10^8 cm/sec	4
	Successive stroke	3.3×10^8	5
	Leader to the first stroke	3.9×10^8	1
	Slow streamer initiating a cloud discharge	5.3×10^6	2
	Fast streamer	more than 10	2
Air discharge		1.2×10^7	10

* Mean Value

i.e., the fast streamer velocity $(3\sim4_7) \times 10^8$ cm/sec, the median streamer velocity $(1\sim2) \times 10^7$ cm/sec, and the slow streamer velocity about 5×10^6 cm/sec. We shall describe hereafter the results of the measurements of the three velocities of intercloud streamers.

(A) Fast Streamer

(a) Multiple intercloud discharge: An example of a fast streamer is illustrated in Photo. 1 (a) which indicates the Boys' camera photograph of a six fold multiple cloud discharge. For the sake of comparison the flash resolving photograph of dart leaders preceding the successive stroke of a multiple ground discharge is illustrated in Photo 1 (b). Fig. 2 is the sketch of Photo. 1 The time values written to the left hand side of the sketch (a) represent the time of occurrence of individual lightning strokes. The direction of streamer progress and the velocity of it are written beside the sketch of the second and the third strokes. The figure (b) represents the sketch of the second and the third strokes of a multiple ground discharge. The dart leaders are expressed with broken lines and the return strokes with full lines. The time interval between the two corresponding point on the dart leader and the return stroke, and the measured progressive velocity of the dart leader are written along the dart leader sketch expressed with broken line. The streamer velocity indicated in the figure (a), $(5.5\sim7.2) \times 10^8$ cm/sec, coincides very well with the dart leader velocity $(4.7\sim8) \times 10^8$cm/sec represented in the figure (b). Moreover the comparison of details of the both leader images in Photo. 1(a) and (b) shows that no differences seem to exist between them. These observational facts lead us to the conclusion that the fast streamers appearing in a intercloud discharge have the character of a dart leader. Further it is very clear from Table 1. that the above point will not be changed whether the discharge being composed of a single stroke or of multiple strokes.

(b) An intercloud discharge involving the first stroke composed of a leader followed by a return stroke: This may be a rare sort of intercloud discharges, because we have succeeded to record the discharge only once till to the present. Photo. 2 indicates a six-fold intercloud discharge, the first stroke of which is composed of a leader followed by a return stroke.
Fig. 3 is the sketch of first stroke of Photo. 2, in which the streamer BC (that constructs) a leader is represebted wuth a broken line and the streamer CB' that constructs a return stroke with a full line and

Fig. 2.

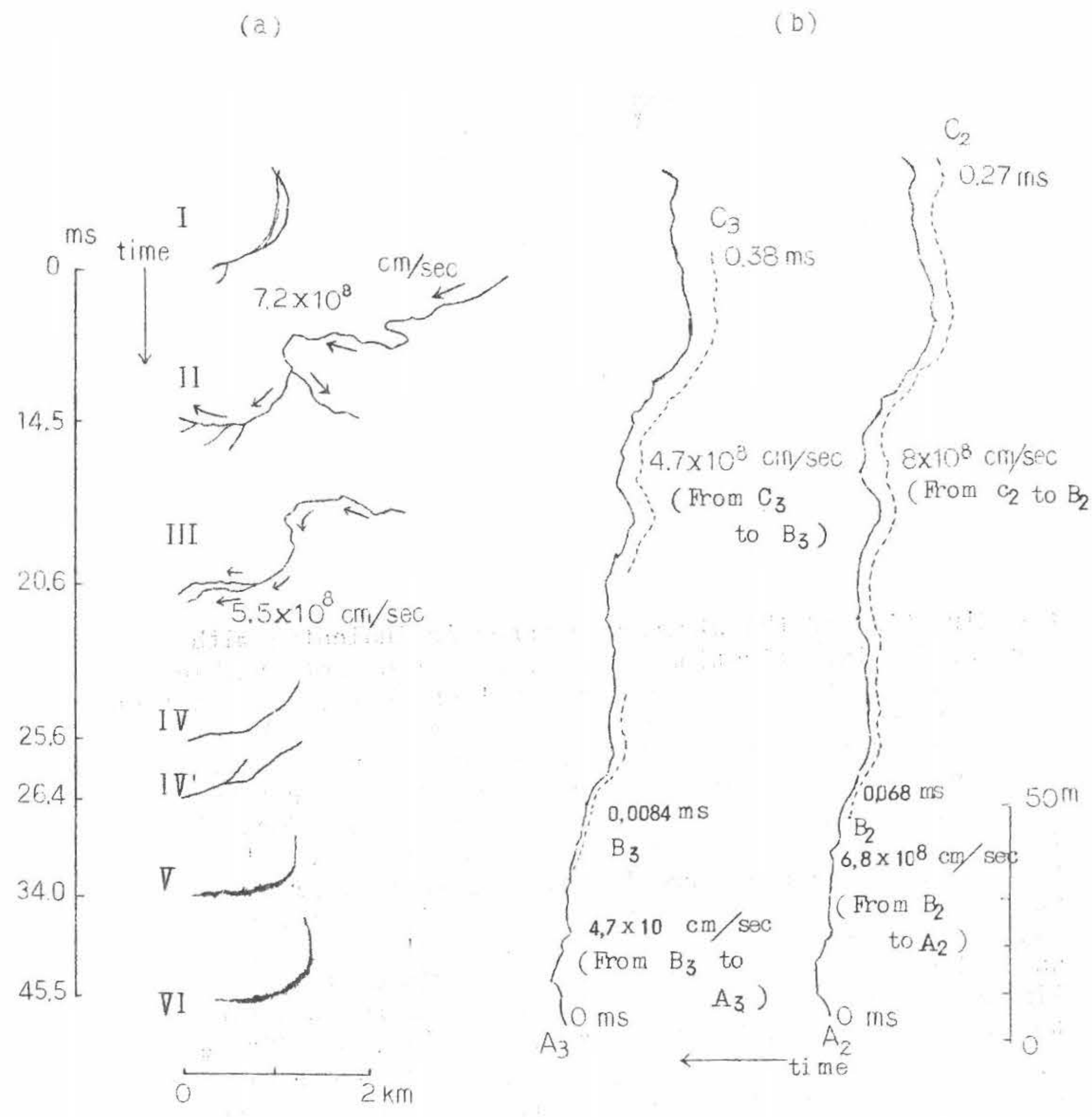
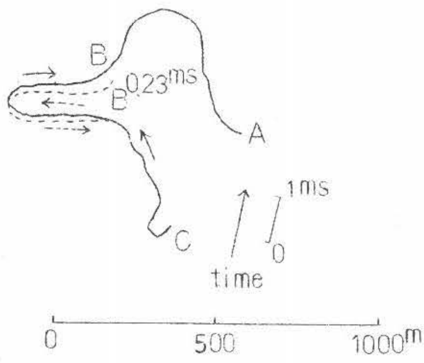

(a)
(b)
ms
time
0
14.5
20.6
25.6
26.4
34.0
45.5
I
II
III
IV
IV'
V
VI
7.2x10^8 cm/sec
5.5x10^8 cm/sec
0
2 km
C2
0.27 ms
C3
0.38 ms
4.7x10^8 cm/sec
(From C3 to B3)
8x10^8 cm/sec
(From c2 to B2)
0,0084 ms
B3
0,068 ms
B2
6,8 x 10^8 cm/sec
(From B2 to A2)
4,7 x 10 cm/sec
(From B3 to A3)
0 ms
A3
0 ms
A2
time
50m
0
1.2
0ms

Fig. 3.



the direction of the streamer advance is indicated with arrows. The investigation of details of the photographic images of the two streamer BC and CB' on Photo. 2 shows that the photographic density of the streamer BC is much lower than that of the streamer CB', which is the relation very similar to that between the dart leader and the return stroke as illustrated in the Photo. 1 (b) Therefore it will be reasonable to consider that the streamer CB' has very higher electric current an very larger progressive velocity than the streamer BC. As the time difference between the two corresponding points B, B' is 0.23 ms as indicated in the figure, and the length of the lightning flash is 0.9 km, so the streamer BC is expected to advance with a velocity $v_L = 0.9 \times 10^5/0.23 \times 10^{-3} = 3.9 \times 10^8$ cm/sec from B to C. This value is comprable with the progressive velocities of individual strokes of an ordinary multiple intercloud discharge, and indicates the streamer BC being not a stepped leader but rather a leader with the profound tendency of a dart leader in spite of the streamer BC occurring at start of the intercloud discharge. Concerning the direction of progression of the streamer CB' it is impossible, from the measurement of Photo. 2, to determine whether the streamer advanced from B' to C or progressed from C to B' because of the slow sweeping speed of the photographic image.

If the streamer B'C progressed to the same direction as that of the leader BC, the latter combined with the streamer B'C would form a β 2 type stepped leader. If the two streamers formed a β 2 type stepped leader, the mean velocity of the streamer BC in the interval between B and C would be about 2 x 10^7cm/sec at most according to the reference (1). But the result of the measurement of Photo. 2 gives V_L = 3.9 x 10^8cm/sec as described above, which seems to indicate that the two streamers do not form a β 2 type stepped leader. Therefore it will be reasonable to consider that the streamer CB' is a return streamer progressing from C to B' in the reverse direction to the leader BC. Thus it is clear that despite of the discharge taking place in the intercloud space, the first stroke of it is composed of a leader followed by a return streamer. Sourdillon(2) also reported in his paper that in some cases, the stroke of a multiple intercloud discharge had the structure composed of a dart leader followed by a return streamer, which seems to coincide with our result.

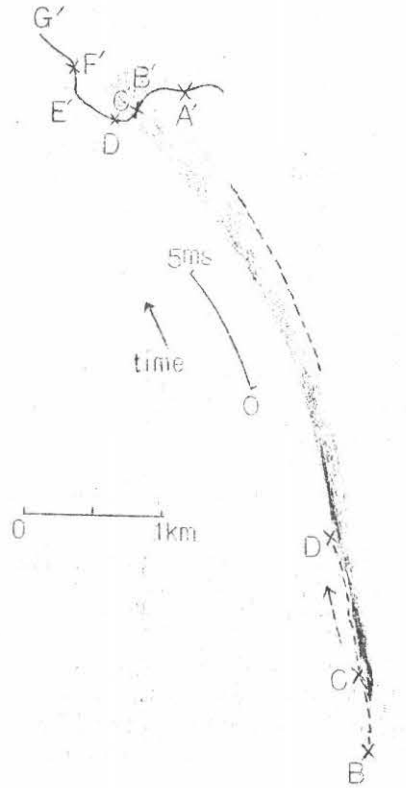
As we have investigated above, the fast streamers with progressive velocities more than (3 ~ 4) x 10^8 cm/sec* appearing in a multiple intercloud discharge usually have not the nature of a stepped leader, but a strong tendency of the nature of a dart leader. Moreover, most of the ordinary intercloud discharges really are composed only of the fast streamers of this kind of dart leaders.

(B) Slow streamer

(a) The intercloud discharge initiated with a slow streamer: There are some intercloud discharges being initiated with a very slow streamers with velocities smaller than 10^7cm/sec. We have succeeded to record two such streamers till to the present, one of which is a single discharge composed only of a slow streamer, and the other of which is a double discharge composed of a slow streamer followed by a fast dart leader of the nature like those composing an ordinary multiple intercloud discharge. The latter is illustrated in Photo. 3, and Fig. 4. represents the sketch of it, in which the slow streamer is represented with a broken line, and the fast streamer composing the secon stroke with a full line, and the corresponding points on the slow and the fast, streamers with (BCD), (B'C'D') respectively,. The direction of the streamer advance is indicated with an arrow.

* Some of the intercloud strokes have a velocity higher than 10^9 cm/sec, and in these, it is impossible to measure a reliable velocity on the photographic record of flash resolving camera.

Fig. 4.

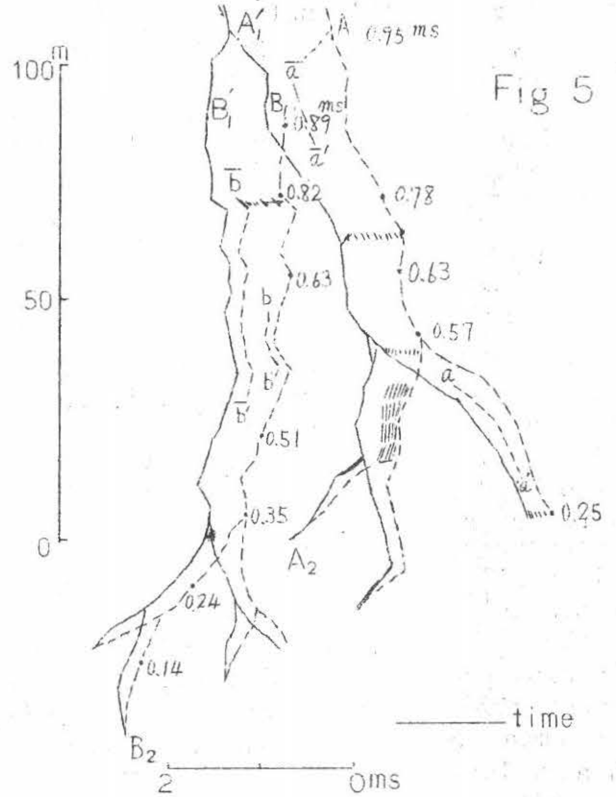


It is clear that the slow streamer gives a photographic image like a coast-line, and the flikering in the photographic densities is observable along the coast-line like image. This feature of the photographic image is the one which is peculiar to a β type stepped leader and must come from the short length of each steps of the leader as well as from the low luminous intensities of individual step streamers. This makes it impossible to record individual step streamer separatedly. If we assume the second stroke A'G' to have a high progressive velocity, we can determine the velocity of the slow leader B D by measuring the photographic image, which gives the value 5.5×10^6 cm/sec. Hence the conclusion is that the β type stepped leader progressed to the direction $\overrightarrow{BCD}$ with the velocity 5.5×10^6 cm/sec. As the second stroke A'G' is preceded by the slow stepped leader BD, the streamer A'G' must be composed of a fast streamer, the progressive direction of which, however, can not be determined from the photographic measurement because of the slow speed of the image sweep. As the velocity of the preceding leader in this case is very smaller than that of the case of photo. 2, and moreover the investigation of the photographic image of the Photo. 3 clearly shows the point that the leader BCD is a stepped leader, so the following two interpretations will be possible in this case, i.e., the one is to consider the succeeding streamer A'G' progressing from A' to G' and the other is to consider the streamer A'G' progressing from G'toA'. If the former is the case, the steramer A'G' must be a negative fast dart leader which, combined with the β type stepped leader BD*, will form a β 2 type stepped leader in a wider sense. If the latter is the case, the streamer A'G' must have a positive polarity, and will form a return stroke preceded by a negative β type stepped leader. The intercloud discharge initiated by a slow streamer process seems to be identical with the cloud discharge that was named by sourdillon the type I. Howeve , if we take the point into account, that many of the multiple intercloud discharges usually are composed of dart leaders, it will be more resonable to consider simply a intercloud discharge composed of a negative β type stepped leader followed by a negative dart leader, i.e., an intercloud discharge with a prodound tendency of a β 2 type stepped leader, in a wider sense, than to conside the latter cloud dishcarge, on the half way of which the polarities of the element streamers are reversed.

(b) Air discharge: As described in Section 1, the air discharge is a lightning discharge, one end of whose channel terminates in a thundercloud and the other end stretches into the clear air. This kindof the lightning discharge generally has a slow progressive velocity, and the measurements of ten photographs give the values ranging within (1.1 - 2.0) x 10^7 cm/sec, the mean of which is 1.2 x 10^7 cm/sec (see Table 1). These velocities are neary equal to the minimum value of the velocity of a stepped leader, which seems to indicate that the air discharges are composed of nothing other than stepped leaders. In fact the investigation of the favorable photographic records of air discharges obtained with our flash resolving camera shows that the discharges really all composed of β type stepped leaders. Photo. 4. illustrates an example of air discharge and the Fig. 5. is the skech of it, in which the last step streamers are indicated with a full lines, the pilot streamers with broken lines, and the time values measured backwards from the streamer ends A_2, B_2 along each channel of a pilot streamer are written beside the streamer A_2 A_1 and B_2 B_1. The streaks aa', $\bar{a}$ $\bar{a}$', and bb', $\bar{b}$ $\bar{b}$' represent the high brightness portions of the individual step streamers caught with our photographic camera, and they belong to the branch A_1 A_2, B_1 B2 of the discharge respectively. The existence of these streaks indicates the point that

* Much of the stepped leaders occurring in association with cloud discahrges generally have a negative polarity (see Section 4 B, Chapter III), therefor it will be reasonable to think that the stepped leader BCD in the 3 will have a negative polarity.

the air discharge is really composed of β type stepped leaders. The velocities of these stepped leaders measured along the branches A_2 A_1 and B_2 B_1 give the value 1.6×10^7 cm/sec and

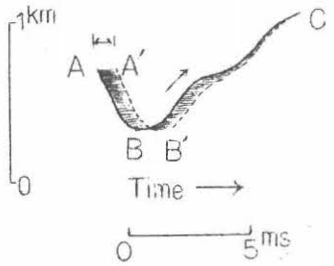


1.2×10^7cm/sec respectively, and the estimated distance of the discharge from the observation station was about 500 meters. According to what we have investigated in this paragraph, it is clear that the streamers, with velocities roughly ranging $(0.5 \sim 2.0) \times 10^7$ cm/sec and occurring in association with an intercloud discharge or an air discharge, all have a strong tendency of the nature of a type stepped leader, so long as our flash resolving camera have succeeded to photograph them.

(c) Medium velocity streamer

The strokes of a multiple intercloud discharge have not always the extremum velocities such as those described in Paragraph A and B. Indeed the velocities of some of them are often intermediate between these two extremums, and of the order of 10^8 cm/sec. An exampoe of a medium velocity streamer is illustrated in Photo. 5. and Fig. 6 is the sketch of it. Judged from the feature of the photographic image, the discharge seems to be composed of triple strokes. As the Fig. 6 indicates, the image of the first streamer, however, is very broad to the lateral direction, and the width of it is seen to decrease gradually from A to C. Further the boundary line ABC to the left handside of the streamer image is very much clearer than that of the right handside A'B'C.

Fig. 6

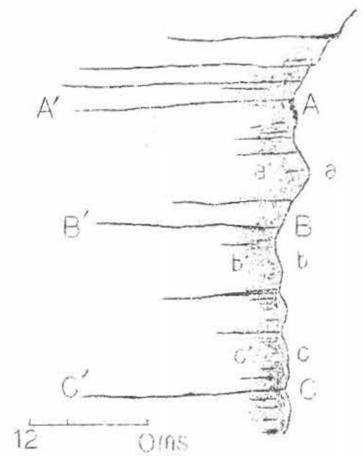


This clearly indicates that the streamer must have the nature of a stepped leader. We can estimate the velocity of the streamer at 1.1×10^8 cm/sec under the assumption that the streamer is a stepped leader. The atreamers, the moving photographs of which indicate the decrease in the lateral extent from one end to the other end of their images, are recorded not always as the first stroke of a multiple intercloud discharge, but often ovservable as the successive strokes of the discharge, hence it is clear that the streamers are of the intermediate nature between the fast streamer and the slow streamer concerning the progressive velocity as well as the structure of the streamer.

(D) Intercloud discharge with point sources of light emissions

The investigation of the Boys' camera photographs of intercloud discharges shows that mainly the zigzag points on a discharge channel sometimes emit the strong light continuously during 30 - 60 ms. These point sources of light emissions will give the streak images on the Boys' camera photograph of a lightning flash. Concerning the streak images of the Boys' camera photographs, there are the afterglows which also give the streak images, however, the durations of these normal streaks due to afterglows are compratively shorter than the streak durations being described just above. In fact the greater portion of the short streaks can be attributed to the afterglows caused by the luminosity durations of zigzag points on the discharge channel after the bright streamer having traveled the whole channel. The afterglows remaning after the completion of a return stroke of a ground discharge generally give the

Fig. 7



streak images as illustrated in the Fig. 7. They can be divided into two categories, i.e., the general afterglow represented by the continuous lateral extent (a a'), (b b'), ...along the image of the return stroke ABC, and the afterglows in the streak form represented by (A A'), (B B'), ... mainly caused by the high ionic density at the zigzag points on the discharge channel. As the Fig. 7 indicates, it is very clear that the durations of the normal streak afterglows are generally much longer than those of the general afterglow. The former durations have been measured on the flash resolved photographs of intercloud discharges and ground discharges, both representing no extremely long streak afterglows. The table 2, represents. The resul **of this measurement is represented in Table 2, which indicates the** maximum duration of the normal streak afterglows not to exceed 12.4 ms.

Therefore the extremely long streak images, which appear from time to time in association with the moving photographs of intercloud discharges, and continu themselves more than 30 ~ 60 ms, can not be interpreted with the light emission

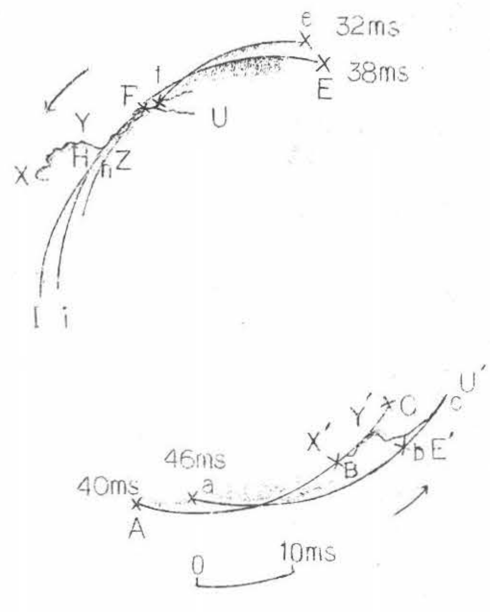
Table. 2

Duration \ Lightning discharge		Intercloud discharge	Ground discharge
Normal streak afterglow duration	Mean value	2, 0 ms	2.1 ms
	Distributed range	0.4 - 5.4 ms	0.2 - 12.4 ms
Number of data		23	43

like as an afterglow of a lightning flash. In some of the intercloud discharges the light emissions producing several extremely long streak images are seen to appear long before the out-break of a fast streamer. Photo. 6 illustrates an example of such a intercloud discharge with point sources of light emissions, the sketch of which is represented in Fig. 8. This intercloud discharge is composed of a single stroke and at least, four very long streaks (A B), (a b), (E F), (e f) are discernible from the moment before the outbreak of the fast streamer XYZU. The regions surrounding these four streak images on the photograph are blackened weakly. This clearly indicates the existence of week luminosities in the neighborhood of the point sources of light emissions throught the whole period of the streak light emissions. The time interval from the start of the streak images to the outbreak of the fast streamer, estimated on the Fig. 8 gives the value at least more than 32 - 46 ms. The detailed investigation of the four long streaks futher shows that they go through the neighborhood of the zigzag points on the fast streamer. The long streaks (H I), (h i) in the Fig. 8 appearing in the period just after the outbreak of the fast streamer continue themselves as long as 20 - 22 ms. These durations of long streaks are clearly much longer than the durations of the normal streak afterglows, therefore, it is evident that the light emissions producing the streak images in the Fig. 8 can not be attributed to the afterglows of zigzag points on the fast streamer, but must be caused by the discharge carrying strong point sources of light which present themselves from the moment 20 - 50 ms before the outbreak of the fast streamer at several zigzag points of it. As the velocity of the main

fast streamer XYZU in Fig. 8 is extremely high and probably exceedes 10^9 cm/sec, so the accurate values of it can not be determined from the measurement of Photo. 6. For the production of a fast streamer with the velocity of this order of magnitude, it is necessary to fill up previously the channel of the succeeding fast streamer with the sufficient density of ions of the order of 10^8 ion/cc (see Section 3). These ions must have been distributed, in this case, along the channel of the following fast streamer XYZU through the period of the preceding discharge with point sources of light. In other words, during the period of the discharge accompanying point sources of light a lightning channel, with so low a luminosity as to make it very difficult to record it with our Boys' camera, must have already bridged the point sources, and a gradual disbharge must have been maintained through this weakly luminous bridging channel. Through this process the necessary ions for the production of the succeeding fast streamer must have been distributed previously along the channel of the streamer.
If we over look the large differences existing in the durations of point luminosities, it is not very difficult to notice the intercloud discharges which actually have many strong

Fig. 8.



point luminosities at the zigzag points of their channels. These intercl ud discharges are usually very rich in crookedness. Photo. 7 represents an example of these intercloud discharges. If the number of strong luminous points are very large, the flash will have the form of a beads-lightning. And, if the durations of luminosities of the individual beads are extremely long, and further, the portions of the discharge channel which bridge the beads have very weak luminosities resulting from a slow rare of discharge, the Boys' camera will be unable to record any image other than the streaks. Sourdillon(2) also reported the intercloud discharges which give the Boys' camera photograph composed only of several long streaks, which he named the type III cloud discharge.

3 General structure of an intercloud discharge

The first stroke of a ground discahrge is initiated always with a streamer of the nature of stepped leader, coresponding to this, the eletromagnetic waveform of it is always initiated with the waveform of a special character, i.e., an Ig section, or a L section. In contrast to this the investigation of the outbreak of a cloud discharge on the electromagnetic waveform of it shows that cloud discharges are not always initiated with the waveform of the nature of an Ig or a L section, but many of the cloud discharges really initiated without this character, inspite of the sufficiently high gain of the amplifier of the waveform recorder to register an Ig section or a L section, and further inspite of the fact that the waveform of a ground discharge recorded on the same 16 mm cine film clearly initiated with an Ig or a L section. The waveforms of cloud discharges obtianed at amplifier gains $0 \sim 20$ db have been investigated to see whether the waveforms were really initiated w.th an Ig or a L section, the result of which is represented in Table 3. The table indicates that about 35 % of the recorded cloud discharges are initiated with a streamer that has more or less the character of a stepped leader, but remaning 65 % are initiated with a discharge process without any stepped leader structure.

We have already investigated in Section 2, the existence of a intercloud discharge which clearly initiated with a β type stepped leader, and of a intercloud discharge, the photographic record of which lacks a clear stepped leader in its initial portion and is composed only of dart leaders, so that the discharge seems as if to start with a dart leader on the

Table 3.

Waveform of a cloud discharge	Percentage of records of waveforms	Number of
Initiated with Ig or L section	34.7 %	395*
Initiated with Ig or a L section	65.3 %	

* The gain of the recorder amplifier 0, 10, 20 db.
The distances of the discharges $20 \sim 60$ km.

Boys' camera record. These two observational facts lead us to the conclusions that many of the intercloud discharges really start with a mechanism without the nature of a stepped leader and are composed only of the fast streamers with the nature of a dart leader. Theoretically speaking, the fast streamer like a dart leader generally progresses with the discharge mechanism given by Cravath and Loeb(3). To make the Cravath and Loeb's mechanism to paly an active role for the development of a streamer it is necessary to distribute previously the ions with densities higher than a threshold value along the channel of the discharge. According to Schonland(4) the ions produced by the immediately preceding return ground stroke in the discharging channel and remaining in it after the completion of the stroke reduce their density through the volume recombination process of ions during the period of the stroke interval. If the stroke interval of a ground discharge is extremely long, the density of ions remaining in the lightning channel at the instant of occurrence of the next ground stroke will be reduced to a value lower than the threshold necessary for a streamer to advance with Cravath and Loeb's mechanism. In this case the streamer leading the next ground stroke can not take the from of a dart leader, but it turns out to progress with a mechanism of a dart-stepped leader with a lower volocity. If the ion density remaning in the the lightning channel after the previous ground stroke is reduced to an extremely low value, the streamer will not be able to take even a from of a dart - stepped leader, but tabke the form of an ordinary slow stepped leader,(1) which progresses into the unionized virgin air. Our investigation of the photographic record of leader streamers appearing in the inter-cloud discharges also has shown that the streamers with progressive velocities higher than 4×10^8 cm/sec usually have a strong tendency of the nature of a dart leader, the streamers with velocities of about 1×10^8 cm/sec represent move or less the nature of a stepped leader and the streamers with velocities smaller than $(0.5 - 1) \times 10^7$ cm/sec all must be inferred as being composed of β type stepped leaders. Following these considerations, the intercloud discharges which seem to start with a dart leader on the Boys' camera records as descrived in Section 2 A, must have the ions previously distributed along the channel of the following first stroke composed of a dart leader, in spite of the fact that no luminosity can be recorded on the flash photograph before the outbreak of the first stroke. There are two possible mechanisms which seem to give these distributions of ions. The one is that the ions accumulated by the mechanisms of separation and accumulation of electricity in and around a thundercloud incerease its density, so as to exceed the threshold value necessary for the formation of a dart leader, and the other is that a gradual discharge without any nature of a stepped leader breaks out before the occurrence of the first stroke of a intercloud discharge, and emits a very low intensity of light which can hardly be recorded with our Boys' camera. Our statistical estimations of the minimum ion densities necessary for a streamer to take the from of a dart leader give the value of the order of 8×10^7 ion/cc**. In contrast to this, the direct measurement of electrical charge density inside the active thundercloud cells carried by Ross Gunn(7) shows that the electricity with the ion density of about 2.1×10^5 ion/cc is distributed inside a thundercloud cell. Therefor we see the difference of the two units exisiting between these two values. On the other hand the ion density of the electrical charge center relating to the first stroke of a ground discharge has been estimated, through the discussion in Section 4 of Chapter III, from 0.9×10^7 ion/cc to 1.4×10^7ion/cc, which are nearly comparable with the ion density 8×10^7ion/cc necessary for the formation of a dart leader. This mean that the density of ions which must be distributed previously throughout the whole length of a lightning channel to let the following streamer to take the from of a dart leader is comparable with the ion density at the electrical charge center producing the stroke of a ground discharge. However, the statistical measurement of length of the visible part of a lightning channel involved in a intercloud discharge gives the mean value 2.6 km* therefore it will be very implausible to assume that a very long volume statistically extending to a length 2.6 km, which composes a portion of a discharge channel previously prepared in the atmosphere to guide the following dart streamer, is really filled with ions of the

---

* Mean value of the 10 flash lengths on our photographic record. Median value of the same data gives 2.5 km.

** The statistical investigation of the stroke intervals of ground discharges(5) has shown that the probability distribution of stroke intervals represents a clear bending at the time interval value of about 130 ms. This means that the lightning strokes whose relating time intervals do not exceed 130 ms all have the same mechanism of stroke initiations. Therefore it will be reasonable to consider that the maximum time interval between ground strokes, which may not change the nature of a dart leader to a succeeding stroke, is statistically about 130 ms. If we assume that the coefficient of volume recombination of ions is given by $\alpha = 10^6$ following to Meek's book(6), the ion density remaining in the lightning channel 130 ms after the previous ground stroke will be 7.7×10^7 ion/cc, because the ion density in the channel at time t after the preceding ground stroke may be expressed as $N = 1/\alpha t$.

density comparable with that inside a electrical charge center. Therefor inspite of the fact that the greater part of the recorded intercloud discharges, judged on the Boys' camera photographs, each seem to start with a dart leader, it is very probable that in the reality, they are initiated with a mechanism of a very slow β type stepped leader or of a gradual discharge without any step structure, both of which will very hardly be recorded with our flash resolving camera. The necessary ions for the formation of the succeeding dart streamer must be produced and distributed along the channel by the process of these low luminous discharges not recordable with our photographic apparatus. An example of these gradual intercloud cischarges preceeding a dart leader forming up a cloud discharge has alreay been investigated in Section 2D. This streamer with several point sources of light emmissions on it does not represent a clear stepped leader structure, however, it must have an ability to advance into the unionized virgin air. Following these postulations, we may expect that an intercloud discharge will be initiated generally with a stepped leader that has an ability to advance into the unionzied virgin air, or with a gradual and very weakly luminous discharge which does not represent any character of a stepped leader, however, has the same ability as the leader. In some cases, many zig-zag points on the channel of a very weakly luminous discharge may emit the relatively strong light for more than several ten milli-seconds, and the strong point luminosities at zig-zag points combined with the weakly luminous channel bridging the these point sources may complete a intercloud beads lightning. The ions distributed along the discharge channel, through the process of a stepped leader or a gradual discharge, will be left behind in the channel so as to make it possible the streamer composing the second stroke to take the from of a fast dart leader. This will be the general structure of an ordinary intercloud discharge. The differences between a stepped leader and a grdual discharge with point sources of light emissions on it seems to consist in the point that the former takes place outside a thundercloud and the latter mainly inside the cloud. The observational facts which seems to support the above deduction will be the following three, so long as we consider mainly the measurement of moving photographic records of intercloud flashes obtained by us. The first, the air discharges which gave the photographic images having spread out downard from thundercloud bases were all composed of β type stepped leaders, the second, the number of intercloud discharges, whose moving photographs represented nothing other than the fast streamers with the nature of a dart leader, were much larger than the number of records of the intercloud discharges which were initiated with β type stepped leaders, and the third, the

investigation of the electromagnetic waveforms of all the recorded cloud discharges, the majority of which, of course, were considered statistically to correspond to intracloud discharges, clearly showed that the number of cloud discharges which were initiated each with a process without any nature of a stepped leader were generally twice as much as the number of the cloud discharges which were initiated with a stepped leader process (see Table 3.).
Follwoing the above deduction, the major part of the intracloud discharges should be initiated by a gradual discharge mechanism with a large time duration without any stepped character. However, the nature of a gradual discharge will be expected to become clearer, if we can investigate the electrostatic field changes due to these discharge processes.

4. interpretation of atmospheric radiation pulses emitted by streamer discharges

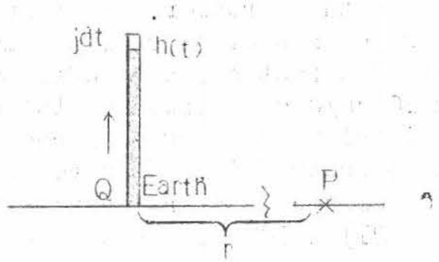
As we have alreay investigated in the previous section, fast streamers involved in a cloud discharge must generally be preceded either by the process of a stepped leader, or by the process of a complex streamer* in a thundercloud, or by the ionic distribution remaining along a discharge channel developed by the preceding fast streamer. The velocity of a fast streamer is greatly influenced by the ion density exisiting in a discharge channel at the moment the outbreak of the streamer. The investigation of the flash photograph in section 2 D, has made it clear that the velocity of a fast streamer often attains the value larger than 10^9cm/sec provided the density of ions previously distributed along a discharge channel being high enough to produce it. This velocity of a fast streamer more than 10^9 cm/sec is nearly comparable with the velocity values $(1.5 \sim 21) \times 10^9$ cm/sec of return strokes,(4) and belongs to a very high value as a streamer velocity. Therefore a strong radiation pulse may be expected to radiate from a dart leader with the velocity this order through the similar mechanism to that of the return streamer of a ground discharge. The photographic image of a return ground stroke caught with the Boys' camera clealy indicates that the width of the image decreases with the progress of a return streamer from the earth's surface toward the cloud base. This means the bright channel of a return streamer growing upwards from the earth to the thundercloud base. Therefore electrically the return streamer of a ground discharge may be replaced, as a way of an approximation, with a vertically growing electric current channel, the upper end of which increses its altitude from the earth's surface toward the thundercloud with the velocity of a return streamer, and the current density of which is uniform everywhere along its length. As an uniform current density is assumed in this approximation, the measurement of a return streamer current at the earth's surface will be sufficient for the determination of variation in the return streamer current. This means that the waveform of a return streamer current can be given by the lightning current variation

---

* Hereafter a discharge process, which relates to a discharge in a thundercloud, and produces gradual field changes with a long duration, and sometimes likely carries many point sources of strong ligh emissions on its, channel under a favorable conditions, will be named as a intercloud comples streamer. It is very evident that the complex streamer is of the similar nature as that of the J-streamer appearing in the stroke intervals of a ground discharge.

corresponding to a ground stroke striking a structure on the earth's surface, such as a lightning rod. Taking these approximation into account, let us consider the model illustrated in the Fig. 9, which represents the return streamer at the time t after the start of the streamer from the earth's surface.

Fig. 9



Following this model the variation of a dipole-moment dp in the time interval between t and t + dt will be represented as dp = jdt x 2h, where j(t) and h(t) are the return streamer current and the altitude of the upper end of it at time t, from which the following relation will be obtained.

$$\frac{dp}{dt} = 2jh \qquad (1)$$

Generally, the electromagnetic field change E produced by vertical dipole discharge can be represented by the sum of the three components, i.e., the electrostatic field change E_S, the induction field change E_I and the radiation field change E_R. If we denote the horizontal distance PQ of the return stroke from the obsavation station lying on the earth's surface and the altitude of dp with r and H respectively, and further assume that these satisfy the conditon $r \gg H$, the three components E_S, E_I, E_R will be represented as follows:(8)

$$E_S = \frac{1}{r^3}p, \quad E_I = \frac{1}{cr^2}\frac{dp}{dt}, \quad E_R = \frac{1}{c^2 r}\frac{d^2p}{dt^2} \qquad (2)$$

where

$$E = E_S + E_I + E_R$$

The widths of atmospheric radiation pulses which have each an appreciable amplitude have been measured on the electromagnetic waveforms of lightning discharges, which have been inferred to break out at distances 10～60 km apart from the station. Table 4. represent the result of the measurement.

Table. 4.

Sort of measured waveforms	Pulse type	Rise width (Median value)	Tail width (Median value)	Total pulse width	Number data
Cloud discharge	Diffe-rential form	———	———	** 40 µs	616
Ig process of a ground discharge	" "	———	———	26 µs	733
Return stroke voltage* waveform of a ground discharge	Peaked form	10 us	90 us	100 us	19

* The data referring to the Journal of the Power and Weather Coordinating Comittee.

** The results of statistical measurements of the radiation pulse widths indicate the existence of the minor group which has the median value 90 µs, other than the major group represented in the table.

Following the statistical result indicated in the table, the widths of two sorts of differential type pulses with appreciable amplitudes indicate the median values 26 µs and and 40 µs respectively. But when the electromagnetic field change of a return stroke involved in a ground discharge is recorded with our waveform recorder at a distance roughly larger than 30 km, the peaked type radiation pulse corresponding to return stroke is always more less influenced either by the induction component or by the existence of ionosphere. Therefore it is difficult to find out a peaked type pulse which corresponds purely to the radiation component E_R of the electromagnetic-field change due to a return stroke and to measure the correct radiation pulse width corresponding to a return stroke. For this reason we have measured the widths of peaked type voltage-waveform produced by ground

strokes striking either electrical power lines, or some other installations of this kind instead. The lowermost row of the Table 4 represents the voltage pulse width. According to the theory of the electromagnetic radiation from a vertical dipole anntena, the main part of the field change E of the formulae (2) recorded at a distance larger than a wavelength is occupied by the radiation term E_R, if the height of the dipole is sufficiently smaller than the wavelength.
If we assume the above pulse widths represented in the table being identical with the period of the field changes, the pulse widths 26, 40 and 100 μs in the table must correspond to the wave-lengths 7.8, 12 and 30 km respectively. Following this, the differential type pulse* involved in a cloud discharge waveform and the peaked type pulse corresponding to a return ground stroke may be considered, as the first approximation to correspond to the radiation component E_R, if the two types of waveforms are recorded at distance roughly larger than 10 km for the former case and 30 km for the latter case respectively (see Fig. 14, Section 30, Chapter II), which point is indicated in the Table 5.

Table. 5.

Sort of pulse	Distances, at which the radiation field change predominated
Differential type pulse (cloud discharge)	12 km
Differential type pulse (Ig process of ground discharge)	7.8 km
Peaked type pulse (return ground stroke)	30 km

In this case, it is evident that we can replace the field change E with the radiation component E_R as the first approximation. In this approximation, we can get following representation of E_R by using the formrlae (1) and (2)

$$E_R = \frac{2}{C^2 r}\left(\frac{dj}{dt}h + j\frac{dh}{dt}\right) \qquad (3)$$

This relation indicates that the pulse width of a radiation field charge E_R is really determined by that of the related

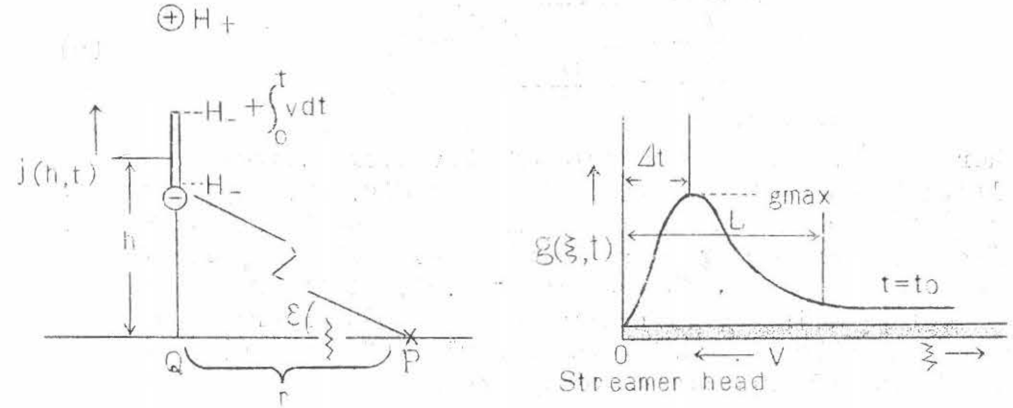
* As the lightning cnannels of the greater part of real cloud discharges are inferred usually to incline from the vertical axis, we must consider the vertical conponent of them in most cases.

current pulse j, so long as dh/dt does not represent a comples variation. The mean length of the related streamer will be given by $(\int^{H_n} h\,dh)/H_n = H_n/2$. If a return streamer bridges the half of the lightning gap length $H_n/2$ at a tremendous speed in an infinitesimal time length given by t=0, t=dt, and after this the progress of the streamer ceases, and if the current flowing through the lightning channel varies in accordance with the function $j = j(t)$, then the following approximation will be allowed.

$$E_R = \frac{H_n}{c^2 r} \frac{di}{dt} \qquad (4)$$

In this approximation we can see the E_R is directly proportional to the differentiation of the current wavefrom of a ground stroke. According to a simple theory of electromagnetic radiation from a dipole antenna(9), it will be evident that the field change due to a cloud discharge recorded on the earth's surface that has a good electrical conductivity can be approximated with a field change produced by the vertical component of a dipole discharge in a thundercloud. So let us consider the model of a vertical intercloud so let us consider the model of a vertical intercloud discharge illustrated in Fig. 10 (a)

Fig. 10



(a) (b)

In this model we consider a vertical fast streamer running upwards from the lower negative charge center with the altitutde H- to the upper positive charge center with the altitude H+ . Let us assume that the linear density of the electrical charge along the vertical streamer can be represented by $q = q(\xi, t)$ as illustrated by Fig. 10(b), where represents the vertical length measureed from the streamer head downwards, and t the time measured from the moment of start of the streamer. If the streamer carrying the above charge distribution moves with a velocity v upward, then the electric current appearing along the streamer channel will be given by

$$j(\xi, t) = q(\xi, t)v(t)$$

If we introduce the electric moment p representing the resultant moment of a vertical dipole, which is determined by the electric current $j(\xi, t)$ moving together with the fast streamer from H- to H+ , dp/dt will be obtained as follows, after some deformations of the relation representing dp/dt given in the reference (10) considering the electrical image of the dipole into account

$$\frac{dp}{dt} = \int_{H-}^{H-\ vt} 2j\,(H- + vt - h, t)\,dh = \int_0^{vt} 2j(\xi, t)\,d\xi \ * \tag{5}$$

where the streamer is assumed to have uniform velocity. In this case E_R and E_I will be expressed with respect to p as follows.

$$E_R = \frac{1}{c^2 r}\ \frac{d^2p}{dt^2}(1 - \varepsilon^2)$$
$$E_I = \frac{1}{cr^2}\ \frac{dp}{dt}(1 - \varepsilon^2) \tag{6}$$

where ε represents the angle of elevation of the discharge altitude measured at P represented in Fig. 10. (a) and $(1 - \varepsilon^2)$ is the correction term of this angle of elevation, when r is not negligble relative to H. For example, if H = 5 km r = 20 km, then $1 - \varepsilon^2 = 0.94$. In this case we can neglect ε^2 , if the approximation with the error as much as 6 % is allowed. Using the formulae (5) and (6) we can get following expressions of E_R and E_I

$$\left.\begin{aligned} E_R &= \frac{2}{c^2 r}\left[vj(vt,t) + \int_0^{vt}\frac{\partial J}{\partial t}\,d\xi\right](1 - \varepsilon^2) \\ E_I &= \frac{2}{cr^2}\left[\int_0^{vt} j(\xi, t)\,d\xi\right](1 - \varepsilon^2) \end{aligned}\right\} \tag{7}$$

Here, let us consider two extreme cases concerning $J(\xi, t)$.
Case I: The case where the approximation $j(\xi,t) = g(t)v(t) = j(t)$, similar to that of the return ground streamer is allowed.

---

*If the velocity v is not uniform, but represented $v = v(t)$, v.t must be replaced by $\int_0^t v(t)\,dt$.

$$E_R = \frac{2}{c^2 r} \left[vj(t) + (vt)\frac{dj}{dt} \right] (1 - {}^2) \qquad (8)$$

$$E_I = \frac{2}{cr^2} \left[(vt).j(t) \right] (1 - \xi^2)$$

Case II: The case where the linear electrical density along the streamer does not very with time, so that

$$j(\xi, t) = q(\xi).\ v = j(\xi)$$

then,

$$E_R = \frac{2}{c^2 r} \left[v\ j(vt) \right] (1 - \xi^2) \qquad (9)$$

$$E_I = \frac{2}{cr^2} \left[\int_0^{vt} j(\xi) d\xi \right] (1 - \xi^2)$$

In the approximation I, if we assume that the fast streamer of a cloud discharge instantaneously bridges the gap length $\frac{1}{2}(H_+ - H_-)$, like the case of a return ground streamer just described above, and after this the progress of the streamer is ceased. If the streamer current remaining hereafter varies with time t following the relation $j = j(t)$, then E_R will be expressed as

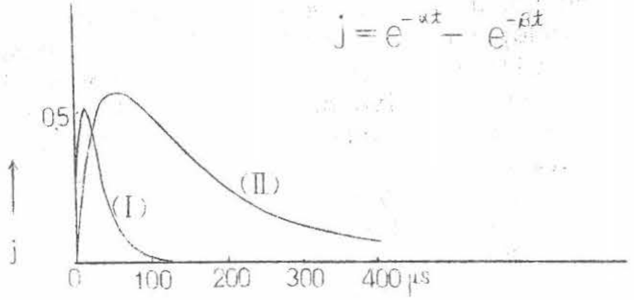
$$E_R = \frac{1}{c^2 r} (H_+ - H_-) \frac{dj}{dt} \qquad (8')$$

This is just the same relation as the formula (4). In this approximation the waveform E_R is given by the differentiation of the waveform of a streamer current, independent of the fact that the streamer assumes the form of a return stroke of a ground discharge or the form of a fast streamer of a cloud discharge. However, if we consider the optical structure of a fast dart leader, involved in a cloud discharge the case II, which assumes a linear charge-density q( ), distributing independent of time t along the streamer head advancing with a unform high velocity v as illustrated in Fig. 9(b), seems to give an approximation nearer to the actual streamer than the case I. If we put $H_- = 0$ into the formulae (5), it becomes to represent the case of a return ground streamer. Therefore it is very clear that the fast streamer involved in a cloud discharge really has an ability to emit an atmospheric radiation pulse, if the velocity of the streamer relating to the cloud discharge is comparable with that of a return ground streamer. We shall next inverstigate the nature of an atmospheric waveform produced by a ground stroke 30～100 km apart from the observation station following the above approximations. Bruce and Golde[11] showed that the waveform of a return ground stroke current can be represented by the following relation

$$j = j_0 (e^{-\alpha t} - e^{-\beta t}) \quad (10)$$

Generally, if the equivalent resistance R which the input terminal of a lightning voltage waveform recorder has against an earthed line, carries no appreciable inductance the voltage output E(t) of the recorder will be proportional to R x j(t). In this case we can deduce the variation of a ground stroke current j(t) by measuring the voltage waveform E(t) relating to it. The result of the statistical measurement of ground stroke voltage waveforms recorded through the thunderstrom observations from 1948 to 1956 is represented in the last row of Table 4. The current waveform with this rise time and the total pulse width can be represented by puting $\alpha = 4 \times 10^{+4}$ sec^{-1}, $\beta = 2 \times 10^{+5}$ sec^{-1} into the formulae(10). These , values are seen to be comprable with the values $\alpha = 4.4 \times 10^4$ sec^{-1}, $\beta = 4.6 \times 10^5$sec^{-1} given be Bruce and Golde(11). In contrast to this, the current waveform of a ground stroke, statistically investigated by Norinder, has appreciably larger pulse width than that given by Burce and Golde. Concerning this point, Morrison(8) pointed out that the Norider's waveform can fairly well be represented by the formulae (10), by assuming $\alpha = 7 \times 10^3$sec^{-1}, $\beta = 4 \times 10^4$sec^{-1}. Fig. 11 indicates the current waveforms calculated from the formulae (10), in which the waveform (I) represents the case of $\beta = 4 \times 10^4$, $\beta = 2 \times 10^5$ indicating a narrow pulse width, and the waveform (II) represents the case of $\alpha = 7 \times 10^3$, $\beta = 4 \times 10^4$ indicating a wide pulse width. Morrison further pointed out in his paper (8) that the ground strokes

Fig. 11.



producing current waveforms with the wide pulse width break out more frequently than those producing current waveforms with the narrow pulse width. In contrast to this the result of our statistical measurement of the ground stroke voltage waveforms represented in Table 4 shows the reversed situation, i.e., the latter breaks out more frequent than the former. However, at present, it is difficult to determine whether the discrepancy either coming from the difference in the method of measurement or from the difference in the occurrence probabilities of these two types of ground strokes existing between our country and England*. As we shall describe afterwards, the first pulse involved in a main discharge type atmospheric waveform,**which can be considered to originate from a ground discharge roughly more than 300 km apart from the observation station, statistically has a pulse width of about 135 μs[12] in the median value. For this reason we shall take the current waveform (II) represented in Fig. 11 into account inspite of the statistical result of the measurement of ground stroke voltage waveforms having indicated the predominance of the narrow pulse width. As we shall see in the following discussion, the theoretical estimation of the atmospheric pulse width of a return ground stroke derived from the assumption of the current waveform (II) gives the value only about 80 μs, so it is very clear that the assumption of a current waveform of a return ground stroke with much wider pulse width is nesessary to explain the actually measured value 135 μs of the atmospheric radiation pulse width. As to the altitude of the top of a return stroke, let us assume, following to Morrison[8], that the altitude h of a return stroke varies with time as follows

$$h = H_n(1 - e^{-rt})\text{***}$$

where $r = 3 \times 10^4 sec^{-1}$. Then E_R can be derived from the formulae (3), (10) and (11) as follows.

$$\frac{C^2 r}{C} E_R = \frac{d}{dt}(jh) \; \alpha \Big[(1 - e^{-rt})(\beta e^{- \; t} - \alpha e^{- \; t}) \quad re^{-rt} \; (e^{-\alpha t} - e^{\beta t}) \Big] \qquad (12)$$

The value of E_R can be obtained by giving in the formulae (12) the above numerical value. Further the waveform dj/dt can also be calculated in the same way, since the

** As the main discharge type waveforms selected for this statistical measurement all have appreciable amplitudes, so the waveforms may be concidered statistically to correspond to return strokes of ground discharges.

***As the upward velocity of the return streamer following to the first stroke is generally uniform, the formulae (11), strictly speaking, can not be applied to the successive stroke.

* The difficulty mainly comes from the minority of the available records of voltage waveforms of ground strokes.

differentiation of j is given by

$$\frac{dj}{dt} = J_0 \left(e^{- \ t} - e^{- \ t} \right) \tag{13}$$

Fig 12

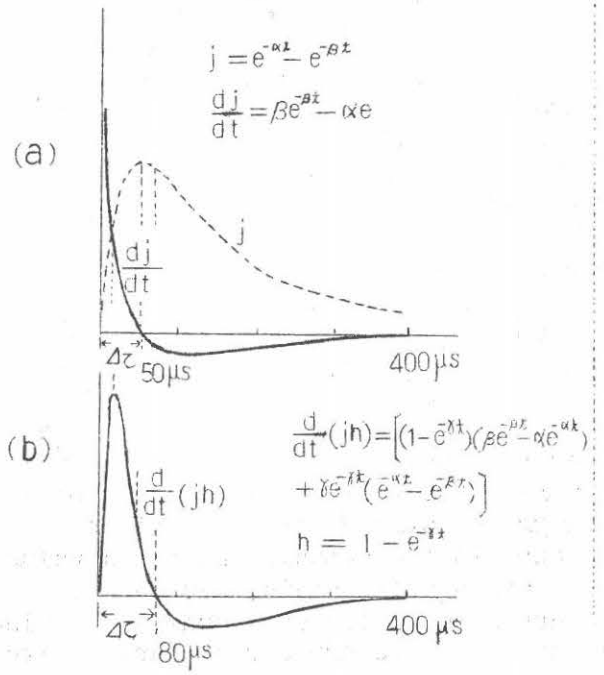


Fig 13

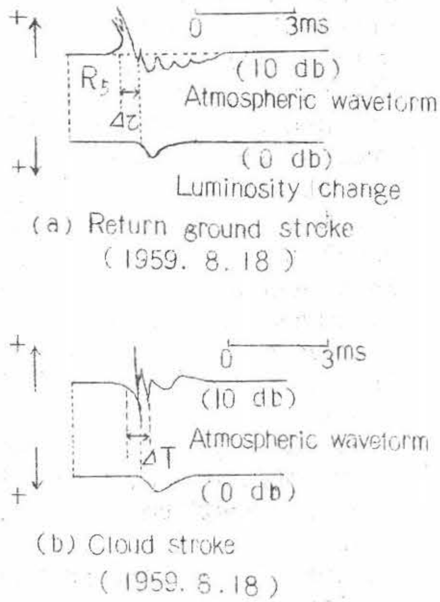
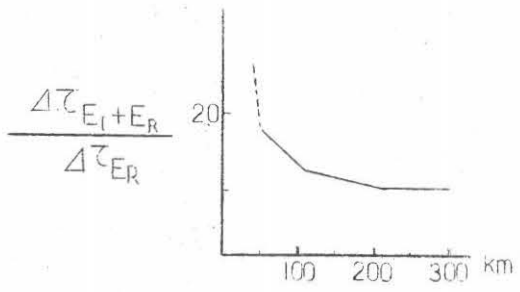


Fig. 12 represente the result of numerical calculations of the formulae (12) and (13), in which (a) indicate the time dependent part of (j and dj/dt), and (b) indicate those of d(jh)/dt. It is clear from Fig. 12. that the general features of the two waveforms representing dj/dt and d(jh)/dt are, as the first approximation, analogous to each other, and the measurement of the pulse width $\Delta\tau$ of the two pulse waveform dj/dt and d(gh)/dt in Fig. 12. gives the values 50 μs and 80 μs respectively, moreover the peak amplitude of the waveform dj/dt, breaks out only 15 μs earlier than that of the waveform d(jh)/dt. Therefore we may consider that the waveform of a ground stroke, as the first approximation, can be expresed by the formula(4). Concerning the mechanism of atmospheric radiation, the vertical component dp/dt corresponding to a return ground stroke and that corresponding to a intercloud stroke are represented simply by the same formulae (5), and there are no differences existing between these two strokes except for the limit of integration of the formulae(5), so it is evident that the above result relating to a ground stroke can be applied for the case of a intercloud stroke.

The first pulse involved in a train of main-discharge type waveforms, which probably originate from the return streamers more than 300 km apart from the observation station, has statistically the pulse width of about 135 μs in the median value, on the otherhand, the atmospheric radiation produced by the first return ground streamer appearing within a range of distances*, at which the light pulse associated with the streamer can be recorded with an appreciable difficulty, usually gives the waveform as illustated in Fig. 13. (a), and the measurement of pulse width $\Delta\tau$ of 15 such first pulses gives the values ranging within $130 \sim 230\mu s$, the mean value of which amounts to 199 μs. According to the above result, it is evident that the measurement of pulse widths of return ground stroke waveforms recorded at these distance results in the overstimation of the pulse width of E_R component of about 1.5 times larger than the true value. The reason of this discrepancy seems to come from the influences of the term E_I on the term E_R, when the electromagnetic waveform of a ground stroke is recorded at distances about 50 km apart from the observation station. To clear out this point we have calculated numerically the half pulse widths $\Delta\tau\ E_I + E_R$ of a return ground stroke waveforms recorded at several distances more than 50 km apart from the discharge taking the influences of the E_I term into account and then obtained the values $\Delta\tau_{EI+ER} / \Delta\tau_{ER}$, the ratio of the half pulse width $\Delta\tau_{E_I + E_R}$, which takes the influence of the E_I term into account, to the half pulse width $\Delta\tau_{E_R} = 80\ \mu s$ of the E_R term. The result is represented in Fig. 14. According to these estimations, the overestimation of the pulse width 1.5 times larger than the true value would being produced when the distance of the concerning discharge amounts to about 75 km. So that it can be conclouded that the measurement of the half pulse with $\Delta\tau$ of atmospheric waveform of a return ground stroke does not give the true half pulse width of the E_R component of the waveform, so long as the distance of the ground discharge does not exceed roughly 200 km.

Fig. 14



* Probably about 50 km.

In contrast to the case of a ground stroke, when the pulses appearing on the atmospheric waveforms of a cloud discharge are recorded at distances about 50 km apart from the discharge, they usually take the form of a differential type as illustrated in Fig. 13 (b). The point that the differential type pulse really coresponds to the discharge taking the form of a fast streamer can clearly be recognized by the light pulse* indicated in the simultaneous record of luminosity change illustrated in the lower half in Fig. 13 (b). These simultaneous record of the electromagnetic waveform and the luminosity change seems to give the verification of the fact that a fast streamer really emits an atmospheric radiation pulse.

The atmospherics radiation pulse involved in the waveform of a cloud discharge 10 ~60 km apart from the observation staion generally are classifiable into three types, each of which includes both positive and negative polarities. Fig. 15 illustrate these three types. Following the approximation represented by the formula (8'), (3), (3') correspond to the case in which the streamer current waveform has the analogous form with that of a ground stroke, (1), (1') correspond to the case in which the streamer current waveform has the form reverse to that of a ground stroke, and (2), (2') correspond to the case in which the streamer current waveform is symmetrical with respect to time.

As we shall see later in Table 3. of Section 3 Chapter V, about 64% of the recorded waveforms of cloud discharges are the aggregation mostly of the negative radiation pulses with the nature illustrated by the waveform (2), or (3), in Fig 15, of with the intermediate nature between (3) and (1'), so long as the appreciable amplitude pulses appering on the waveform of a cloud discharge being taken into account. The statistical investigation further shows that more than 50 percent of the recorded negative radiation pulses of appreciable amplitudes, which break out on the cloud discharge waveforms, are classified into the type 2 of Fig. 15. The result of the statistical measurement of the total pulse width ΔT(see Fig, 13 (b)) of the type 2 pulse

* Exactly speaking, the light pulse recorded with our luminosity change recorder does not correspond to the light emission from the streamer itself, but coresponds to that from the whole of a streamer discharge. So that the peak of a light pulse is recorded generally at the moment somewhat after the dissapearance of the streamer, and the light pulse seems rather to correspond to the discharge remaning after the end of the streamer. The situation is kept the same for the case of the fast streamer appearing in a cloud discharge as well as for the case of the return streamer involved in a ground discharge. (See Fig. 13)

waveforms has already been given in Table 4.
Following the principle which derived the formulae (9), the total pulse width ΔT is to be determined by the duration of the streamer current, therefore it will be reasonable to consider that ΔT may be given by $\Delta T = L/v$*, where L represents the length of the linear charge distribution along the streamer, and v the velocity of the streamer progress. The Table 6 represent the lengths of several sorts of streamers estimated from the relation $\Delta T = L/v$. Schonland (4) showed in his paper relating to the

Fig. 15

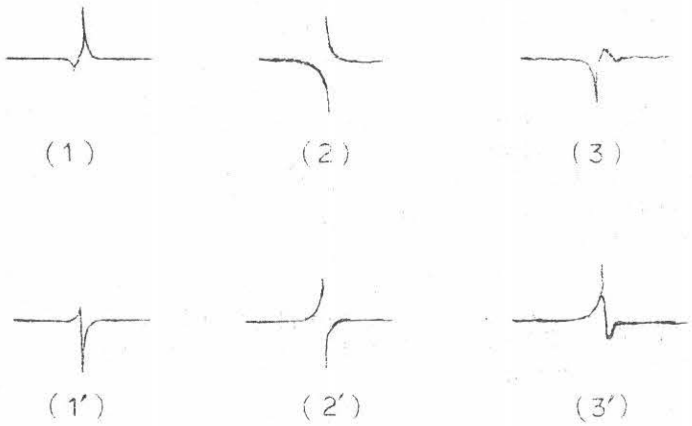


Table. 6

Sort of streamers	ΔT	v	L
Return ground streamer (successive stroke)	100 μs	4×10^{9}*	4000 m
Fast dart streamer (cloud discharge)	40 μs	$>10^{9}$	> 400 m
Step streamer leading a ground stroke	26 μs	$>10^{9}$	> 260 m

* The values given by Schonland (4)

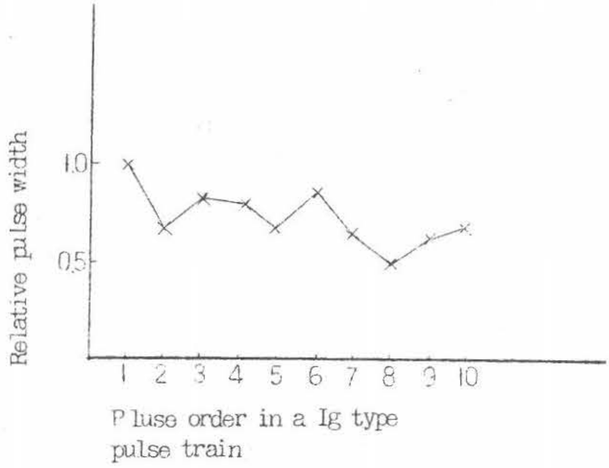
---

* The total pulse width ΔT may not influenced so severely by the term E_I as the half pulse width $\Delta\tau$ being influenced by it.

photographic investigation of lightning flashes, that the measurement of the length of the highly luminous part of a step streamer that composes an element of a stepped leader preceding the first ground stroke gave the mean value 24.6 m, while the measurement of the length of the highly luminous part of a dart leader leading a successive ground stroke gave the mean value about 40 m. These values given by Schonland are only 1/10 of the lower limit of the streamer length given in the Table 6. These discrepancies probably partly come from the overstimation of the total pulse width ΔT of a differential type radiation pulse caused by the short propagation distance (10∼60 km) of the atmospheric waveform, however, the main part of them may be attributed to the fact that the effective length of a streamer contributing to the radiation of an atmospheric pulse is very longer than the optical lengh of the streamer which emits strong luminosity and gives the luminous image on the photographic record of it. Table 6 further indicates the length of a return ground streamer amounting roughly to 4 km, which is the length being enought to bridge the distance between the earth's sureface and the negative electrical charge center in a thundercloud, and which seems to support the fitness of the model of a ground stroke illustrated in Fig. 9.* As described briefly in the above discussion, the effective length of a dart streamer or of a step streamer contributing to the emission of an atmospheric radiation pulse should be considered to be very short compaured with the discharge gap length. To know the variation in the effective lengths of individual step streamers, which construct a stepped leader appearing in a cloud discharge, in accordance with the development of the leader, the widths of individual differential type pulses forming a Ig type pulse train involved in a cloud discharge waveform have been measured on 10 waveforms of the discharges, and then the relative pulse widths thus obtained for each of the Ig type waveforms have been averaged among those relating to the same pulse order in a Ig type pulse train, the result of which is represented in Fig. 16. It is eveident from the figure that no materical variations in the relative pulse widths can be detected except for a little decrease with the increasing pulse order, which means the effective lengths of step streamers contributing to

* The value 4 km in Table 6 has been obtained by assuming the current waveform with a narrow pulse width (see Fig. 11.), which result in the smaller value of ΔT. If we assume the current waveform with the wider pulse width, instead, ΔT will take the value 3∼4 times larger than that of the narrow current waveform. In this case the electric current must continue its flowing through the time length $(2\sim3) \times 10^{-4}$ sec, after the return streamer has bridged the discharge gap.

Fig. 16.



the emission of an atmospheric radiation pulse decreasing a little with the progress of the Ig discharge in a thundercloud.

We shall next investigate the amplitude of the E_R term following the streamer model illustrated in Fig. 9. If we follow the approximation represented by the formulae(4) or (8'), the pulse width of E_R must be proportional to (dj/dt) max. Therefore, the value proportional to (E_R) max, as the first approximation, can be obtained by putting the maxmum current value jmax and the rise time $\Delta\tau$ measured on the streamer current waveform (see Fig. 10(b)) into the approximate relation

$$dj/dt \doteqdot j_{max}\Delta\tau.$$

For the case of a return ground stroke, the rise time $\Delta\tau$ of the current waveform given in Table 4 is $\Delta\tau$ = 10 us, and the measurement of the maximum current j_{max} observed in our country(13) gives the most frequent value $j_{max} = 60 \times 10^3$ amp. So that the radiation field E_{ret} produced by a return ground stroke will be

$$E_{ret} \; \alpha \; j_{max}/\Delta\tau = 6 \times 10^9 \text{amp/sec} \qquad (14)$$

For the case of a fast dart leader, Table 4 gives the total radiation pulse width ΔT = 40 µs. If we assume the current waveform of a dart leader being usually symmetrical with respect to time t, the first approximation will give the relation

$\Delta\tau \doteqdot \Delta T/2$, which results in $\Delta\tau$ = 20 µs. The peak value j_{max} of the current waveform of a dart leader will be estimated as follows. Let us assume that the magnitude of eledtrical charge trancsferred by a dart leader preceding one of the successive strokes of a ground discharge is statistically equal to the mean value $Q_{L1} = 1.4$ coul as indicated in Table 26(b) Section 5B, Chapter II. If we take the duration of a dart leader, which statistically has the progressive velocity 5.5×10^8 cm/sec as a mean, being qual to the over all mean 0.9 ms of the values indicated in Table 18 in Section 4B, Chapter II, mean duration of the dart leaders which have the progressive velocity as large as 2×10^9 cm/sec will be given by

$$\bar{T}_i = 0.90 \times 5.5 \times 10^8/2 \times 10^9 = 0.25 \text{ ms}.$$

Therefore the mean electric current along a dart streamer will be

$$\bar{Q}_{Li}/\bar{T}_i = 1.4/2.5 \times 10^{-4} \doteq 5.6 \times 10^3 \text{ amp}.$$

Further if we assume the peak value of the current waveform being twice as lerge as the mean value of it, following to the analogy of the current waveform of a return ground stroke, the peak current value of a dart leader will be given by $j_{max} \doteq 11.2 \times 10^3$ amp. Taking the above estimated values of $\Delta\tau$ and j_{max} into account, we can estimate the value proportional to amplitude of the atmospheric radiation pulse emitted by a fast dart streamer as follows:

$$E_{dart} \propto j_{max}/\Delta\tau = 5.6 \times 10^8 \text{ amp/sec} \qquad (15)$$

From the relation (14) and (15) we can get

$$E_{dart}/E_{ret} = 5.6 \times 10^8/6 \times 10^9 \doteq 0.093$$

To compare the estimated value with the observed values, we have measured the amplitudes E_r of differential type radiation pulses which were recorder on the electromagnetic waveforms due to a few sort of non-ground stroke processes probably having occurred at distances $40 \sim 100$ km apart from the station, and then calculated for each E_r the ratio E_r/E_{ret}, where E_{ret} is the mean radiation pulse amplitude due to return ground strokes recorded on the same 16 mm cine film as the record of the respective E_r pulse. The statistical result of the estimation of E_r/E_{ret} values is represented in Table 7. In the case of dart leaders, it becomes evident from the table that the theoretical value can roughly be made equal to the observed value, if we assume the velocity of a dart leader being 2×10^9 cm/sec. Judged from the configuration of individual atmospheric radiation pulses, the nature of a dart streamer involved in a cloud discharge and that of the fast streamer appearing in the junction process of a ground discharge seem to be identical with each other exception for the fact that these two streamers statistically emit the atmospheric radiation pulses of opposite polarities with each other. Further the relative ampitudes of these two are, as indicated in the table, nearly equal with each other. Considering these points, it will be resonable to conclude that the fast streamers occurring in a junction process, which takes place in a thundercloud during the period of a ground stroke interval, generally have the nature of a dart streamer, however, the directions of progression of the streamers involved in a junction process of a ground discharge are statistically reversed from those of the fast streamers involved in a cloud discharge.

Table. 7.

Relative amplitude	Ground discharge		Cloud discharge
	Junction process	Stepped leader	Dart leader
E_r/E_{ret}*	0.092	0.050	0.10
Number of data	736	179	702

* Median value

Concerning the step streamers, the Table 4 gives the median pulse width $\Delta T = 26$ micro-sec, so that it follows $\Delta\tau = \Delta T/2 = 13$ micro-sec. As it is not possible at present to estimate the magnitude of electrical charge transferred by a step streamer, and to obtain the observed value E_r/E_{ret} directly, because of the shortage of the data suited for the purpose, we shall intend to estimate the electrical charge indirectly from the following method.

Let the mean value of the linear electrical charge density be $\bar{q}$, and the mean progressive velocity of it be v, then we get the relation

$$E_{step} \propto \bar{q}.v/1.3 \times 10^{-5} \qquad (16)$$

Using the formula (14) and the value 0.05 indicated in Table 7, we can est mate E_{step} value as follows.

$$\bar{q}.v/1.3 \times 10^{-5} = 0.05 \times 6 \times 10^{9}$$

Therefore we get

$$j = \bar{q}.v = 3.9 \times 10^{9} \text{amp.}$$

If we assume $v = 5 \times 10^{9}$ cm/sec following to Schonland,(4) then we get $\bar{q} = 8 \times 10^{-7}$ coul/cm. Further let us assume that the total length of a stepped leader preceding the first ground

* 0.83 represents the correction factor to eliminate the error caused by the inclination of the discharge channel from the vertical axis.

stroke will take the value $3.5/0.83 = 4.2$ km* following to the result represented in Table 16 in Section 4A, Chapter II. Then the total electrical charge transferred by all of the step streamers will be

$$Q''_{L1} = \bar{q}L = 8 \times 10^{-7} \times 4.2 \times 10^{5} = 0.34 \text{ coul.},$$

provided the overlapping of the step streamers with each other being neglected. Following the result represented in Table 26(b) of Section 5B, Chapter II, the total charge transferred by a stepped leader will be given by $Q_{L1} = 2.6$ coul, so that the electrical charge transferred by a pilot streamer must be $Q'_{L1} = 2.6 - 0.3 = 2.3$ coul. Table 8 represents the result of the above estimations. Following these results, it is evident that the electrical charge transferred by step streamers, in spite of their strongly luminous charasters, occupied only 13 % of the electrical charge transferred by the non luminous pilot streamer associated with them.

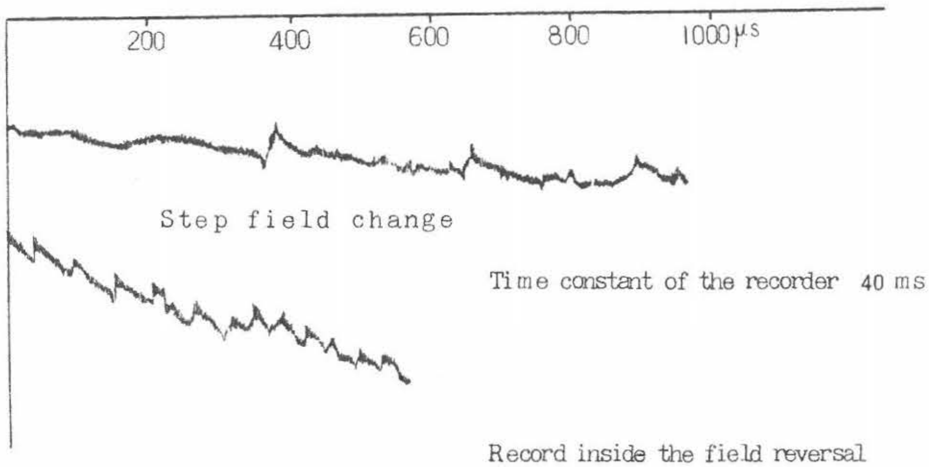
Table 8.

Total electrical charge contributing to the first leader (Q_{L1})	2.6 coul.	100 %
Total electrical charge contributing to the pilot streamer (Q_{L1})	2.3 coul.	88.5 %
Total electrical charge contributing to step streamers (Q_{L1})	0.3 coul	11.5 %

If the electromagnetic waveform corresponding to the first leader of a ground discharge breaking out within a distance roughly 1 km apart from the station is recorded under a favorable conditions with the waveform recorder with a long enough time constant, e.g., 40 ms, in comparison with the duration of the electromagnetic field changes the waveform will give nearly the correct electromagnetic field-changes corresponding to the fine structures of discharge mechanisms of a stepped leader. An example of this kind of waveforms is illustrated in Fig. 17.

The figure clealy indicates that the magnitudes of the step electrostatic field changes which probably correspond to each of the step streamers are generally smaller than those of the continuous electrostatic field changes which present themselves in the intervals between two successive step field changes, and therefore which must correspond to the pilot streamer advancing continuously throughout the process

Fig. 17.



Record inside the field reversal distance.
(1952. 8.20 0 db)

of a stepped leader. This point seems, as the first approximation, to coincide with the above result given by $Q''_{L1}/Q'_{L1} \doteqdot 0.13$. To confirm this point further, the magnitude of a step field change ΔE_{step} and the continuous field change ΔE_{pilot} appearing in the interval between the relating step field change and the immediately following on have been measured on the waveforms of stepped leaders, and the value $\Delta E_{step}/\Delta E_{pilot}$, i.e., the ratio of ΔE_{step} to the relating ΔE_{pilot}, has been calculated for each ΔE_{step} value. Following the result of these estimations, it has become clear the values of the estimated ratios are all included in the range of numerical values 0.2 - 0.5. Therefore $\Delta E_{step}/\Delta E_{pilot} = 0.13$ estimated half theoretically in the above discussion, seems somewhat to be too small in comparison with the observed value. One of the principal reason of this discrepancy may be attributed to the neglection of overlapping of the individual step streamers with each other, however, the decision of this point should be postponed to the future investigations. If we consider the mechanism of radiation of the electromagnetic waves from a vertical dipole discharge which is represented by the formula (2), the electromagnetic waveform corresponding to a discharge taking the process of a stepped leader should be interpreted the with a grouping of the model waveforms illustrated in Fig. 18. The investigation of details of the stepped leader waveforms illustrated in

Fig. 17 (the record obtained inside the field reversal distance) and Fig. 19 (the record obtained outside the field reversal distance) shows that the polarity of the step radiation pulse E_R and that of the continuous

Fig. 18

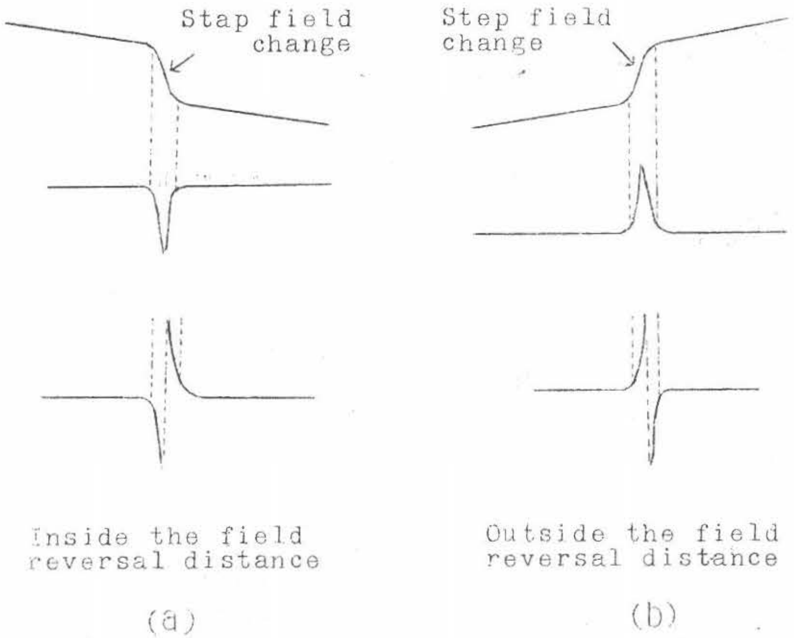
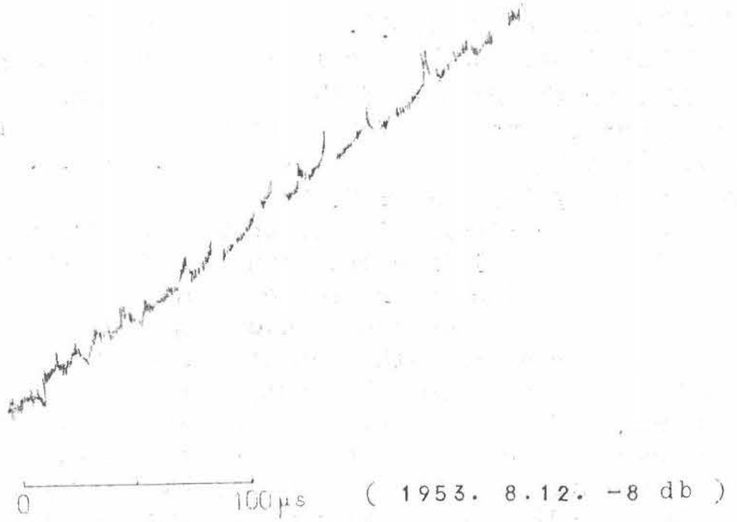


Fig. 19



(Record outside the field reversal distance) electrostatic field change ΔE_{pilot} taking place between two successive step field changes roughly coincide with the theoretical epectations illustrated in Fig. 18. However, the polarities of the individual step electrostatic field changes ΔE_{step} on the waveforms are seen not always to coincide with the theoretical expectation as illustrated in the figure. This may partly come from the fact that, strictly speaking, the approximated formulae (2) can not be valid for such a case as the distance of a ground discharge is comparable with the altitudes of the discharge. However, if we consider the point that the polarities of the step radiation pulse E_R and the continuous elestrostatic field change ΔE_{pilot} roughly concide with the theoretical expectation, it will be reasonable to consider that the disagreement of polarity of the step electroststic field change with the theoretical expectation would mainly be attributed to the magnitude of $|\Delta E_{step}|$ being smaller than the lower limit of the amplitude measurement. If the above estimated value $\Delta E_{step} / \Delta E_{pilot} = 0.13$ tell the real situation, the estimation of the true value of ΔE_{step} will become very difficult because of the small amplitude of the step electrostatic field changes recorded with our waveform recorder.

5 Gemeral character of a cloud discharge deduced from the record of electromagnetic field changes

Because of the difficulty to photograph the lightning flashes occurring inside a thundercloud, it is very difficult to make clear the structure of a intracloud discharge, on the contrary to the case of a intercloud discharge. At night when a thundercloud was floating overhead, we had many times the experience that the curtain lightnings, which did not produced any luminous phenomens other than the glows of the overhead portion of the cloud base filling up the whole sky, were observed much more frequently than discharges accompanying visible flashes. It was not seldom that most of the discharges breaking out in a thundercloud 10 - 20 km apart from the observation station were composed only of curtain lightnings. Of couse, it is evident that the percentage number of discharges whose flashes are intercepted by cloud bodies should increase with the increase in their distances from the station. This must result in the increase in the number of curtain lightnings. However, despite of this, the experience described above seems clearly to indicate the point that statistically the number of intracloud discharges really predominates the numberof intercloud discharges and of air discharges. Therefore the statistical investigation of the nature of discharges including all kinds of non-ground lightnings inveitably result in studying the nature of intracloud discharges. Following these views, we have separated the records of atmospheric waveforms, lightning flash luminosity changes, and electrostatic field changes, all produced by cloud discharges, from the records corresponding to ground discharges, and investigated the above sorts of cloud discharge records, through which the structure of intracloud discharge may statistically be expected partly to become clear. The situation will not be changed, as the first approximation, even if the record of discharges including all sorts of lightnings are investigated instead of the records of cloud discharges, because the occurrence probability of gr und discharges is generally much smaller than that of cloud discharge (see Table 1, Section 1, Chapter II).

(a) Time interval between two successive lightning discharges:

The time intervals between two successive lightning discharges, including not only ground discharges but also cloud discharges, generally represent different probability distribution from a thunderstrom to another, if the small differences existing between the individual distributions are to be taken into account. However, if we neglect these rather small differences existing in the probability distributions representing pecuriarities of individual

thunderstroms, the general character of the distribution based on the data of lightning luminosity changes can be represented by the curve (I) of the Fig. 20.
The statistical mean of the discharge intervals estimated from the inclination of the curve (I) are seen to be composed of the two values, i.e., the value in the range 3 - 20 sec corresponding to the major group of the discharges and the value in the range 50 - 100 sec corresponding to the minor group of them. Of these two groups, the majority group has been recorded in every thunderstom, while the minority group has not been recorded in much of the observed thunderstorms. An example of the probability distribution of discharge time intervals obtained through a thunderstom that lacks the minority group is illustrated by the curve (II) indicating the result obtained from the data of the luminosity changes. The statistical result of the investigation of CW records is represented by the curve (III) of the same figure, which gives the statistical mean value 2.7 sec as indicated in Table 9.

Table. 9

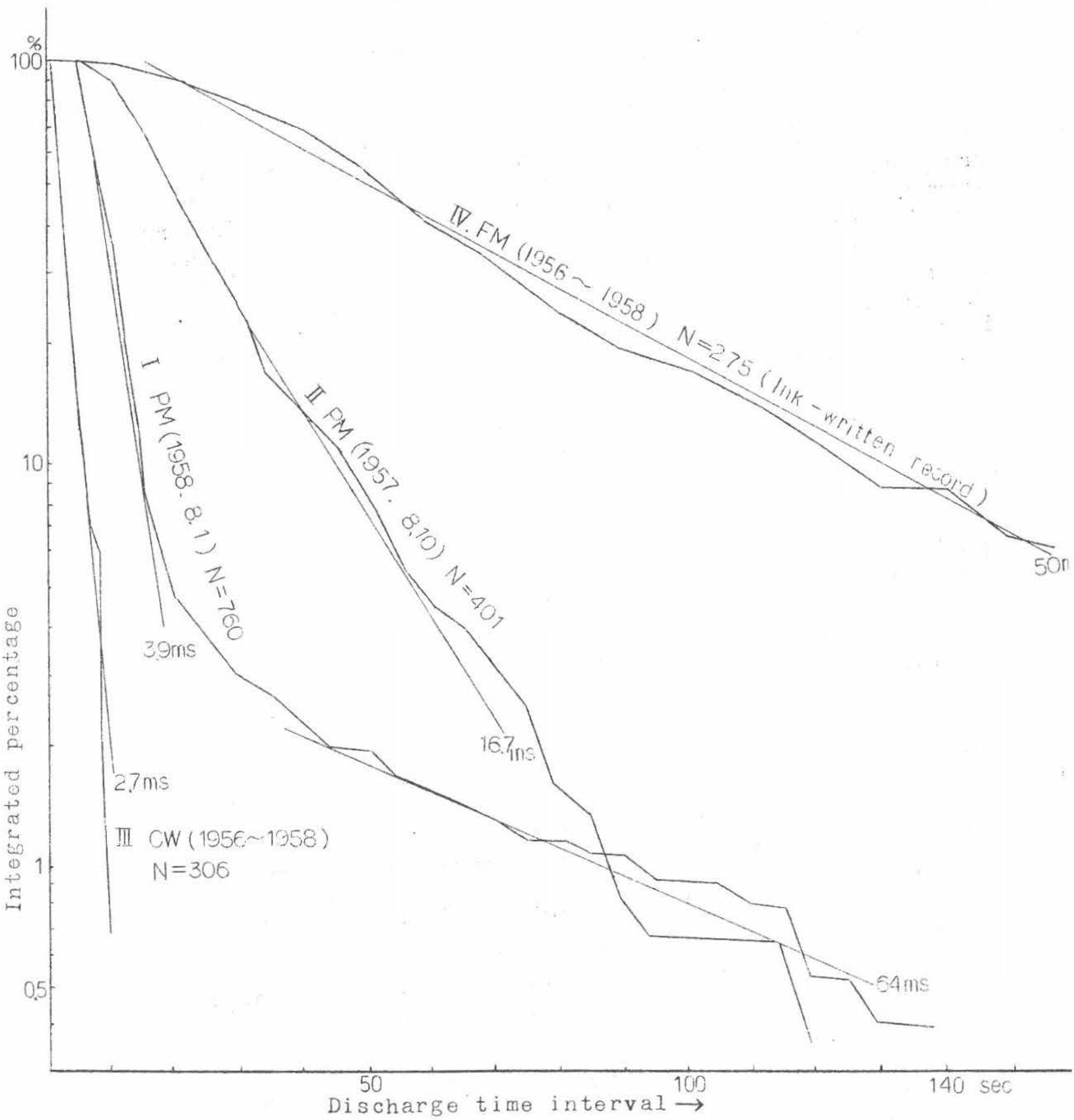
Discharge interval / Method of measurement	Statistical mean value		Median value	Number of data
	Majority group	Minority group		
Lightning luminosity change(PM)	11.4 sec*	65.5 sec	10.2 sec**	2226
Atmospherics (CW)	2.7 sec	———	1.8 sec	306
Electrostatic field change (FM)	18.0 sec	50.0 sec	13.3 sec	1763

* Mean of the statistical mean values ranging 3.9～16.7 sec, and obtained from the distributions corresponding to individual thunderstroms.

** Mean of the median values ranging 3.7～16.2 sec, and obtained from the distributions corresponding to individual thunderstorms.

This value is somewhat smaller than the minimum value 3.9 sec of the statistical mean obtained from the data of lightning luminosity charges. As the sensitivity of the CW method of

Fig. 20



%
100
10
1
0,5
Integrated percentage
50
100
140 sec
Discharge time interval →
IV. FM (1956 ~ 1958) N=275 (Ink-written record)
50m
I PM (1958. 8. 1) N=760
3,9ms
II PM (1957. 8,10) N=401
16,7ms
2,7ms
III CW (1956~1958)
N=306
64ms

recording is generally higher than that of the luminosity method so the former will catch the more minute discharges than the latter will do, and further in the method of CW recordings, the waveforms are recorded on a running 16 mm film of 100 feet in length in about 4 minutes, which makes it impossible to record many lightning discharges with long time intervals on one film, therefore it is very natural that the probability distribution of discharge time intervals measured on the CW records is composed only of the part representing a shap linear inclination which gives the smaller statistical mean corresponding to themajority group. In contrast to this the statistical result obtained from the ink-written records of electrostatic field-meter, which is not suited for recording small scaled lightning discharges because of its low sensitivity, has the character represented by the curve(IV) in Fig. 20, which gives the statistical mean 50 sec that clearly corresponds to the minority group giving the long mean value represented by the curve(I) of the same figure. Following the above deduction, the short discharge time intervals seems statistically to correspond to the majority group of lightning discharges which have a small scale, while the long time intervals to correspond to the minority group of discharges which have a large scale. On the other hand, the ink-written record of an electorstatic field-change, which correspond to a lightning discharge appearing within a distance less than 5 km, enables us to measure the time necessary for the electrostatic field to recorver its initial value after the occurrence of the field change due to the related lightning discharge. Probability distribution of field recorvery time thus obtained represents roughly a linear relation not illustrated here, from the inclination of which we can estimate the statistical mean of it. Table 10 represents the result of this estimation.

Table 10

Statistical values / Field-recovery	Statistical mean value	Median value	Number of data
Electrostatic field-recovery time**	19.7 sec	24.6 sec	74*

* The major part are occupied with ground discharges
** Ink-written records

Comparing Table 10 with Table 9, we can easily see that the time length necessary for the recovery of a step electrostatic

field change produced by a lightning discharge is the intermediate between the two categories of discharge time interval values. Hence it is evident that in the case of short discharge time intervals the succeeding discharge breaks out statistically before the completion of recovery of the charge dissipated by the preceding one.
This may limit the magnitude of the electrical charge discharged by the succeeding one. On the contrary, in the case of long discharge time intervals the succeeding discharge breaks out statistically after the completion of recovery of the charge dissipated by the previous one, hence the scale of the succeeding discharge may not be limited by the incompleted recovery of the charge dissipated by the previous one. These two facts seems also to support the above views that the majority ground of lightning discharges relating to short discharge time intervals probably corresponds to those with small scales, while the minority group of the discharges relating to long discharge time intervals corresponds to those with large scales.

(b) Duration of a lightning discharge:

The statistical nature of the duration of a lightning discharge is not so complicated as that of the discharge time interval. Fig. 21 represents the several cases of probability distributions of lightning discharge durations. As the first approximation, they all can be represented their inclinations each by a straight line. Curves (I) and (II) are the probability distributions obtained from the data of atmospheric waveforms corresponding to lightning discharges having appeared in the range of distances roughly less than 100 km, and correspond to the ground discharges and the cloud discharges respectively.

Curves (III) and (IV) are the distributions obtained respectively from the measurements of atmospheric waveforms and from those of lightning luminosity changes, and both are the statistical results including ground discharges as well as cloud discharges, all having been recorded at distances roughly less than 30 km apart from the station. Curve (V) is the sitribution obtained from the records of lightning luminosity changes corresponding to all lightning discharges having occurred within distances roughly less than 10 km. Table 11 represents the statistical mean and the median of the discharge durations obtained from the data giving the curves in Fig. 21.
The table clearly indicates that the duration of a ground discharge is generally longer than that of a cloud discharge, this seems to mean that the magnitude of electrical charge dissipated by a ground discharge is statistically larger than that dissipated by a cloud discharge process, i.e., the former usually has a larger scale than the latter, if the mean discharging

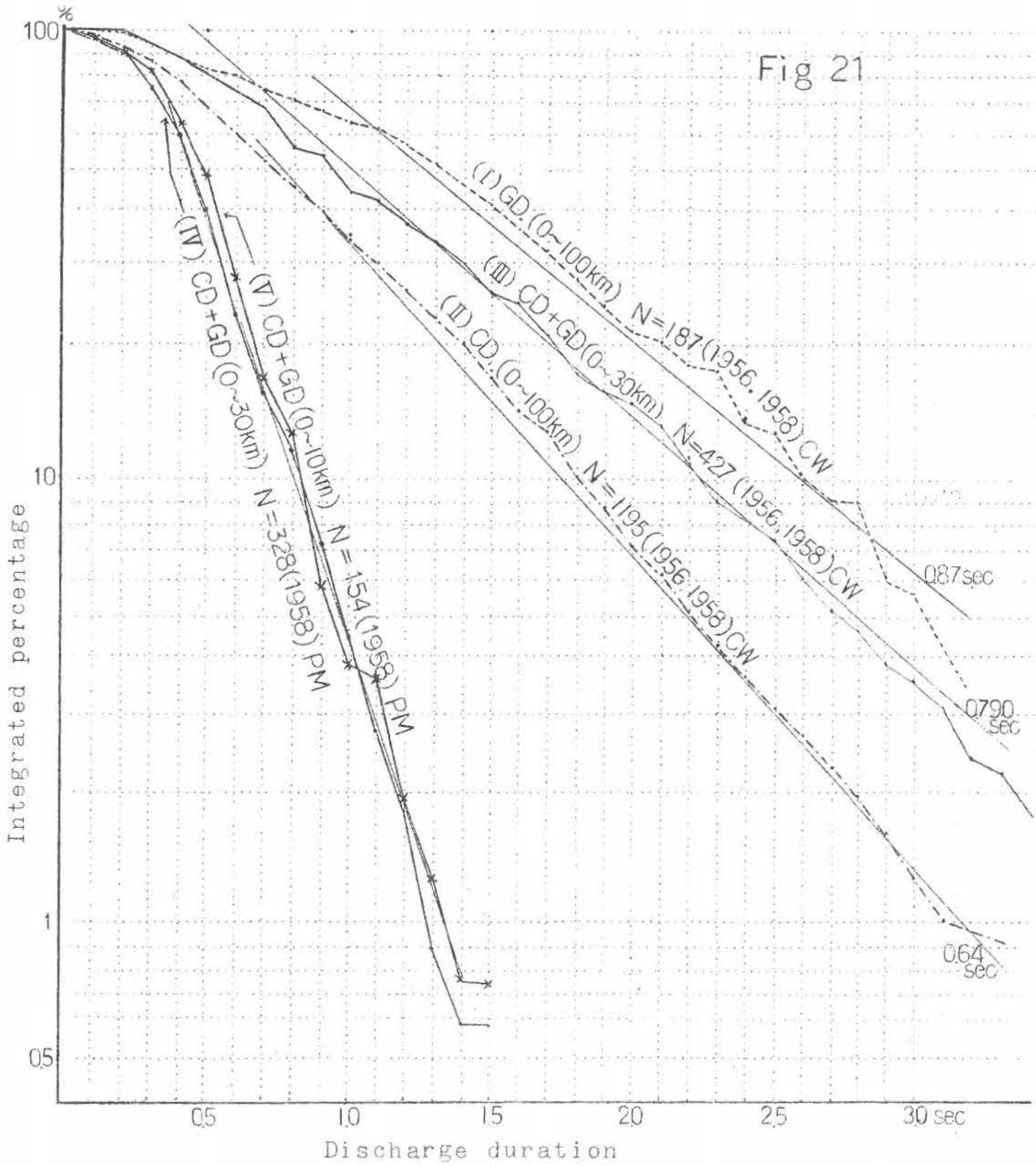


Table. 11

Method of measurement \ Discharge duration		Statistical mean value	Median value	Number of data
Atmospheric waveform	Ground discharge	0.88 sec	1.30 sec	187
	Cloud discharge	0.64 sec	0.74 sec	1195
Atmospheric waveform(T_A)	All lightning discharges	0.80 sec	0.94 sec	427
Lightning luminosity(T_{PM})	All lightning discharges	0.22 sec	0.44 sec	328

rates*
of the two do not differ appreciably from each other. Curves (III) and (IV) have been introduced to see the difference in the statistical mean values resulting from the difference in the measuring methods. Because of the high sensitivity of the atmospheric waveform recorder the durations of lightning discharges measured on the CW records give the larger statistical mean value than those obtained from the data of lightning luminosity recorder which generally has a lower sensitivity than the former recorder. This is the tendency roughly coinciding with that indicated by Curves (III) and (IV) in Fig. 20. Further this may partly come from the fact that the high sensitivity recording method actually catches the minute processes involved in a lightning discharge and inevitably gives statistically a long discharge duration, however, it may also be evident that we must take the following point into account: Because of the high sensitivity of the recorder, the lightning discharges occurring in a wider range of distances from the station are to be registered with it, which will increase the chance that two independent discharges appearing in the above range of distances partly overlap with each other with respect to the time. This may result in the statistical increase of apparent durations of the recorded lightning discharges. If we consider these two factors, it will be probable to deduce that the discharge durations estimated from the data of atmospheric waveforsm statistically correspond to the group of upper threshold, while those estimated from the data of lightning luminosity changes statistically to the group of lower threhold. Follwoing these views, the true statistical duration of a lightning discharge, in which attention is period to the minute discharge processes associated with it, must be the intermediate between the above two extreme cases. Hence let us assume here that the corrected statistical discharge duration T_C corresponding to all lightning discharges is given by the mean of the two values T_A and T_{PM} indicated respectively in the third and the f urth rows of Table 11. The corrected statistical duration of a ground discharge and that of a cloud discharge will be given by multiplying each of the two T_C/T_A values, respectively relating to the two discharges, by the values indicated respectively in the first and the secon rows of the corresponding column in Table 11. The results of this estimation are shown in Table 12. The statistical duration of a lightning discharge obtained in this table be the duration which takes minute discharges occurring in the initial portion as well as in the final portion

---

* If Q and T represent respectively the quantity of the electrical charge dissipated by a lightning discharge, and the duration of it, the mean discharging rate will be represented by $\overline{Q/T}$.

Table 12

Sort of lightning discharges	Method of estimation	Statistical mean value	Median value	Number of data
All discharges	Corrected value (T_C)	0.51 sec	0.69 sec	855
	Atmospheric waveform (TA)	0.80 sec	0.94 sec	427
Ground discharge	Corrected value	0.56 sec	0.95 sec	187
Cloud discharge	Corrected value	0.41 sec	0.54 sec	1195

portion of it into account. To see this point further, we shall investigate the statistical durtation of discharge deduced from the magnetic tape records of the electrostatic field changes due to lightning discharge. Relating to this, we have measured the discharge duration T_{FM} and T_{PM} respectively on the records of electrostatic field changes and on those of lightning luminosity changes, both registered simultaneously on one magnetic tape with a streo-tape-recorder (see Fig. 1 Section 1, Chapter IV) taking the minute discharges associated with the main part of a lightning discharge into account Then we have calculated the ratio T_{FM}/T_{PM} for each of the recorded discharges. From the probability distribution of these ratios we can obtain the median value $(T_{FM}/T_{PM})_{Med} = 1.67$. Next, we shall consider the statistical mean T_{FM} of the discharge durations which will be obtained when we measure the records of electrostatic field changes corresponding to all sorts of lightning discharges. This may be obtained by adopting the procedure of multiplying $(T_{FM}/T_{PM})_{St}$, the statistical mean deduced from the above median $(T_{FM}/T_{PM})_{Med}$,* by the value T_{PM} represented in the last row of the Table 11. The first row of Table 13 represents the result of these estimations.

* Generally, if the probability distribution has a linear relation, the ratio (Statistical mean/median) will approximately be 1.4. So that we may assume the relation $(T_{FM}/T_{PM})_{St} = 1.4 \times (T_{FM}/T_{PM})_{Med}$.

The second and the third rows of Table 13 have been obtained through the same procedure as the estimation of the last two rows of Table 12, using the value T_{FM} given in Table 13 instead of the value T_C that has been adopted to obtain the values indicated in the last two rows of Table 12. Therefore the values represented in the last two rows of Table 13 are respectively the statistical durations of a ground discharge and a cloud discharge, both estimated from the data of the electrostatic field-meter.

Table. 13

Method of measurement	Sort of discharges	Statistical mean value	Median value
Electrostatic field-meter*	All lightning discharges	0.52 sec	0.74 sec
	Ground discharge	0.57 sec	1.02 sec
	Cloud discharge	0.42 sec	0.56 sec

* Record on magnetic tape.

Comparing Table lw with Table 13, we can see that the statistical mean values and the median values indicated in the last two rows of the two tables coincide fairly well with each other. Considered from these points, it will not be unreasonable to deduce that the time durations of lightning discharges, in which attention is paied to minute secondary discharge processes, may roughly be given by the values represented in Table 12. As the main part of a lightning discharge, however, shoud be considered to produce a strong luminosity, so the time duration of the main part of a lightning discharge may be given by the duration of lightning luminosity changes produced by a discharge occurring at a distance close to the station. When the luminosity changes due to a lightning discharge is recorded with a recorder adjusted to a sufficiently high gair, at a distance 20 - 30 km apart from the discharge, it is not unusual that they are composed of the mixtures of the two characteristic luminosity changes, i.e., the continuous luminosity change and the pulsive luminosity change. The time length of a Continous luminosity change usually increases with the decrease in the diatcone of the discharge from the station. Especially when the distance of the discharge reduces to less than 10 km, it becomes not seldom that more than 90% of the total duration of a lightning discharge is really.

occupied by these continuous luminosities. According to what the above fact indicates it is evident that the intensity of the continuous luminosity is generally so weak that we can not catch it with our luminosity change recorder unless the discharge does not break out close enough to the station. Conversely, if the major part of the luminosity duration due to a lightning discharge is occupied by long contonuous luminosities, the distance of the discharge may statistically be estimated at less than 10 km. Curve (V) indicated in Fig. 21 is the probability distribution of the discharge durations obtained from the records of luminosity changes due to lightning discharge, which includes long contimuous luminosities. From this curve we can get the statistical mean and the median values. The statistical time duration of ground discharges and that of cloud discharges can be calculated in the same way as the case of Table 13, using the above statistical values in the place of T_C indicated in Table 12. The result of this estimation is given in Table 14. When we intend to investigate the general mechanism of a lightning discharge, it will be needed to take only the main part of it into account. The values represented in this table will be suited for such purposes.

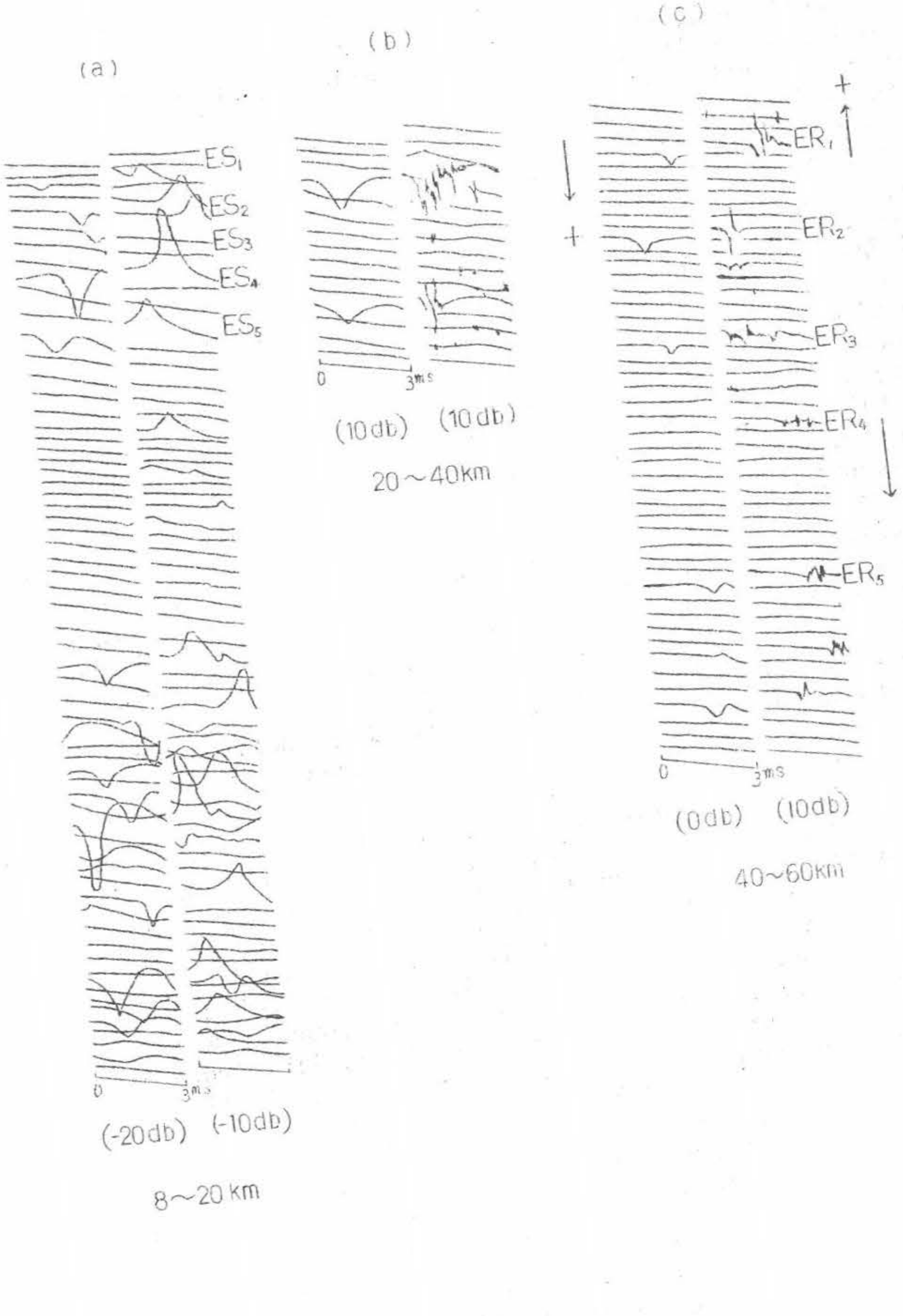
Table 14

Method of measurement	Sort of dis-charges	Statisti-cal mean value	Median value	Number of data
Lightning luminosity change	All lightning discharge	0.22 sec	0.48 sec	328
	Ground discharge	0.24 sec	0.66 sec	187
	Cloud discharge	0.18 sec	0.38 sec	1195

(c) General shape of atmospheric waveforms produced by a cloud discharge:

When the electromagnetic waveforms of a ground discharge are recorded at a distance less than 30 km from the discharge, they generally have the shape illustrated in Fig. 2(f) of Section 1, Chapter II, i.e., they are composed of a series of characteristic pulse groups marked with I_g L_1R_1, L_2R_2, L_3R_3,.....which respectively correspond to each of the ground strokes. Besides this, the electrostatic pulses marked with ES_1, ES_2, ES_3, ...are scattered between two successive LR type pulses. In contrast to this, the waveform of a cloud discharge recorded at a distance comparable with the former generally has no LR type pulse and is composed only of a series of the electrostatic pulses marked with ES_1, ES_2, ES_3, ..., as illustrated in Fig. 22, in which (a) represents the waveform of a cloud discharge recorded at a distance less than 20 km from it. The luminosity changes simultaneously recorded together with the electromagnetic waveforms as, illustrated in Fig 22 (a), clearly indicate the existence of a light pulse exactly corresponding to each of the ES pulses, which tells the fact that each ES pulse really corresponds to a minute discharge that accompanies a light pulse emission. If the minute discharge producing a ES pulse is recorded at a distance 20 - 40 km apart from the discharge, the ES pulse will turn out to take the complex structure composed of a superposition of a group of differential type pulses on a simple electrostatic pulse. Fig. 22 (b) gives the examples of such complex ES pulses. As the simultaneous record of lightning luminosity changes illustrated in the Fig. 22(b), on the other hand, indicates that the light pulses each actually correspond to a complex ES pulse, hence it is very clear that a light pulse does not correspond to each of the differential type radiation pulses, but correspond to the whole of a complex ES pulse. If the distance of a lightning discharge is increased roughly beyond 50 ~ 60 km, the ES pulses will become hardly to be recorded on the atmospheric waveforms, and the atmospheric waveform corresponding to each light pulse appearing on the record of luminosity changes comes out to take the form of ER pulse composed of a group of several differential type pulses. This point is illustrated by the example ER_1, ER_2, ...of Fig. 22(c). In this case, the whole atmospheric waveforms due to a lightning discharge are clearly composed of an aggregation of these ER pulses, i.e., aggregation of groups of the differential type radiation pulses. A light pulse that really corresponds to a group of differential type radiation pulses is clearly discernible in this case too. The investigation of exact correspondences between the two, simultaneous records giving the Fig. 22 (c), clearly indicates the fact the the maximum of a light pulse generally appears after the disappiarance of the corresponding electromagnetic radiation pulse. So that the light emission from a fast discharge process producing a radiation pulse - probably a fast streamer process - must be much weaker than the luminosity relating to the slower discharge occurring in association the fast processes - probably a discharge process producing a local glow of the internal portion of a thundercloud, This latter slower

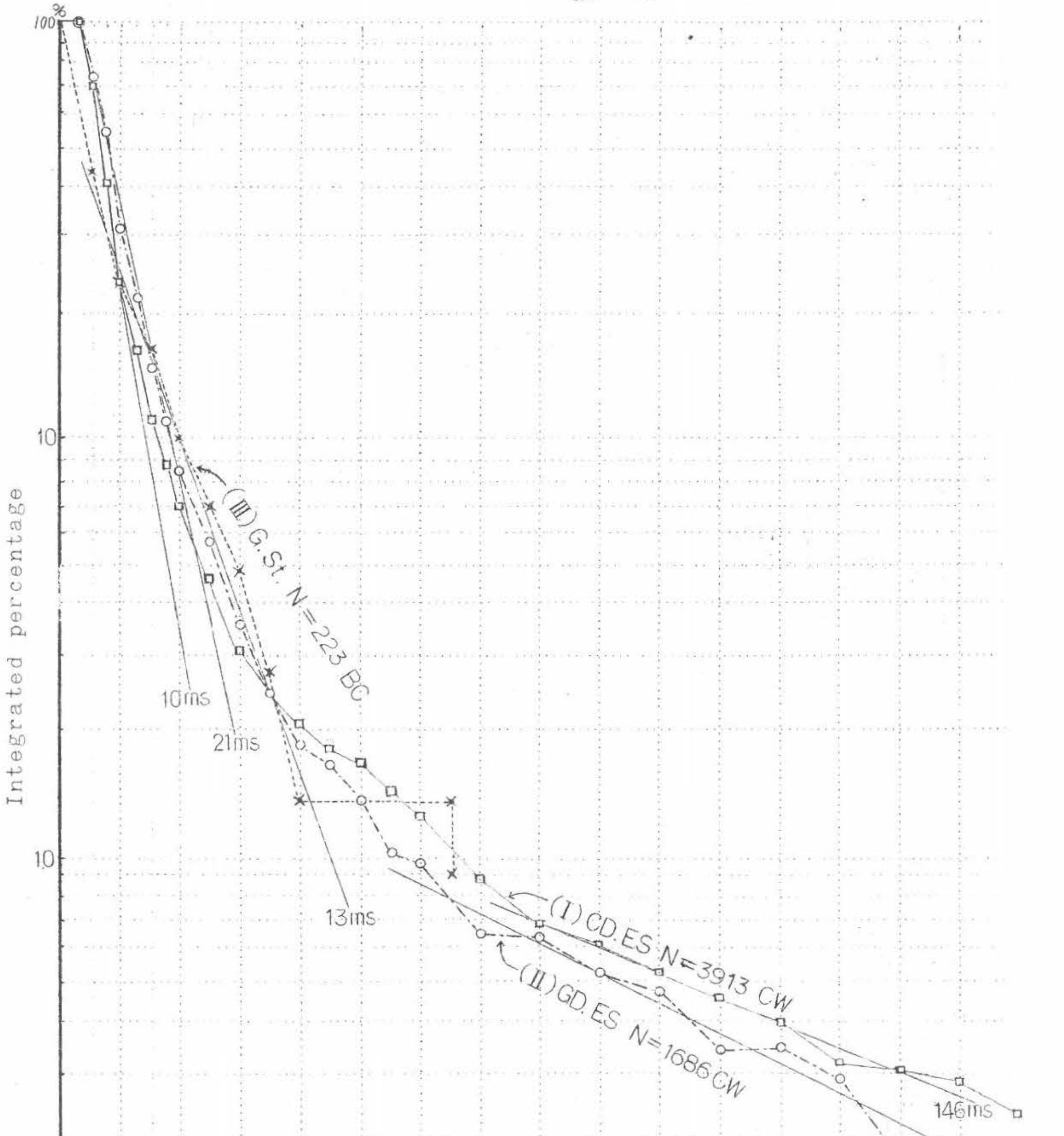
Fig. 22


(a)
ES1
ES2
ES3
ES4
ES5
0
3ms
(-20db) (-10db)
8~20 km
(b)
0
3ms
(10db) (10db)
20~40km
(c)
+
ER1
ER2
ER3
ER4
ER5
0
3ms
(0db) (10db)
40~60km

process of discharge may be the main cause to produce an ES pulse. This is just the same conclusion as what has been described breifly in Section 4 of this chapter, concerning the light emission from ground a stroke. The electrostatic field changes due to a cloud discharge usually do not represent anything other than slow and relatively simple variations which are illustrated in Fig. 1 of Section 1, Chapter IV. As we have already deduced from the investigation of Table 4 in Section 4^{D}, Chapter III, the greater portion of these slow electrostatic field changes due to lightning discharges in thunder-clouds can be interpreted by the simple model of a vertical dipole discharge. Following this result, the ES pulses as well as the ER pulses, both appearing on the electromagnetic waveforms of cloud discharges recorded at appropriate distances, should be considered to have their origins in the minute local discharge processes appearing from time to time in association with a large scaled discharge process in a thundercloud, which can be replaced by the discharge of a huge vertical dipole. A local discharge of this kind, as a whole, will produce an individual ES pulse on the electromagnetic waveform of a lightning discharge, if the local discharge appears near to the observation station, while a group of fast minute streamers involved in a local discharge process will produce a group of differential type radiation pulses which as a whole, from up, an ER pulse on the waveform, if the local discharge is recorded at a distance larger than the former case. (see Fig. 18, Section 4 Chapter IV) To know the nature of minute discharges producing these ES pulses, we have measured the time interval between two successive ES pulses in the record of CW, and tried to obtain the probability distribution of them. The result is indicated by Curve (I) and (II) of Fig. 23, which respectively correspond to cloud discharges and ground discharges*. As there is no appreciable difference existing between the two curves, it will be evident that the mechanisms of the discharges producing ES pulses do not differ appreciably from a cloud discharge to a ground discharge. It is very clear that Curves (I) and (II), like those in Fig. 20, are composed of the two parts of inclinations, which indicates the existence of the majority group of local discharges that has the short statistical mean value of time intervals ranging 10 - 20 ms, and the minority group that has the long statistical mean value of time intervals ranging 120 - 150 ms. Curve (III) represents the probability distribution of time intervals

* Time interval between an ES pulse and an adjacent LR type pulse has been omitted in this measurements.

Fig. 23


%
100
10
1.0
0.1
Integrated percentage
(III) G.St. N=223 BC
(I) CD.ES N=3913 CW
(II) GD.ES N=1686 CW
10ms
21ms
13ms
146ms
125ms
100
200
300m
ES pulses time interval

between two successive ground strokes involved in ground discharges, and has been obtained from the analysis of data of the Boys camera photograph of the discharges. It is very clear that Curve (III) fairly well coincide with the part of Curves (I) and (II), which corresponds to the majority group. Hence the local discharges which produce ES pulses relating to short time intervals, must be considered to possess the discharge mechanism roughly identical with that of the strokes composing a ground discharge in many respects. Table 15 represents the statistical mean and the median, both obtained from the curves illustrated in Fig. 23.

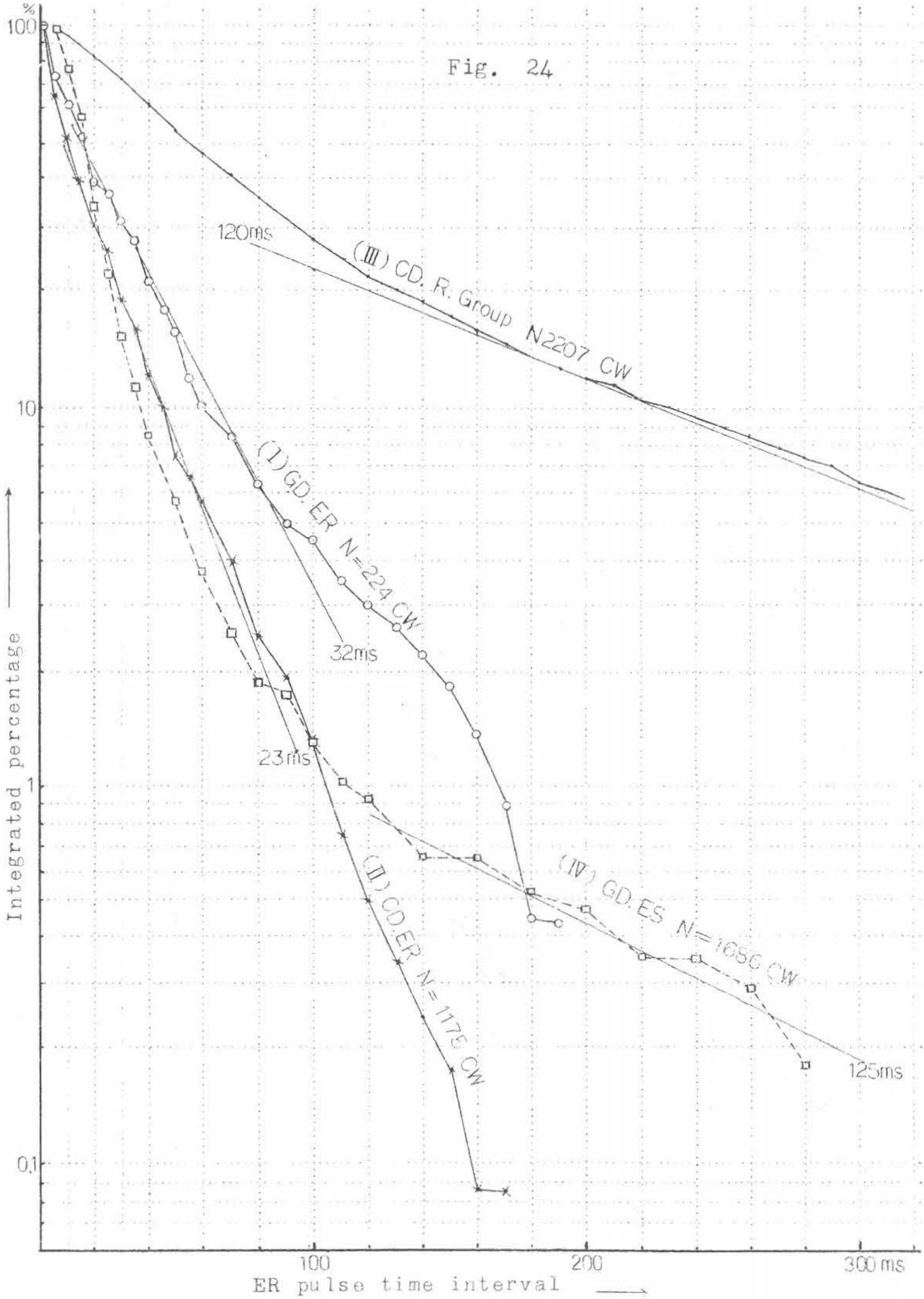
Table 15

Sort of time intervals		Statistical mean value		Median value	Number of data
		Short value	Long value		
Ground stroke interval		21 ms	______	6.7 ms	223
ES pulse interval	Ground dis-charge	13.0 ms	125 ms	10.2 ms	1686
	Cloud dis-charge	10.0 ms	146 ms	8.6 ms	3913

As illustrated in Fig. 22 (b) the ER pulse, a group of appreciable radiation pulses, is generally recorded superposed on a ES pulse, if the sensitivity of the short range waveform recorder and distance of the local discharge are suited for obtaining such a complex ES pulse.Therefore the probability distribution of the time intervals between the two successive ER pulses, which can usually be obtained on the record of atmospheric waveforms originating from lightning discharges 60~100 km apart from the station, should statistically be identical with the probability distribution of time intervals between the two successive ES pulses, which usually appear on the record of atmospheric waveforms originating from lightning discharges less than roughly 50 km apart from the station. This point is indicated in Fig. 24, in which Curves (I) and (II) are the probability distributions of ER pulses and respectively correspond to ground discharges and to cloud discharges. The general tendencies of these two distributions are seen roughly to coincide with that of the short time interval portion of the ES pulse distribution represented by Curve (IV), which is identical with Curve (II) in Fig. 23, and represents the case of ground discharges. Because of the complexity of structure of atmospheric waveforms recorded within the range of distances, 60~100 km it is very difficult to verify the existence of the minority group of local discharges, which relate to the long statistical time intervals, on the ER pulse interval distributions, which take all ER pulse intervals appearing on a record of CW into account. However, if we neglect the ER pulses which are not composed of a group of appreciable radiation pulses on a CW record of atmospherics due to discharges 50 - 150 km apart from the station, the measurement of time intervals between the remaning ER pulses, each composed of a group of appreciable radiation pulses, gives the probability distribution represented by Curve (III) indicating the case of cloud discharges. The comparison of the two Curves (III) and (IV) clearly indicates that the statistical mean time interval roughly identical with that of the minority group measured on the probability distribution of ES pulse intervals, can also be obtained on the distribution of ER pulse intervals, if the ER pulses appearing on the atmospheric waveform record of a lightning discharge are selected with respect to their amplitudes. The above statistical facts seem to indicate the point that the majority group of ES pulses representing short time intervals are produced by small scaled local discharges and the minority group of ES pulses representing long time intervals are produced by large scaled local discharges accompanying a group of a few appreciable fast streamers. Table 16 represents the statistical mean and the median obtained from the curves represented in Fig. 24.

Table 16

Sort of pulses	Sort of discharges	Statistical mean value		Median value	Number of data
		Minority group	Majority group		
R pulse group	Cloud discharge	———	120 ms	46 ms	2207
ER pulse (group)	Ground discharge	32 ms	———	15.9 ms	224
	Cloud discharge	23 ms	———	10.4 ms	1175

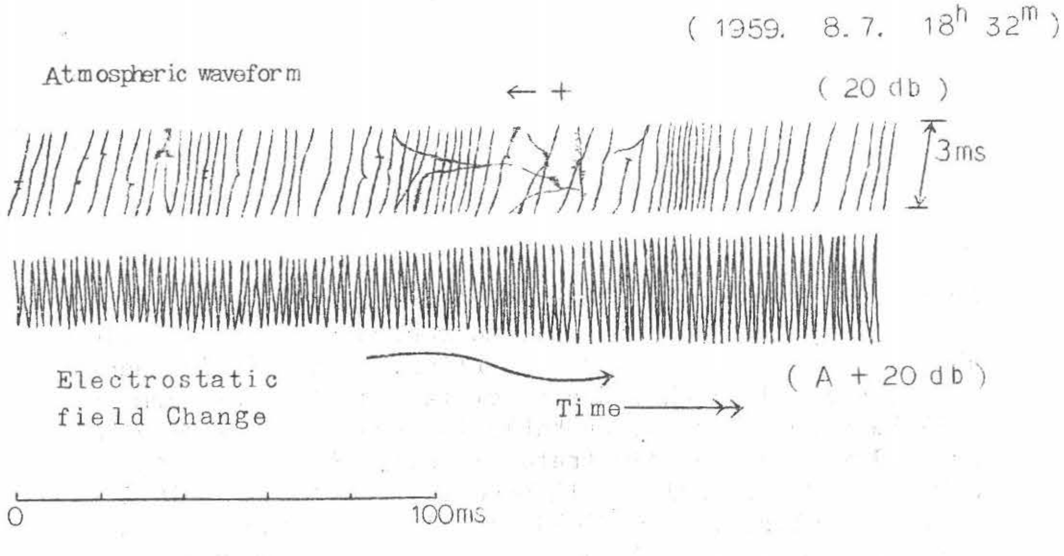


%
100
10
1
0,1
Fig. 24
120ms
(III) CD. R. Group N2207 CW
(I) GD. ER N=224 CW
32ms
23ms
(II) CD.ER N=1178 CW
(IV) GD. ES N=1656 CW
125ms
Integrated percentage
100
200
300 ms
ER pulse time interval

(d) Polarities of electrostatic field changes and those of ES pulses and ER pulses:

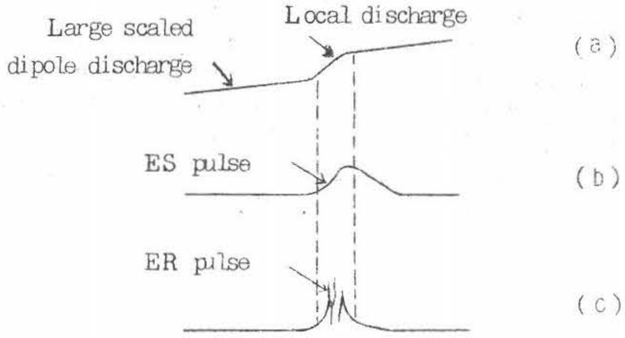
When the electrostatic field changes due to a lightning discharge are recorded with an electrostatic field-meter, we generally see that they usually do not represent anyting but the gradual variations which indicate a slow rate of discharge processes, with the exception of stepwise field changes mainly corresponding to individual strokes composing a ground discharge. And, it is somewhat difficult on the record of electrostatic field-meter to detect the existence of minute field changes which correspond each to ES pulse or to a ER pulse appearing on the atmospheric waveforms simultaneously recorded with the record of electrostatic field changes. This point is indicated by the simultaneous records of electrostatic field changes and atmospheric waveforms illustrated in Fig. 25.

Fig. 25



This situation may partly come from the difference in the sensitivities of the two recording methods and parly from the difference in the recording frequency ranges of the two. However, if a ES pulse is really produced by a local discharge composing a minute part of or a minute secondary part of a large scaled cloud discharge representable with a vertical dipole model, it will be very natural to consider that the direction of a minute local discharge will generally coincide with that of a large scaled dipole discharge representing the whole of a cloud discharge. Fig. 26 (a) represents an idealized case, in which a stepwise field change due to a local discharge is superposed on a gradual field change corresponding to a large scaled dipole discharge occurring in the same direction as the local discharge.

Fig. 26



As the time constant of our short range waveform recorder is not long enough to be able to record a stepwise field change without any serious distrtion, so the field change due to a local discharge can not take a stepwise form but will be deformed so as probably to have the form of a ES pulse like the one illustrated in Fig. 26 (b), and the polarity of a ES pulse will become generally to coincide with the polarity of a field change due to the relating large scaled dipole discharge statistically occurring in the same direction as a local discharge. Following the result obtained in the above discussion, the form of a ES pulse produced by a local discharge will be changed into the form of a ER pulse, if the distance of the local discharge is increased roughly beyond 50 km, and further, the discharge involves the process of fast streamers. Concerning this point, the coincidence of the three occurrence probability distributions (I),(II) and (IV) given in Fig. 24 clearly indicate that several remarkably fast streamers usually break out during the process of a local discharge as one of the elementary processes composing it. Following these ideas, the direction of electricity transfer produced by a fast streamer will statistically be coincide with that of the electricity transfer prcduced by the remaining portion of the local discharge process giving a ES pulse. The Fig. 26(c) illustrates an idealized ER pulse whose polarity coincide with that of the gradual field change due to a large scaled discharge. The Table 17 (a) indicates the corelation between the polarities of gradual electrostatic field changes due to a lightning discharge and those of the ER pulses appearing on the atmospheric waveforms simultaneously recorded along with the former changes, and the Table 17(b) the corelation between the polarity of a ES pulse and that of a ER pulse, both overlapping with each other on an atmospheric waveform. The Table (a) indicates that the observed percentage of the case, in which the polarities of the two corresponding records are reversed with each other, is really equal to zero, and the Table (b) also indicates the reversed polarities to occupy only 11.7 % of all the examined polarity combinations of the two corresponding pulses These are the observational facts which statistically coincide with the above expectation deduced from the possible structure of a minute discharge

Table 17 (a)

Polarity corelation / simultaneous records of field changes	Same polarity	Mixed polarity	Reversed polarity
Polarities of ER pulses on an atmospheric waveform	+ − + −	[illegible]	+ −
Polarity of gradual electrostatic field change	+ − 0* 0	+ + 0 0	− +
Number of cases	36	9	0
Precentage	80 %	20 %	0 %

* The symbol 0 indicating the record, on which it was very difficult to determine the polarity.

Table 17 (b)

Polarity corelation / Sort of corresponding records	Same polarity		Reversed polarity	
Polarity of ES pulse on an atmospheric waveform	+	−	+	−
Polarity of ER pulse on an atmospheric waveform	+	−	−	+
Number of cases	224		30*	
Percentage	88.3 %		11.7 %	

* Many of the ER pulses included in this space have the forms which make it difficult to determine the polarities of the pulses.

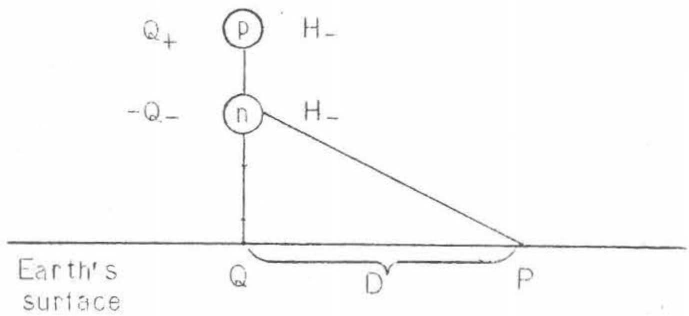
producting a ES pulse or a ER pulse on the atmospheric waveforms due to a lightning discharge. These minute discharges have been termed the local discharges in the above investigation. Following the above results, it will be possible to infer the probable structure of the gradual electrostatic field changes due to a lightning discharge, and to know the movement of electricity produced by the discharge, if we measure the polarity variations of ES or ER pulses, with the progress of a discharge on the atmospheric waveforms produced by it.

6 Gradual discharge process in a thundercloud

(A) Electrical charge transfer resulting from a cloud discharge

The electrostatic field changes produced by a cloud discharge are generally very gradual and usually do not represent any appreciable stepwise structure. The Fig. 25 in the previous section illustrates an example of electrostatic field changes due to a cloud discharge, which indicate this point. As we have already investigated in Section 4D, Chapter III, many of the cloud discharges generally produce each the simple electrostatic field change resulting from a simple movement of electricity in a thundercloud. Hence it becomes possible to approximate a cloud discharge with the model of a vertical dipole discharge. Moreover, if we consider the general model of distribution of electricity inside a thundercloud illustrated in Fig. 1, Section 1, Chapter II, the structure of the greater portion of cloud discharges may be interpreated with the discharge processe breaking out between the upper positive charge distribution P and the lower columnar negative charge distribution n represented in the figure, except for the small portion of cloud discharges which have a reversed polarity to the above case. Following this idea, let us assume the discharge of a positive electrical dipole pn located on a vertical axis as illustrated in Fig. 27, and consider the electrostatic field E_s due to the dipole measured at the observation point P on the earth's sureface, distance D apart from the point Q lying on the earth's sureface just beneath

Fig. 27.



the vertical dipole pn. Then E_s will be expressed as follows:

$$E_s = \frac{2Q_+ H_+}{(H_+^2 + D^2)^{3/2}} - \frac{2Q_- H_-}{(H_-^2 + D^2)^{3/2}} = \frac{2Q_+}{D^2} f(x_+) - \frac{2Q}{D} f(x_-)$$

Where Q_+, Q_-, and H_+, H_-, are respectively the magnitude of electrical charges and the altitudes of the two charge centers p and n, and f(x) is represented by

$$f(x) = \frac{x}{(1+x^2)^{3/2}}, \quad x_+ = H_+/D, \quad x_- = H_-/D$$

In the above expression of E_s, the term $f(x_+)$ or the term $f(x_-)$ must be treated as a variable function in accordance with the discharge being advanced by a positive streamer, or by a negative streamer. The electrostatic field E_s at the moment, when the dipole discharge has proceeded the half way, will be represented as follows:

For the case of a positive streamer discharge,

$$E'_s = \frac{2Q}{D^2} f(\xi) - \frac{2Q_-}{D^2} f(x_-)$$

For the case of a negative streamer discharge,

$$E'_{s-} = \frac{2Q_+}{D^2} f(x_+) - \frac{2Q_-}{D^2} f(\xi)$$

where $\xi = x = H/D$ the relative altitude of the streamer head advancing the discharge gap pn from p to n (a positive streamer), or from n to p (a negative streamer). The electrostatic field change produced by the above dipole discharge will be :

For positive steamer discharge

$$\Delta E_{s+} = E'_{s+} - E_s = \frac{2Q_+}{D^2} \left\{ f(\xi) - f(x_+) \right\} \qquad (1)$$

For negative streamer discharge

$$\Delta E_{s-} = E'_{s-} - E_s = \frac{2Q_-}{D^2} \left\{ f(x_-) - f(\xi) \right\} \qquad (2)$$

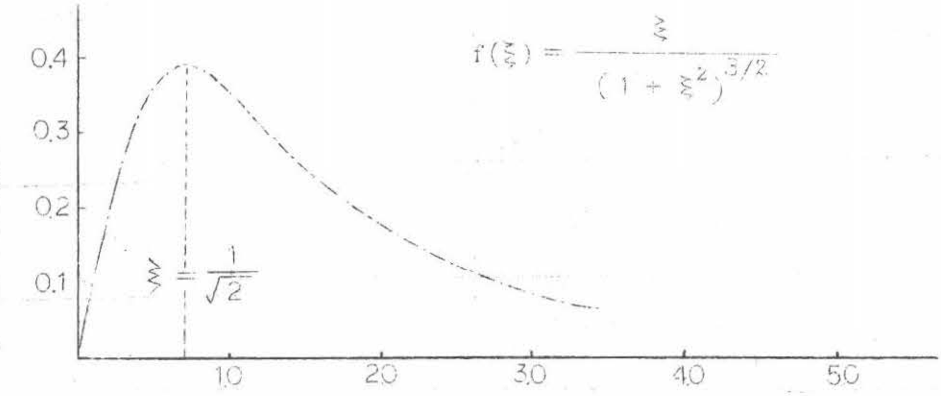
where $x_- \leqq \xi \leqq x_+$

and ξ decreases from x to x_- in the formula (1)

ξ increases from x_- to x_+ in the formula (2)

Therefore we can see that the change of the electrostatic field due to a vertical dipole discharge is determined by the term given by $f(\xi)$. It is evident that the polarity of E_s will become positive or negative according as the range of the variable ξ, given by $H_+/D \leqq \xi \leqq H_-/D$ really occupies what portion of the curve illustrated in the Fig. 28. If the distance of a discharge from the observation station is adequate, the range of the variable ξ will include $\xi = 1/\sqrt{2}$ (the field reversal distance) which gives the maximum of the curve illustrated in Fig. 28. In such cases the formulae (1) and (2) respectively tell that a positive streamer must produces a maximum and a negative streamer must produce a minimum. Therefore if we consider the records of electrostatic field changes due to lightning discharges having been observed in the region of their field reversal distances and investigate the number of the field

Fig. 28



change records each representing a maximum and that of the field change records each representing a minimum, then we can obtain the occurrence probabilities respectively of the positive and the negative streamers which produce the gradual field change, the characteristic of a non-ground discharge. The result of this investigation is represented in Table 18, which indicates that the gradual electrostatic field change due to a ground discharge generally has the simpler structure than that corresponding to a cloud discharge. If we take the stepwise field change produced by a ground stroke outside of account, 92 % of the recorded gradual electrostatic field changes, each resulting from a "junction process " involved in a ground discharge, have each a maximum on themselves, while the recorded field changes, which have each a minimum on themselves.

Table 18

Type of gradual electrostatic field-changes \ Sort of discharge		Cloud discharge	Ground discharge
Simple change	Maximum type	67.9 %	92.0 %
	Minimum type	6.6 %	2.2 %
Complex change*		25.5 %	5.8 %
Number of data		53	87

* The field change that has more than two extreme values

occupy only 2.2 % of all the recorded gradual field changes, each corresponding to a ground discharge, and representing a few extreme values on it. Considering the possible error probably occurring in the processes of recording and measuring the electrostatic field changes, it will be reasonable to conclude that nearly all of the junction streamers - the streamer producing a junction process - involved in ground discharges and producing each a simple gradual field change must have a positive polarity. In the case of ground discharges the records of complex field change which can not be interpreted by the process of a simple vertical movement of a single junction streamer, clearly occupy only 5.8 % of all the recorded gradual field changes due to ground discharges, while the case of cloud discharges indicates that the records of such complex field changes occupy as much as 25.5 % of all the recorded gradual field changes. This observational result seems clearly to indicate that the greater portion of the junction streamer processes each involved in a ground discharge are generally simpler than those each involved in a cloud discharge. Further, the case of a cloud discharge indicates that the recorded discharges, which are advanced each by a positive slow streamer giving a maximum on the record of electrostatic field change, really occupy about 68% of all the recorded cloud discharges, and compose the majority group of them. On the other hand, the recorded cloud discharges, which are advanced each by a mixture of positive and negative slow streamers giving few extremed on the record of the field change, also occupy as much as 25.5 % of all the recorded cloud discharges, so that the mixed process of positive and negative streamers composing the minority group also can not to be neglected thoroughly. Following these facts, the cloud discharges may be divided, at least, into the following two categories, i.e., the majority group of simple discharges which are advanced each by the process of a positive slow streamer, and the minority group of complicated discharges which are advanced each by a mixed process of positive and negative slow streamers probably the process of a mid-gap streamer that will be described later in Section 7C, Chapter IV.

(B) Complex streamer inside a thundercloud

We have investigated in the previous paragraph (A) the fact that the main part of a cloud discharge is generally composed of the streamer process which produce a gradual electrostatic field change, and further studied that in many cases, the streamers of this kind has a positive polarity, and accordingly they can be regarded as to posess the character similar to that of the junction streamers appearing in the intervals between strokes of a ground discharge. Here let us intend to estimate the progressive velocity v_c of the positve streamer in a thundercloud, composing the main part of a cloud discharge. Let the statistical length of the separation of the two charge centers composing a vertical dipole be 3.2 km following Workman (14), and take the median value, 0.38 sec, of the durations of cloud discharges given in Table 14 Section 5, then it follows $v_c = 3.2 \times 10^5/3.8 \times 10^{-1} = 0.84 \times 10^6$ cm/sec. As to the progressive velocity of a junction streamer occurring in the stroke interval of a ground discharge, the averaging of the values of altitude differences between two successive ground strokes (I,II), (II,III),..... (VIII,IX) represented in Table 19 of Section 4B, Chapter II gives the value 0.2 km and the statistical mean of the time intervals between the two successive strokes given by the probability distribution curves illustrated in Fig. 20 of

Section 4B Chapter II is 20 ms. So that the velocity v_J of a junction streamer will be $v_J = 0.2 \times 10^5/20 \times 10^{-3} = 1 \times 10^6$ cm/sec. So the conclusion $v_c \doteq v_J$ can be obtained. It is now evident that the slow streamer composing the main part of a cloud discharge generally has the natures similar to those of the junction streamer appearing in the stroke interval of a ground discharge with regard not only to its polarity but also to its progressive velocity. The velocity value 1×10^6 is a actually still lower than the lowest observed velocity 5×10^6 cm/sec of the beta type stepped leader described in Section 2B of this chapter. Honda (15) pointed out in his paper that a positive streamer generally has a velocity about twice as large as that of a negative streamer. Our comparison of the progressive velocities of positive streamers with those of negative streamers, both obtained from the data of indoor experiment of spark discharges, also clearly confirmed this point, according to which(16) a positive streamer generally has a larger progressive velocity than a negative streamer, if the experimental conditions producing the two streamers are kept the same with each other. However, the case of an actual cloud discharge indicates, on the contrary, that the positive slow streamer that composes the main part of a cloud discharge statistically has the velocity only equal to a franction of the lowest observed velocity of a stepped leader which has a negative polarity. These contradicting facts existing between experimental spark discharges and lightning discharges seem to be attributed to the fact that the slow streamer process appearing in a thundercloud is not composed of single streamer but actually has a complex structure constructed from a group of a large number of small positive streamers, each of which probably has the nature actually confirmed in the experiment of a spark discharge. The streamer of a complex structure that probably includes a large number of minute streamers in it may have, as a whole, an average velocity of a very low value, which can be deduced from the nature of the gradual electrostatic field change due to a cloud discharge, in spite of the high velocities of the minute component streamers, so long as the component streamers break out intermitently through-out the gradual discharge process. Following this postulation we shall term the slow streamer compsoing the main part of a cloud discharge, as well as the junction streamer appearing in the intervals between two successive stroke of a ground discharge," the complex streamer" in a thundercloud.
In the sense that a complex streamer is constructed from a number of minute component streamers appearing intermitently throughout a non-ground discharge process, this streamer contains some aspects of a corona discharge.
In fact, several kinds of statistical characteristics relating

to a cloud discharge can really be interpreted by a model that assumes a cloud discharge thoroughly composed of a corona processe.[16] If the velocities of minute component streamers are sufficiently high, a complex streamer of a corona like character should produce a great many radiation pulses, each corresponding to a component streamer, randomly occurring through the process of a gradual electrostatic field change. Therefore if the distance of a complex streamer process from the observation station is appropriate, and if the gain and the frequency characteristics of the short range waveform recorder are suited for recording the radiation pulses produced by component streamers, then the radiation pulses should be registered on the atmospheric waveform record of a cloud discharge throughout the period of the gradual electrostatic field change indicating the existence of a complex streamer. However, we have not succeeded till to the present to confirm the existence of the random repetition of small radiation pulses appearing throughout the period of a gradual field change. The reason of this will be either of the following two: our waveform recorder, which is designed to record the electromagnetic field changes composed from Fourier components distributing in the frequency range 1 ~ 100 kc, is not capable of recording the radiation pulses corresponding individual minute component streamers, or the velocities of the minute component streamers are not sufficiently high so as to produce each a sharp radiation pulse. Because of the shortage of the reliable data suited for the investigation of the above point, it is very difficult to determine which of the two factors being the more important.

Following the idea of a complex streamer which continuously develop a cloud discharge forward, the luminosity recorder should ragister the continuous luminosity exsisting throughout the period of a gradual electrostatic field change which indicates the existence of a complex streamer. As the continuous luminosity, however, generally has a weak indensity, so it is usually difficult to catch it with our luminosity recorder unless the sensitivity of the recorder being adjusted to a sufficiently high degree and the discharge to be reocrded being located close to the observation station. Table 19 represents the number of records of cloud discharges which involve each a continuous luminosity with a duration longer than 100 ms measured on the simultaneous records of the luminosity and the electrostatic field changes due a cloud discharge appearing close to the station*.

The result indicated in Table 19 shows that our luminosity recorder is incapable of recording the continuous luminosity in spite of its high gain, so long as the cloud discharge producing the continuous luminosity does not break out within a distance roughly less than 5 km from the recording station.

Table 19

Distance from cloud discharge	Grade of electro-static field-change *	Record of cloud discharge containing continuous luminosity longer than 100 ms		Number of examined data
		Percentage	Number of records	
0 - 5 km	Large	100 %	11	11
5 - 10 km	Medium	76 %	19	25
10 - 15 km	Small	11.1 %	2	18

* The gain of the electrostatic field-meter: - 10 db
The gain of the luminosity recorder: 20, 30 db

Further see the point that how large portion of a lightning discharge duration does the continuous luminosity duration, occupy the total duration T_{total} and the continuous luminosity duration T_{cont} have been measured on each luminosity record corresponding to a lightning discharge appeared within the distance less than 15 km from the station. The statistical result of investigation of ratio values T_{cont}/T_{total}, caluculated from the above data, has been represented in Table 20, which indicate that the ratios are lying in a wide range of values 0.01 - 1.0 and the part of ratio values, which are larger than 0.8, occupies only 7.6 % of all the examined records. However, if we take the point into account that the distances of lightning discharges giving the data of Table 20 distribute in a wide range as large as 15 km from the station, it will be very probable that the larger portion of a total luminosity duration corresponding to a lightning,

---

* The continuous luminosity recordable with our luminosity recorder seems not always to come from the light emission from the advancing head of a complex streamer in a thundercloud, because the light from this portion will generally be disturbed by the opac cloud body. Therefore, especially when a thundercloud covers the overhead portion of the sky, the greater part of the continuous luminosity records caught with our apparatus, at least, may be considered to result from the light emission of the overhead portion of the cloud base.

Table 20

Ratio of luminosity durations	Distance lightnind discharge	Distribution range of the radio values	lightning discharges possessing the ratio larger than 0.8		Number of examined data
			Percentage	Number of data	
T_{cont}/T_{total}	0 - 15 km	0.01 - 1.0	7.6 %	12	157

independent of being a ground discharge or a cloud discharge, will really be occupied by a continuous luminosity in most of the records of luminosity changes, provided that, the first, the distance of a discharge from the station is short enough, the seond, the sensitivity of the recorder is suffciently high, and the third, the conditions of the light emission from a discharge in a thundercloud is fabourable for recording the continuous luminosity change. We have already described in Section 2D of this chapter the nature of an intercloud discharge, whose channel emits the weak light continuously throughout a relatively long period occupying an appreciable portion of a lightning duration, and which has several point sources of strong light emissions on its channel. This kind of slow continuous process of a intercloud discharge will probably be the possible appearance of a complex streamer described in this section.

7 Fine structure of a cloud discharge

(A) Local discharge

As we have already investigated in the previous section, the main part of a cloud discharge and the part of a ground discharge exclusing the process of ground strokes are generally composed of the slow process of a complex streamer, during the life of which thelocal discharges described in Section 5 break out intermittently. The statistical character of the time intervals between two successive local discharges, independent of being accompanied by a cloud discharge or by a ground discharge, fiarly well coincide with that of the time intervals between two successive ground strokes involved in a discharge to ground (see the Fig. 23 Section 5), from which we can deduce the resemblances of the mechanism of a local discharge in a thundercloud with that of a ground stroke. The point, whether the small discharge in a thundercloud will end as a local discharge in the cloud or will grow to a dart leader to lead a return ground stroke, it will depend on the density and the extent of the volume of the locally accumulated electricity. Following the results obtained by Malan and Schonland(17) the process of a junction streamer conecting two successive ground strokes will be as follows: When the process of a ground stroke involved in a multiple ground discharge has completed, a conductive discharge channel is stretching upward from the earth's surface to the dissipated negative charge center related to this ground stroke, so that the negative charge accumulation, which is located just above the discharged center and occupies the lowermost portion of the relating negatively charged column existing in the cloud, will instantly induce the positive electricity around the upper-end surface of the dissipated charge center through the intermediation of the remaining conductive channel connecting the center with the earth's surface. As the mean saparation of the two charge centers producing two successive strokes of a ground discharge is only 0.2 km (see Fig. 21, Section 4B, Chapter II), the negative charge accumulation at the lowermost portion of the negatively charged column and the positive charge accumulation induced by the former at the uppermost portion of channel of the previous ground stroke will build up a strong negative electrostatic field, by the action of which a complex positive streamer- the junction streamer with a positive polarity-will be started from the induced positive charge accumulation and stretch upwards. When the advancing ramified head of the complex streamer reach the lowermost one of the negative charge centers scattered along the vertical negatively charged column, several dart streamers will start successively from the upper negative charge center taking the opposite direction to the complex streamer advancing upwards, and travel downwards along the discharge channel built up by the complex streamer. If the charge accumulation at the lowermost portion of the negatively charged column is sufficiently high enough so as to advance one of the dart streamers further along the remaining discharge channel having been built up by the previous return ground stroke, then a minute dart streamer, which happens to statisfy the condtion most favorrable for the further progress, will grow to a huge scaled dart leader and lead the next return stroke. On the contrary, in the case of a cloud discharge the both electrodes of the discharge are located vertically within a thundercloud, and statistically the upper electrode is charged with positive electricity, while the lower one with a negative electricity. This is the dipole polarity just reverse to that of a ground discharge. As the two electrodes relating to a cloud discharge are composed each of a volume charge distribution, the two electrodes must be considered to be equivalent with each other. This may inevitably result in the production of a positive complex streamer stretching downward from the positive electrode located in the upper portion of a thundercloud*. The positive complex streamer thus produced will advance downward along the negatively charged column extending vertically beneath the positive electrode, and nentralized the column from the upper-end to the lower-end of it.

If the supposedly ramifield head of a positive complex streamer growing downward reaches one of the negative charge centers scattered along the column, the continuous discharge advanced by the process of a complex streamer will be activated locally, which results in the production of a small scaled local discharge in this moment. The local discharge thus produced will give a ES pulse on the waveforms of a cloud discharge recorded at distances less than 50 ~ 60 km apart from the station. At this moment a group of appreciable but small scaled fast streamers** may break out in accordance with the electrical conditions producing a local discharge and will give a group of radiation pulses forming a ER pulse on the atmospheric waveforms of a cloud discharge recorded at a distance lying

** Following the discussion given in Section 4. the probable length of these fast streamers would be 0.5 ~ 1 km.

* In the case of an artificial spark discharge produced between two metal electrodes, a positive streamer generally has the tendency to grow more easily than a negative streamer can do it, if the discharge conditions of the two are kept the same with each other.

in the range 50 - 150 km apart from the discharge. Following the analogy of a junction streamer process involved in a ground discharge, the fast streamers which break out in the process of a local discharge occurring in a cloud discharge will be nothing other than the negative dart streamerswhich progress upward and are directed toward the inside portion of the complex streamer head advancing downwards. This point will be touched once more in the following discussion. If the scale of a local discharge happens to be remarkable, some of the fast streamers which are included in a local discharge and give each a radiation pulse will have a chance to grow to a huge scaled dart streamer, and construct a component cloud stroke involved in a multiple cloud discharge. Further, if a portion of a huge scaled dart streamer extends through the outer-edge of a thundercloud, the streamer may be photographed by the flash resolving camera as a component flash of a multiple cloud lightning discharge. Following this idea, the number of radiation pulses involved in a ER pulse, or in a complex ES pulse, must represent the number of remarkable fast streamers breaking out in association with a local discharge. The statistical investigation of the number of remarkable radiation pulses involved in the waveform of a local discharge gives the median value 2, which point is indicated by Table 21 suggesting the existence of, in average, 2 fast remarkable streamers per local discharge.

Table 21

Statistical value	Median value	Number of data
Number of R pulses per ER pulse	2	1425

Table 22

Sort of discharges / Distance / ES pulse polarity variation		Cloud discharge			Ground discharge*		
		0-8 km	8-20 km	20-60 km	0-8 km	8-20 km	20-60 km
Simple variation	+ +	57.8 %	45.7%	24.5 %	17.6%	45.2%	62.1%
	+ —	31.4 %	8.8%	7.9 %	17.6%	14.6%	13.9%
	— +	3.8 %	16.2%	16.9 %	8.3%	15.9%	5.6%
	— —	2.2 %	13.1%	39.6 %	39.8%	14.6%	8.3%
Complex variation		4.8 %	16.2%	11.1%	16.7%	9.7%	10.1%
Number of data		185	160	33	108	82	108

*ES pulses existing between two successive IR type pulses, which correspond to ground strokes later than the first, have been measured on the CW records of ground discharges.

the two types + + and - - must correspend to the record of the electrostatic field change due to a lightning discharge breaking out outside the field reversal region*
surrouding the recording station, and the type + - and - + must correspond to the record of the field change due to a discharge breaking out inside the field reversal region, provided the discharge being representable with a vertical dipole model. The estimation of distances represented in the table has been made from the consideration of the recording gain of the short range waveform recorder and from the average amplitude of the recorded ES pulses, hence the distance values only have a statistical meaning. One of the outstanding evidences the table indicates is that, in the case of cloud discharges, the variation type is seen predominating over the variation type - - in the short distances, while the type - - conversely predominating over the type in the long distances, and in contrast to this, the case of ground discharges represents just the reversed relation. On the otherhand, the polarity of

* Following the model illustrated in the Fig. 27, Section 6A, the field reversal region will be given by $\sqrt{2}.H - \leqq D \leqq \sqrt{2}.H$.

(B) ES and ER pulses appearing on the atmospheric waveforms

Following the result obtained in Section 5, the polarities of the ES pulses, of the ER pulses, and of the gradual electrostatic field changes, all recorded simultaneously, are statistically coincide with each other. Therefore it becomes possible to infer statistically the probable apprearance of the electrostatic field changes, which may be produced by a complex streamer, from the investigation of the polarity variation of these pulses on the atmospheric waveforms with the development of theconcerned discharge. The polarities of ES pulses or of ER pulses appearing on the atmospheric waveforms due to a lightning discharge generally represent a very complicated variation during thedevelopment of a discharge. Hence it is always very difficult to find two atmospheric waveforms on which the polarities of ES pulses or of ER pulses vary in a completely identical manner with the development of the relating discharges. However, if small differences in the ES pulse polarities may be ignored and merely the polarity variation characteristi s represented by the majority of ES pulses are taken into account, it may be possible to determine the type of the variation of ES pulse polarities with the development of the relating lightning discharge. Table 22 represents the percentage numbers of the records which belongs to each one of the five categories of the polarity variation type of ES pulses measured on atmospheric waveforms recorded at several different distances from the relating lightning discharges.

The category marked as " simple variation" includes the lightning discharges which can be interpreted each by the vertical movement of a positive or a negative complex streamer, i.e., the cloud discharges representable with a vertical dipole discharge, and the category marked as "complex variation" includes the lightning discharges which can not be interpreted each by the simple vertical movement of a complex streamer, i.e, the complicated cloud discharges not representable with a simple vertical dipole discharge. The two types + +and - - represent equally the case in which the ES pulses appearing on the CW record of a lightning discharge have each an identical polarity throughout the discharge except for minute polarity fluctuations occasinally appearing on the CW record. The types + - and - + represent the case in which the polarities of ES pulses on the respective record of a lightning discharge vary respectively once from + to - or from - to + with the development of the respective discharge, so long as the minute fluctuations of the polarities may be ignored. Following to the coincidence principle of the polarity of ES pulses and that of the gradual electrostatic field change, both obtained simultaneously, concerning the same lightning discharge, ER pulses are in a relation roughly to coincide with the polarity of ES pulses, provided these two sorts of pulses being recorded coincidently at two places lying at respectively appropriate distances from a common lightning discharge, So that polarity variation of ER pulses with the development of a lightning discharge, measured on the atmospheric waveforms due to a relatively far distant discharge, must be expected statistically to coincide with the polarity variation of ES pulses, measured on the waveforms due to a discharge appeared at an appropriate distance from the station. The statistical result of the investigation of polarity variation of ER pulses corresponding to lightning discharges 40 - 150 km distant from the station is given in Table 23, which represents, though roughly, the similar tendencies with those of the respectively corresponding columns of Table 22, so long as the small difference may be ignored. When the head of a positive complex streamer that progresses inside a thundercloud with a slow velocity, makes contact with a highly charged center of negative electricity, the velocity of the streamer head may be increased sudenly at this moment for a very short time length in a remarkable degree. For this reason, we may replace the process of a local discharge with a small but sudden local displacement of the electricity accumulated in a point like shape*

Let the earth's surface be expressed by xy - plane, and the vertical direction by z-axis, and assume that the magnitude of an ES pulse is given by the electrostatic field change resulting from the movement of a point electric charge q from the point Q(x,y,z) to the adjacent point Q + dQ. If we assume the opposite point electric charge -q being located at the image point Q (x,y,-z), the vertical component of the electrostatic field, which the point electric charge q produces at the observation point P(ξ , η , 0) lying on the earth's surface, will be given by

$$E_s = 2qz/r^3$$

where $r^2 = (x - \xi)^2 + (y - \eta)^2 + z^2$.

Hence the vertical component of a electrostatic field change E_s produced by the displacement d of the point electric charge q will be

$$\Delta E_s = \Delta Q(z/r^3) d\,\upsilon \qquad (1)$$

where $d\upsilon \equiv (dx,\ dy,\ dz) = (\alpha\ \beta\ \gamma) d\ell$.

* Generally a discharge can be approximated by a movement of positive or negative electricity concentrated in a small volume.

Table 23

Sort of discharges / Distance / ER pulse polarity variation		Cloud discharge	Ground discharge*
		40 - 50 km.	40 - 150 km.
Simple variation	+ +	9.3 %	57.3 %
	+ —	8.5 %	30.4 %
	— +	15.2 %	1.1 %
	— —	53.7 %	0.0 %
Complex variation		13.3 %	11.2 %
Number of data		375	89

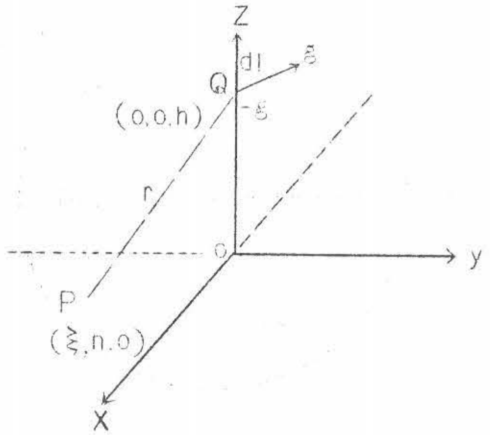
* ER pulses existing between two successive L_R type pulses, which correspond to ground strokes later than the first, have been measured on the CW records of ground discharges.

This value is equivalent to the twice of the electrostatic field which is produced by an electric dipole* composed of a point charge q place at point Q + dQ and an opposite point charge -q placed-at point Q, and therefore possessing an electric moment p = q.dl lying in the direction given by (α β γ). The conefficient 2 comes from an image dipole introduced to let the electrostatic field due to the dipole pair to take the vertical direction to the earth's furface, when it is measured on this surface. The generality of the formula (1) will not be disturved, even if the position of the local diple is given by Q(0,0,h), and the direction of it by ($\cos\lambda$, $\cos\mu$, $\cos\nu$). (see Fig. 29). Let us take the expression $d\varpi(\cos\lambda.\ \cos\mu,\ \cos\nu).\ d\ell$ and calcuate the differential formula (1). The result obtained under the assumption $\cos\nu \neq 0$ will be

$$\Delta E_s = \frac{2qdl\ \cos\nu}{r^5}\left\{\left(\xi + 3/2\ h\ \frac{\cos\lambda}{\cos\nu}\right)^2 + \left(\eta + 3/2\ h\ \frac{\cos\mu}{\cos\nu}\right)^2 - h^2\,\frac{9 - \cos^2\nu}{4\ \cos^2\nu}\right\} \qquad (2)$$

* In the followings this will be termed as "the local dipole".

Fig. 29



The generality of the formula (2) will not be lost, even though the direction of the local dipole is taken in the xz-plane so as to make $\cos\mu = 0$. In this case the formula (2) will be somewhat simplified as follows:

$$\Delta E_s = \frac{2qdl\ \cos\nu}{r^5}\left\{(\xi + 3/2\ htg\,\nu)^2 + \eta^2 - h^2\ \frac{9-\cos^2\nu}{4\ \cos^2\nu}\right\} \quad (3)$$

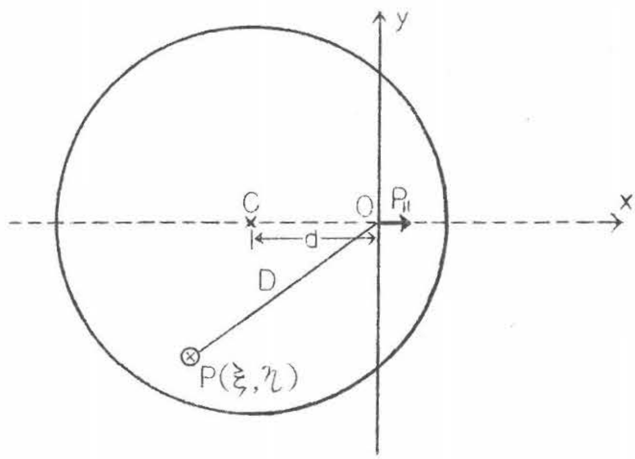
Putting $\Delta E_s = 0$ into the equation (3) we can get the field reversal boundary as follows:

$$(\xi + 3/2\ htg\nu)^2 + \eta^2 = h^2\ \frac{9-\cos^2\nu}{4\cos^2\nu}$$

This is a circle whose center is placed at $(-3/2htg\nu, 0, 0)$, and whose radius is $R = h\sqrt{9-\cos^2\nu}/2\cos\nu$. As the direction of a local dipole approaches to a horizontal direction, the angle ν will increase to $\pi/2$, hence the position of center of the circle will be displaced horizontally away from the local dipole, which results in the increase of the radius R. Fig. 30 represents the horizontal projection of a local dipole on the xy plane and the field reversal boundary circle relating to it.

In the figure p" represents the horizontal projection of a local dipole, C the center of the field reversal circle. The polarity of ΔE_s, when the observation station is placed inside the field reversal circle or when it is placed outside

Fig. 30



the circle, will coincide with the polarity of ΔE_S, when $(\xi, \eta) = (0, 0)$ or $(\xi, \eta) = (\xi_\infty, 0)$ is put into the equation (3) respectively (ξ_∞ represents a large value). That is, the polarity ΔE_S can be determined by the following formulae:

$$\left.\begin{array}{ll} \text{For field changes inside the reversal circle} & \Delta E_S = -4qd\ell\cos\nu \\ \text{For field changes outside the reversal circle} & \Delta E_S = 2qd\ell\cos\nu/|\xi_\infty| \end{array}\right\} (5)$$

As the relation $qd\ell \cdot \cos\nu \gtrless 0$ (where $q>0$) will be concluded in accordance with a local dipole respectively directing upwards or directing downwards with reference to the horizontal plane, so it becomes possible to determine the relation of the upward of downward direction of a local dipole to the polarity of ES pulses (identical with the polarity of ΔE_S) recorded inside or outside of the reversal circle by using the formulae(5). The result of this investigation is represented in Table 24, The table also includes the relation between the sense of a local dipole and that of a complex streamer being concerned with the former i.e., the relation which would be relaized if the directions of the two coincide with each other. Following what the table indicates, it is very clear that the sense of a vertical dipole representing a cloud discharge developed by a complex streamer (see Fig. 27, Section (A) and the sense of a local dipole associated with the discharge are always reversed with each ther. If a local

Table 24

Sewse of a local dipole	Correlation of the sense of a local discharge with		ES pulse polarity due to a local dipole	
	the sense of the related positive comples streamer	the sense of the related negative complex streamer	Inside the reversal circle	Outside the reversal circle
Upward sense	Same sense	Reversed sense	−	+
Downward sense	Same sense	Reversed sense	+	−

dipole lies in a horizontal plane so that $\cos\nu = 0$, we must consider the following formula (6) instead of the formula (2).

$$E_s = \frac{6qdl}{r^5}(\xi h \cos\lambda + \eta h \cos\mu). \qquad (6)$$

The generality of the formula (6) will not be lost even though the assumption $\cos\mu = 0$ is adopted, i.e., the direction of a local dipole becomes identical with that of the vector $\overrightarrow{ox}$. This simplifies the formula (6) as follows

$$\Delta E_s = \frac{6\,qdl}{r^5}\xi h \qquad (7)$$

In this case, y axis given by $\xi = 0$ represents the field reversal boundary (see Fig. 30). The relation of the direction of a horizontal local dipole to the polarity of the corresponding ES pulse will be obtained by investigating the polarity of formula (7), the result of which is indicated in Table 25.

Table 25

Direction of a horizontal dipole	ES pulse polarity due to a horizontal local dipole	
	$\xi < 0$	$\xi > 0$
Parallel to $\overrightarrow{ox}$	−	+
Reverse to $\overrightarrow{ox}$	+	−

As the probability of a local dipole taking nearly a horizontal direction will be remarkably smaller than that of the dipole taking non-horizontal directions, we shall assume $\cos\gamma \neq 0$ in the following discussions. As we have already investigated, center and radius of the field reversal circle are given by

$$R = h\sqrt{9 - \cos^2\gamma}/2 \cos\gamma$$

$$C(-d, 0, 0) \equiv C(-3/2\ h\,tg\,\gamma, 0, 0) \qquad (8)$$

Generally, a local discharge will break out, when a comples streamer composing the main part of a non-ground discharge makes contact, in its progress, with a local charge center of electricity accumulated to a remarkable degree. So that the directions of the produced local discharges will be very variable from a local discharge to another according to the magnitude of accumulated charge, to the shape, and to the relative position of the local charge center. For the sake of simplicity, let us assume here that the direction of a local dipole takes a constant inclination given by γ = const., but as to the azimuthal angle, it can take any value equally. Then the formulae (8) become to indicate that the radius R of the field reversal circle and the distance d of the center of the circle from the origin O of the Cartecian coordinates, which coincides with the horizontal projection of the local dipole (see Fig. 30), will be kept at constant values independent of the azimuth of the local dipole. Therefore the observation point P on the earth's surface, distance D apart from the local dipole, will come out being placed inside or outside the reversal circle in accordance with the azimuth of the local dipole. Let the probability that the point P is included inside the reversal circle be p, and the probability that P is excluded outside the circle be p', then a simple calculation shows that p and p' = 1 - p can be expressed by the following relation

$$p = 1 \qquad p' = 0 \qquad K > 1 \qquad D < (R - d)$$

$$p = 1 - \frac{1}{\pi}\cos^{-1}K$$

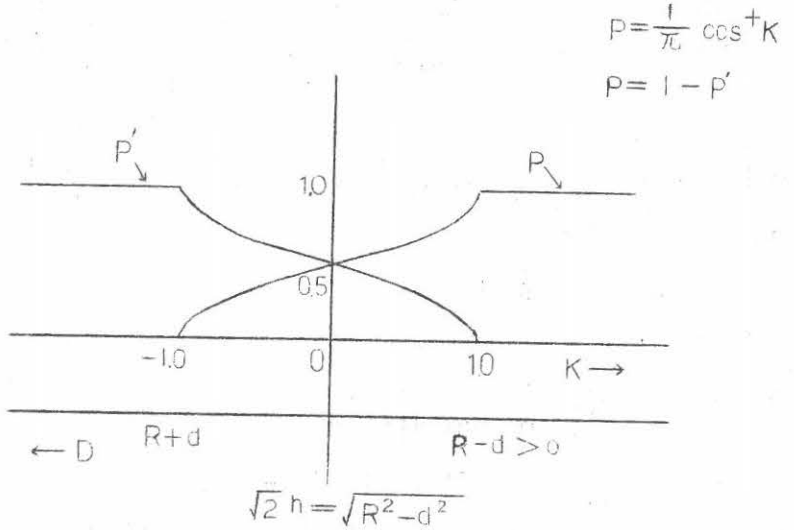
$$p' = \frac{1}{\pi}\cos^{-1}K \qquad |K| \leq 1 \quad (R - D) \leq D \leq (R + d) \qquad (9)$$

where $K = (2h^2 - D^2)/3Dh\,tg\,\gamma = (R^2 - d^2 - D^2)/2dD$ (10)

Fig. 31 illustrated the function p and p'.

If p = p' = 0.5, so that the observation point comes to a position where the probabilities that the position is included of excluded respectively inside or outside of the circle, are equal with each other, then the relation $D = \sqrt{2}.h$

Fig. 31



will be concluded. This is the similar relation to that given by $\xi = H/D = 1/\sqrt{2}$ (see Fig. 28, Section 6A) representing the relative field reversal distance resulting from the vertical electricity transfer taking the form of a comples streamer that produces a cloud discharge representable with a vertical electric dipole. Let us assume that the ES pulse due to a discharge of a local dipole with an altitude h is observed at an arbitrary point on the earth's surface, distance D apart from the dipole horizontally, then the comparison of polarity of the recorded ES pulse when $D > \sqrt{2}.h$ is satisfied with that of the ES pulse when $D < \sqrt{2}.h$ is satisfied will show the relation that the probability, the ES pulse polarities of the two cases being reversed with each other, is larger than that, the ES pulse polarities of the two being idntical with each other. If we denote the altitudes of the positive and the negative charge centers concerning a cloud discharge by H+ and H-respectively, the altitude h of an individual local discharge must satisfy the relation $H_- < h < H_+$. So that the region of field reversal distances in a statistical sense will be given by $\sqrt{2}.H_- < D < \sqrt{2}.H_+$. Following Workman and his colleagues(14), let us assume the altitudes H- and H+ of a cloud discharge center being 5.2 km and 5.8 km respectively, from which the relation 7.4 km $< D <$ 8.2 km will be concluded. Hence it will be evident that the polarities of ES pulses corresponding to the distance $D \ll 8$ km and those of ES pulses corresponding to the distance $D \gg 8$ km should statistically be just in a reversed relation with each other. This is the relation which actually interpret the observational result indicated in Table 22.

Generally in the actual cloud discharges, however, the altitude h, the inclination γ from the vertical axis, and the horizontal distance D, of a local dipole will be changed as the concerning complex streamer progresses continuously. Therefore the probability that n successive ES pulses appearing on the atmospheric waveforms of a cloud discharge all have an identical polarity must be given by

$$P = \prod^{n} p_i + \prod^{n} p_i' \qquad (11)$$

where p_i and p_i' are the functions respectively identical with the functions p and p', but the values of variables of them are dependent on i. So that they can be written as

$$p_i = p(K_i), \qquad p_i' = p'(K_i) = 1 - p(K_i)$$

Following the result of a statistical investigation, the number of ES pulses per waveform due to a lightning discharge amount roughly to 21 in the median value, as Table 26 indicates.

Table 26

Sort of discharges	Cloud discharge	Ground discharge	All lightning discharges
Number ES pulses included in a lightning idscharge waveform(median value)	21	24.5	21.5
Number of data	194	76	270

Considering this observational fact, let u assume n = 21 in the relation (11), and further 21 pair values of (h_i, γ_i) having been given. Then putting the above 21 pair values (h_i, γ_i) into the equation (8) we can get 21 pair values of (R_i, d_i) from which 21 values of (R_i+d_i), and those of ($R_i - d_i$) will be obtained.

Next let us assume that these in total 42 pairs vatues arranged accordance with their magnitude will be represented as follows:

$$R_1' + d_1' > R_2' + d_2' > \ldots\ldots R_{21}' + d_{21}' > R_1'' - d_1'' > R''-d_2'' > \ldots > R_{21}'' - d_{21}''$$

For che D values which statisfy the relation

$$R_{21}' + d_{21}' > D > R_1'' - d_1'' ,$$

we can get the following relation by using the formula (10)

$$|Ki| = |R_i^2 - d_i^2 - D^2|/2d_iD < 1$$

where $(i = 1,2,3, \ldots 21)$

Therefore if the observation point is placed in the range of distance expressed by the above relation that limits the D value, $p_i < 1$ must be satisfied for all i values, so that $\prod^{21} p_i \ll 1$ and $\prod^{21} p_i' < 1$* will result. Hence we can get following conclusions from the formula (11)

$$P \doteqdot 0$$

where $R_{21}' + d_{21}' > D > R_1'' - d_1''$

In contrast to this, according as the observation point being placed in range of distances represented respectively by the relation $D > R_1' + d_1'$ or by the relation $D < R_{21}'' - d_{21}'$, the relation $p_i = 0$, $p_i' = 1$, or the relation $p_i = 1$, $p_i' = 0$ will be concluded respectively. So that the following conclusion will be obtained:

$$P \doteqdot 1$$

where $D > R_1' + d_1'$ or $D < R_{21}'' - d_{21}''$

Therefore the curve which the probability function P represents will take the from illustrated by the generalized figure in Fig. 32, which clearly indicates the point that the region of D practically corresponding to $0 < P < 1$, that is, the region of D, in which an appreciable number of lightning discharges producing atmospheric waveforms falling into the ++variation type or into the - - variation type of ES pulses are to be recorded mixed with an appreciable

---

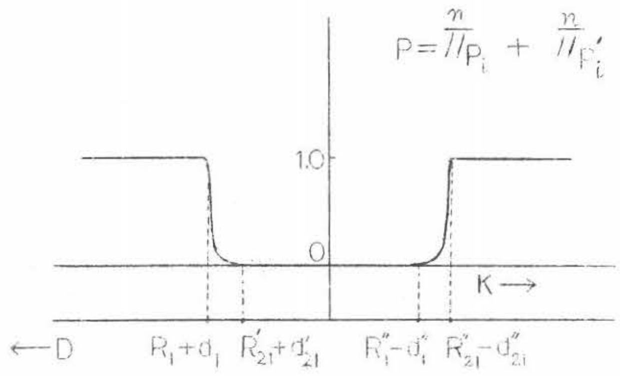
* For example even though $p_i = 0.9$ for all i values, $p_i = (0.9)^{21} \doteqdot 0.1$, so that $\prod^{21} p_i' = (0.1)^{21} \doteqdot 0$ will be concluded.

number of discharges producing waveforms falling into the + - variation type, or into - + variation type of the ES pulse, must be limited to a very narrow range. So that it is to be expected that nearly all of the waveforms recorded in the range of near distances, or those recorded in the range of long distances, statistically become to fall respectively into the + + variation type or into the - - variation type and almost of all the waveforms recorded in the range of medium distances come out to fall into + - mixed variation types. In contrast this, the investigation of ES pulse polarity variations measured on the actual atmospheric waveforms of lightning discharges indicates that the columns representing the distances 8 - 20 km in the Table 22 are occupied chiefly by the lightning discharges which give the waveforms falling into + + variation type, or into - - variation type, despite the fact that distance range 8 - 20 km probably corresponds to the field reversal region in a statistical sense*, and therefore many of the discharge waveforms contributing to these columns should represent ± - mixed variation type of ES pulse polarities. This is incompatible with the above theoretical expection that $P \doteqdot 0$ should result, when the discharges break out in the range of field reversal distances. On the contrary to this, the columns of the distance range 0 - 8 km in the same table, the case of short distances, and the columns of the distance range 20 - 60 km, the case of long distances, are occupied chiefly by the lightning discharges which give the waveforms representing no variation of ES pulse polarities throughout the duration each discharge. This point really coincides with the above theoretical expectation that $P \doteqdot 1$ must be concluded when the discharges break out in the range of short distances, or of long distances. The principal cause of the fact that the theoretical expectation does not coincide with the statistical result of the actual measurement of waveforms, so long as the range of medium distances being concerned, seems to be attributed to the point that the assumption that a local dipole can take any azimuth with equal probability, is not applicable to the actual case.

Considered from this point, the local discharges breaking out during the process of a lightning discharge should not be inferred to change their directions randomly from a local discharge to another, but must be presumed to take roughly a fixed direction throughout the process of a lightning discharge. We have already investigated in Section 5 that the polarity of electrostatic field changes due to a complex streamer process of a cloud discharge statistically coincide with those of ES pulses appearing on the atmospheric waveforms produced by the same discharge

* See foot note in the following paragraph C, (a).

Fig. 32



(Refer to Table 17 (a), Section 5). Hence, it will be very natural to infer that the local discharges generally have their directions roughly agreeing with that of the complex streamer composing the main part of a lightning discharge throughout the process of it.*

If we take small fluctuations of ES pulse polarities into account, there are some observational evidences indicating that some of the large number of local discharges included in a lightning discharge actually have the directions remarkably deviated from the mean value in many cases. To see this point more exactly, we have investigated the existence of small fluctuations of ES pulse polarities appearing on the atmospheric waveforms, which originate from lightning discharges occurring in the range of short distances or the range of long distances, and further, which do not represent any variation of ES pulse polarities in a rough sense. The result of this investigation is represented in Table 27, which indicates that nearly half or the recorded lightning discharges represent each some fluctuations in the ES pulse polarities which probably result from the remarkable change in the directions of local discharges. As indicated in Table 27, the investigation of the number of small fluctuations of ES pulse polarities per lightning discharge suggest that the

* The relation between the sense of a complex streamer and that of a local dipole has been represented in Table 24.

Table 27

	Fluctuation of ES pulse polarity	++variation type of ES pulses		--variation type of ES pulses		All lightning discharge
		Cloud discharge	Ground discharge	Cloud discharge	Ground discharge	
Number of data	exist	151	66	94	11	322
	non	181	35	107	36	359

directions of local discharges involved in a ground discharge statistically fluctuate more frequently than those of a cloud discharge, and that generally the waveforms due to lightning discharges occurring in short distances represent more frequent fluctuations in ES pulse polarities than those due to discharges occurring in long distances. The latter seems to come from the fact that small ES pulses will become not to be recorded on the atmospheric waveforms in accordance with the increase in discharge distances, because the ES pulse will be attenuated in proportion to $1/r^3$ with respect to the distance. Further the comparison of the polarity fluctuations between the four types of ES polarity variations, given in Table 28, clearly shows that the variation type + +and - - produce statistically the smaller number of fluctuations than the variation type + - and - + actually do it. Generally spaking , the principal causes of these polarity fluctuations of ES pulses may result from the temporary but complicated changes in the direction of a discharge channel in a thundercloud - probably the change in the direction of a complex streamer -, or from the ramifying, into various directions, of the advancing head of a complex streamer, which may result in temporary direction changes of the discharge channel given by a complex streamer. To produce the polarity change of a ES pulse, it is neccessary to introduce the polarity change of the term $qdl \cos \nu$ in the equation (3), or to introduce the azimuth change of a local dipole, so as to let observation point p to be displaced from the inside toward the outside of a field reversal circle, or displaced from the outside toward the inside of it.

Table 28

Variation type of ES pulses	Number of dssimilar polarity ES pulses per lightning discharge (Median value)					
	Cloud discharge			Ground discharge		
	0 - 8 km*	20-60 km	Number of data	0 - 8 km	20-60 km	Number of data
+ +	0	0	262	1.8	0	121
+ −	4.9	2.3	111	7.0	2.3	47
− +	1.3	0.7	89	5.5	5.5	25
− −	0.3	0	178	2.0	2.8	65

* The estimation of the discharge distances has been made from the adopted gain of the recorder and from the magnitude of electrostatic component appearing on the waveforms, so that the distance values indicated in the table have not any meaning other than a statistical one.

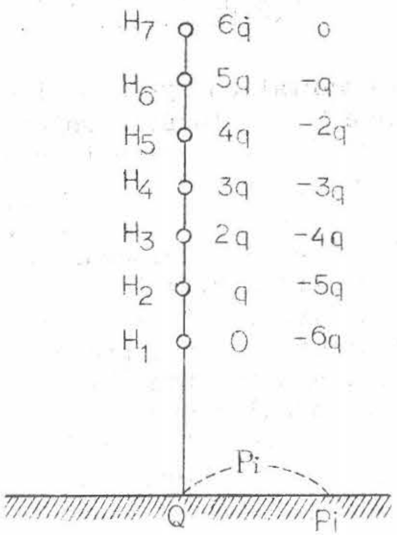
Following this idea, the observation point P generally must be located at distances sufficiently apart from the field reversal circles each corresponding to an individual local discharge, so longas as the polarity variation types + + and - - are concerned Therefore, these cases, a local discharge seems not to be capable of producing a polarity change of an ES pulse, unless the direction of it makes a remarkable fluctuation from the mean direction of the individual local discharges. On the contrary, in the cases of the variation type + - and - + the observation point P must be located statistically at relatively near distances from the reversal circles, so that small fluctuation in the direction of a local discharge will be sufficient to produce the polarity change of an ES pulse on the atmospheric waveforms of a lightning discharge. Therefore the observational fact that the lightning discharges falling into the variation types + + and - - pepresent each only a small number of fluctuations in ES pulse polarities on their atmospheric waveforms, seems to lead us to the conclusion that the directions of individual local discharges, which break out during the gradual process of a non-ground discharge process, generally are kept the same throughout the process of a lightning discharge and hence, do not represent statistically any remarkable fluctuation through the process.

(C) Mechanism of a cloud discharge

(a) Discharge process of a complex streamer:

It has been made clear from the discussion in the previous section that the local discharges appearing in the process of a lighting discharge usually do not represent any considerable changes of their directions throughout the process of a discharge, and that their directions must be considered approximately to coincide with that of a complex streamer composing the main part of a lightning discharge. Considering this point, let us assume a lightning discharge which is composed from a complex streamer accompanying aoubt twenty local discharges, all directed to the common vertical axist.* When we attempt to approximate a discharge in a thundercloud, regardless of being a cloud discharge or junction process that contributes to a ground discharge, with a discharge model of a vertical dipole, the altitude and the electric moment of it must be considered to take the value being different from a discharge to another. Therefore, for the sake of a statistical investigation let us assume that an aggregation of various vertical dipoles, which correspond to individual lightning discharges, are arranged on a vertical axis. Then the point charges resulting from individual dipoles **will** be distributed on a section of the vertical axis, which actually corresponds to the distribution rnage of the possible dipole altitudes.

Fig. 33



* For the case of a positive complex streamer, the local dipoles should be assumed to take the identical "sense" with that of the streamer, and for the case of a negative complex streamer the local dipoles should be assumed to take the reversed "sense" to that of the streamer.

If the number of individual vertical dipoles are numerous, the arranged point charges will from a liner distribution of electricity. Further if we consider the mechanism of the vertical electricity separation which is accomplished by a violent ascending air stream existing in a thundercloud, the linear densities of positive and negative electricities may have the distributions to decrease from the two opposing charge centers towards the directions facing with each other. Following this idea let us assume a pair of statistical linear distributions of the two opposite point charges as illustrated in Fig. 33, in which point charge pairs (0, -6q), (q, -5q), ..., (6q, 0) are located at altitudes H_1, H_2, ..., H_7, respectively. We shall further assume that an individual discharge taking place between two opposing point charge centers involved in the above linear distribution always has a positive polarity, i.e., for example, the negative point charge -6q at the altitude H_1 discharges with each of the positive charge centers each containing electricity +q, located respectively at the altitudes H_2, H_3, ..., H_7. In this case total number of discharges will be $\sum_{i=1}^{6} i = 21$. If we record the electrostatic field changes due to these 21 discharges at the 8 observation points P_1, P_2, ... P_8 which are distributed along the earth's surface, and satisfy the conditions given by

$$D_1 < \sqrt{2}.H_1 < D_2 < \sqrt{2}.H_2 \quad ..... < \sqrt{2}.H_7 < D_8.$$

then the polarity variation types of the gradual electrostatic field changes recorded at these 8 points, and accordingly the variation types of ES pulse polarities at these 8 points must have the occurrence probabilities represented in Table 29 with respect to these 21 lightning discharges. The row(a) of the table represents the case of discharges each developed by a positive complex streamer, which breaks out from the positive electrode of a positive vertical dipole representing a discharge in a thundercloud and progresses downwards along the axis of the dipole, and the row (b), on the other hand, repr sents the case of discharges each developed by a negative complex streamer which breaks out from the negative electrode of a positive vertical dipole and progresses upwards along the axis of the dipole. Table 30 has been introduced, for the sake of a comparison, to show the case of discharges representable with negative vertical dipoles. This can be obtained by reversing the polarities of the point electric charges q indicated in Fig. 33. Hence, the row(a) of Table 30, likewise to that of Table 29, represents the case of the discharges each developed by a positive complex streamer starting from the positive electrode of a negative vertical dipole representing a discharge in a thundercloud, and the

Table 39 (Positive vertical dipole)

Polarity of streamer	Distance / Variation types of ES pulse polarity		D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8
(a) Positive	+	+	21	15	10	6	3	1	0	0
	+	−	0	6	10	12	12	10	6	0
	−	+	0	0	0	0	0	0	0	0
	−	−	0	0	1	3	6	10	15	21
(b) Negative	+	+	21	15	10	6	3	1	0	0
	+	−	0	0	0	0	0	0	0	0
	−	+	0	6	10	12	12	10	6	0
	−	−	0	0	1	3	6	10	15	21

Table 30 (Negative vertical dipole)

Polarity of streamer	Distance / Variation type of ES pulse polarity		D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8
(a) Positibe	+	+	0	0	1	3	6	10	15	21
	+	−	0	6	10	12	12	10	6	0
	−	+	0	0	0	0	0	0	0	0
	−	−	21	15	10	6	3	1	0	0
(b) Negative	+	+	0	0	1	3	6	10	15	21
	+	−	0	0	0	0	0	0	0	0
	−	+	0	6	10	12	12	10	6	0
	−	−	21	15	10	6	3	1	0	0

row (b) represents the case of the discharge developed each by a negative complex streamer starting from the negative electrode of a negative vertical dipole. The comparison of these two tables clearly indicates the following two points. In the first place, the statistical tendencies which the polarity variation type + + and - - would represent with respect to the variation in the distances D, are determined by the polarity of vertical dipoles representing individual discharges and are independent of the polarity of complex streamers developing them, and in the second place, the statisticl tendencies which the polarity variation types + - and - + represent with respect to the variation in the distances D, are determined by the polarity of complex streamers developing individual discharges, and are independent of the polarity of vertical dipoles representing them.
Following the above point of view, we have compared the statistical tendencies of the polarity variation types + + and - - indicated in Table 22 with those represented in Table 29 and 30, and arrived at the conclusion that generally a cloud discharge can be approximated with a discharge of a positive vertical dipole existing in a thundercloud and a ground discharge, on the contrary, can be approximated with a discharge of negative vertical dipole existing in a thundercloud so long as the influences of the individual ground strokes involved in it are ignored. Smith(18) described in his paper the result of his statistical investigation of the polarities of vertical dipoles representing cloud discharges and those of the complex streamers contributing to the discharges. According to this 72.3 % of all the recorded cloud discharges were composed each of a positive vertical dipole, and the remaining 27.7 % were composed each of a negative vertical dipole. On the other hand, the model of a vertical dipole aggregation given by us has indicated the point that the statistical tnedencies which the polarity variation types + + and - - of ES pulses would represnt with respect to the variation in the observation distances D, are thoroughly determined by the polarities of individual dipoles, and they actually represent a completely reversed character when the polarity of the concerned dipoles is reversed. Therefore, if we consider a case in which the variation of ES pulse polarities with the development of a discharge is investigated on each of the atmospheric waveforms due to a discharge group, which is composed from a mixture of certain number of positive and negative dipoles, then it will be expected that the statistical tendency which each of the polarity variation types of ES pulses -for example, the four types indicated, in Table 29-would, represents, will be given by a group of numerical values which can be obtained by multiplying the respective values indicated in the corresponding spaces of Tables 29 and 30 by the respective factors representing the

mixing percentage of positive and negative dipole discharges, and then by adding the pair values obtained through the above multiplication. If we imagine that a practically useful table representing the case of a mixed group of positive and negative dipoles has really been constructed from Tables 29 and 30 through the above procedure, then the table should have the spaces which correspond respectively to the space representing the case (distance D_1, type $_{++}$) and to the space representing the case (distance D_8, type - -), given in Table 29, and represent the percentage value in which the positive dipoles have been mixed. Further it should include also the spaces which correspond respectively to the space representing the case (distance D_1, type - -) and to the space representing the case (distance D_8, type++) given in Table 30, and represent the percentage value in which the negative dipoles have been mixed. Because Table 22 may generally be inferred to represent the case of a mixture of positive and negative dipoles, the above procedure of estimation of the mixing percentages will be applicable to the case of Table 22 that represents the statistical result of actual observations. Following this idea let us assume that the mean of the numerical volues given in the spaces which correspond to the cases (distance D_1, type++) and (distance D_8, type - -) given in Table 22 actually represents the value proportional to the number of positive dipoles and the mean of the numerical values given in the spaces which correspond to the cases (distance D_1, type - -) and (distance D_8, type $_{++}$) given in the same table represents the value proportional to the number of negative dipoles. Then we can get the percentage number of the positive and the negative dipoles relating to all cloud discharges. This point is indicated in the Table 31. According to this 73.7 % of the examined cloud discharges are representable with positive dipoles while 26.3 % are representable with negative dipoles, which is the results coinciding fairly well with the statistical percentage values obtained by Smith.

Table 31

Sort of discharge / Measuring method / Polarity	Cloud discharge	
	ES pulse polarity	Electrostatic field change(Smith)
Positive dipole	73.7 %	72.3 %
Negative dipole	26.3 %	27.7 %
Number of data	323	54

However, so long as we limit our considerations, at least, to the interpretation of statistical characters of the two polarity variation types + + and - -, it will not always necessary to assume a dipole aggregation composed of a mixture of positive and negative dipoles. For example, if we consider the uncertainty in the estimation of distances, and the fluctuation in the directions, from a vertical axis, of the individual discharges, and estimate these quantities adequately, the assumption of a group of dipoles which each have an identical polarity will be sufficient for explaining the statistical result given in Table 22, as the following discussion will indicate. However, the result obtained by Smith, as a clear observational evidence, also should not thoroughly be ignore , so that it will be very reasonable to infer that the actual aggregation of cloud discharges is the mixture of these two factors in certain proportions.

Following the above investigation, the polarity, of a complex streamer contributing to a cloud discharge may be estimated from the statistical tendencies of the polarity variation types + - and - + of ES pulses, in addition, Table 29 and 30 clearly indicate that the greater part of atmospheric waveforms falling into the polarity variation types + - and - + are recorded generally in the region of medium distances D_4 and D_5. Hence, if we investigate the occurrence percentage of the polarity variation types + - and - + of ES pulses on the atmospheric waveforms due to lightning discharges breaking out in the range of medium distances, the result will be the statistical determination of the polarity of a complex streamer. Let us consider a region of distances distributing roughly 7 - 20 km*, whch may statistically include in it a great portion of the number of field reversal regions each corresponding to an acutual cloud discharge, and investigate the recorded percentage of cloud discharges which occurred in this region of distances and accordingly produced the atmospherics waveforms falling into the polarity variation types + - and - + of ES pulses. Table 32 represents the result of this investigation.* *

**As the number of data giving the result of this table is much larger than that giving the result of Table 22, so the former table will give the less reliable result than the latter.

* Workman and his colleauges described in their report (14) that the positive, and the negative electric charge centers composing a dipole of a cloud discharge have the altitudes respectively 5.2 km and 5.8 km in weighted means, hence the statistical field reversal region corresponding to cloud discharges will be 7.4 - 8.2 km provided the horizontal component of the dipole being ignored. However, if the effect of the horizontal component of it is to be taken into account, the region will be extended and include much wider range of distances.

Following this table the complex streamers each contributing to a discharge within a thundercloud, regardless of being a cloud discharge, or a junction process involved in a ground discharge, must be postulated largely to have the positive polarity.

Table 32

ES pulse polarity variation type	Polarity of complex streamer	Cloud discharge	Ground discharge
+ −	+	60.3 %	60.5 %
− +	−	39.7 %	39.5 %
Number of data		318	81

This is the tendency roughly coinciding with what has alreay been indicated in Table 18 of Section 6A, representing the result of polarity measurement on the records of electrostatic field changes obtained with our field-meter. However, if we attach some importance to the details of the two tables, it is evident that for the case of ground discharges, the discrepancy between 60.5 % given by the ES pulse method and 92.0 % given by the electrostatic field-meter method is by no means negligible, while for the case of cloud discharges, the values 60.3 %, given by the ES pulse method and 67.9 % given by the electrostatic field-meter method can actually be regarded as being identical with each other. This may partly come from the fact that a ground discharge generally has a more complicated structure than that of a cloud discharge so far as the ES pulse polarities being concerned (cf. Table 28), and partly from the fact that ES pulse method infers indirectly the polarity of electrostatic field changes due to a complex streamer by investigating the polarities of local discharges associated with the streamer. If the latter factor were more important the coincidence of the two methods in the case of cloud discharges might be rather superficial one. As we investigated already, it was not impossible for us to make the statistical characteristics given in Tables 29 and 30, i.e., the results deduced from the assumption of simple aggregation of vertical dipoles illustrated in Fig. 33, to coincide with the actual statistical result given in Table 22 in a rough sense. Follwing this, it is evident that may deduce the conclusion that statistically a cloud discharge is the discharge of a positive dipole in a thundercloud and a ground discharge, if the portion of ground strokes may be

ignored, is the discharge of a negative dipole in the cloud. However, if we attempt to compare Table 22 with Table 29 and 30 more strictly, some small discrepancies existing between these two may not be ignored.
For example, the columns represent ng the distances D_1 and D_8 of Tables 29 and 30 include the spaces which give the zero statistical values, however, the observational result given by Table 22 has no columns which include the spaces indicating zero values.

Considering the uncertainties existing in the actual estimation of discharge distances given in Table 22 , let us make the distances represented by D_1, D_2 ....., D_8 in Tables 29 and 30 more rough so as to bring the theoretical expection nearer to the observed result, and denote them as follows:

$$(D_1, D_2, D_3,) \equiv D_N, \quad (D_4, D_5) \equiv D_M, \quad (D_6, D_7, D_8) \equiv D_D$$

The rearrangement of Tables 29 and 30 following these divisions of discharge distances will result in Table 33. The remarkable feature which Table 33 indicates is that the columns corresponding to medium distance D_M each give a maximum for the case of the polarity variation type + − indicated in the row of positive complex streamers and for the case of the polarity variaticn type − + indicated in the row of negative complex streamers.

This is a remarkable characteristic which the aggregation of vertical dipoles would represent. The comparison of Table 33 with Table 22 shows that the polarity variation type, which corresponds to a row of the type + − or a row of the type − + and represents a maximum in the medium distance, can not be found in any row given in Table 22 except for that representing the type − + in the column of ground discharge. If we attach large importance to this point, the result will be as follows. The vertical dipole discharges which may be inferred actually to take place should be limited to the case of negative dipole discharges which are developed each by a negative comples streamer and correspond to a partical group of all recorded ground discharges, so that it would be very difficult to interpret the other cases of dipole discharges with the model of a vertically located dipole*.
Table 33 indicates further that for the case of positive dipole, the spaces representing the case, type + +, distance D_D, and the case, type − − , distance D_N, and for the case of negative dipole, the spaces representing the case, type + +, distance D_N and the case, type − −, distance D_D, all hve a statistical value amounting only to 1.6 %. If we compare these values with those represented in the corresponding spaces in Table 22, we can easily see that in

Table 33

		Positive dipole			Negative dipole		
Polarity of complex streamer	Distance / ES pulses polarity variation type	D_N	D_M	D_D	D_N	D_M	D_D
(a) Positive polarity	+ +	73.0 %	21.5 %	1.6 %	1.6 %	21. %	73.0 %
	+ —	25.0 %	57.0 %	25.4 %	25.4 %	57.0 %	25.4 %
	— +	0 %	0 %	0 %	0 %	0 %	0 %
	— —	1.6 %	21.5 %	73.0 %	73.0 %	21.5 %	1.6 %
(b) Negative polarity	+ +	73.0 %	21.5 %	1.6 %	1.6 %	21.5 %	73.0 %
	+ —	0 %	0 %	0 %	0 %	0 %	0 %
	— +	25.4 %	57.0 %	25.4 %	25.4 %	57.0 %	25.4 %
	— —	1.6 %	21.5 %	73.0 %	73.0 %	21.5 %	1.6 %

* In Table 22, there are four cases which fall into the categories of the polarity variation types + — , or — +, however, the three out of these four caaes have the statistical distributions representing no maximum in the medium distances 8 - 20 km. These distributions with no maximums are generally very different from that which can be expected statistically from the model of a vertical dipole. If we attempt to interpret these distributions with the model of an aggregation of vertical dipoles, it will be necessary, for example, to assume a number of additional positive vertical dipoles at two pairs of altitudes (H_1,H_2) and (H_6,H_7), in addition to the vertical aggregation of dipoles illustrated in Fig. 33. The vertical distribution of point charges thus obtained, however, may result in the extraordinary high electric charge densities located at the both ends of the vertical distribution of the point electric charges illustrated in Fig. 33. This would make the statistical distribution of electricity along the vertical direction a thundercloud a very improbable one.

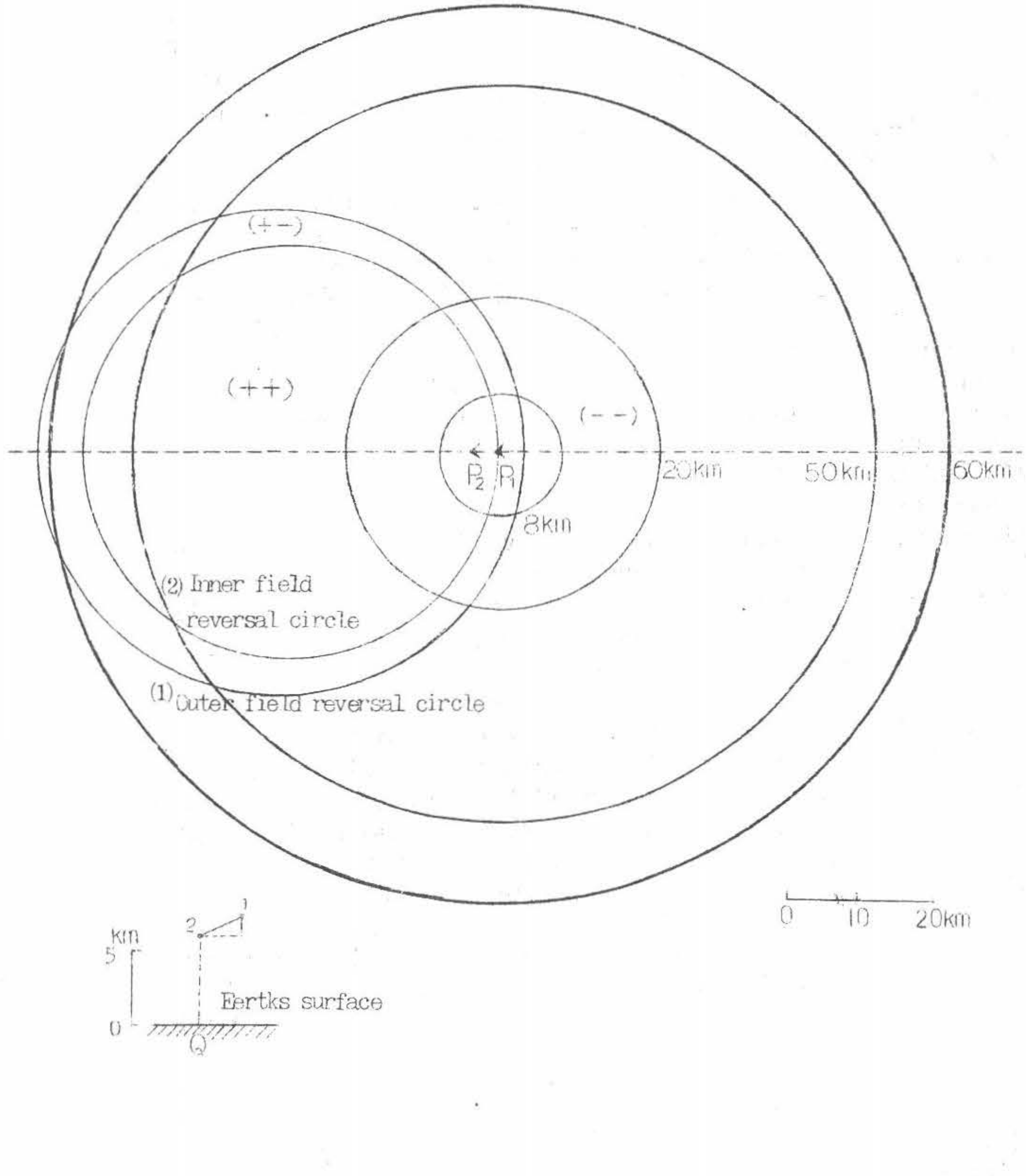
many cases the observed values are remarkably smaller than the corresponding, theoretically expected values. Concerning this point, our trial effort to let the above theoretical values approach a little nearer to the actually observed values, has also indicated that the difficulty of this attempt would not be removed unless the model of a vertically located dipole were not abandoned. One of the most principal reasons why it is difficult, under the assumption of vertical dipoles, to make the statistical tendencies which the theory expects to approach nearer to the observational results in regard to some details, seems to come from the following facts. The condition necessary for a local dipole to take a vertical direction, being put into the formulae (8) will give the result $R = \sqrt{2}.h$, $d = 0$, so that center of the field reversal circle will be located at the position just beneath the vertical dipole. This will tend to limit the possible polarity variation types of ES pulses to the categories denoted by ++ and - -, so long as we consider the two observation ranges respectively given by $D < \sqrt{2}.H_1$ and $D > \sqrt{2}.H_7$ (refer to Fig. 33). These being combined will construct a range of distances, which can include the greater part of the actually observed discharge distances.

Therefore, to improve these points, it is necessary to deviate the direction of a local dipole from the vertical axis and to let the center of the field reversal circle be displaced by the distance d from the position just beneath the dipole, and to make the radius of the circle to take so a large value as it becomes comparable with the distances being considered in Table 22. Concerning this point, let us adopt the model of an inclined dipole representing a discharge within a thundercloud given by Workman and his colleagues (14) on the basis of their thunderstorm observations, and assume the dipole altitudes given by $H_- = 6$ km, $H_+ = 7$ km and the horizontal separation of the dipole electricity given by 3 km. In contrast to a rather complicated distribution of point electric charges illustrated in Fig. 33 representing the case of vertical dipoles, we shall assume, in this case, that all the cloud discharges concerned can be represented with the model of an inclined dipole whose vertical and horizontal separations of electricity are statistically 1 km and 3 km respectively. The direction of local discharges are, of course, similarly to the case of a vertical dipole, to be assumed to coincide with that of a complex streamer developing a non-ground stroke lightning discharge. Fig. 34 represents the relative position of the two field reversal circles and the horizontal projection of the concerning inclined local dipole on the earth's surface.

The aspect of an inclined dipole in the vertical plane including it, is illustrated to the left lower-side of Fig. 34. If we denote the positions of the two electrodes of a dipole respectively with 1 and 2, the two illustrated circles (1) and (2) which represent the two field reversal boundaries given by the local dipole discharges breaking out respectively at the two points 1 and 2, will give the two extreme positions of the possible field reversal circles corresponding to all possible local discharges which take place in the process of a cloud discharge represented by the dipole whose electrodes are located at the points 1 and 2. So that the field reversal circles which relate to all possible local discharges which break out in the process of a cloud discharge, must be placed between these two circles(1) and (2). Considering the above nature of the two circles, we shall term the circles (1) and (2) the outer and the inner field reversal circles respectively, and the region lying between these two circles the field reversal region. p_1 and p_2 indicated in the figure represent the horizontal projections of the two downward local dipoles located respectively at the two points 1 and 2. The figure represents the case of a cloud discharge, in which a positive inclined dipole is discharged by a downward development of a positive complex streamer. The regions which limit the observation distances are given by the four concentric circles with the center located at the middle point between p_1 and p_2. When the complex streamer advances from the point 1 to the point 2 holding its direction constant, the field reversal circles each corresponding to a local discharge appearing in the process of the inclined dipole discharge will be displaced from the position of the circle (1) to the position of the circle (2)*. Therefore if the observation point is placed inside the inner reversal circle or placed outside the outer reversal circle, the ES pulse polarity veriation will fall respectively into the type + + or into the type - -, and if the observation point is included in the field reversal region located between the two circles, the ES pulse polarity variation will fall into the type - + or into the type + -. When the inclination of a dipole from the vertical axis becomes considerable, the center of the field reversal circle will be displaced for more than 30 km from the position of the horizontal projection of the dipole as the example illustrated in Fig. 34 indicates. Consequently the position of the horizontal projection of the dipole will be located at an inner point close to the periphery of the field reversal circle. This makes it possible that an observation point located at a distance less than 8 km or a distance lying in

* If the advancing direction of a complex streamer is reversed and the discharge of a dipole is advanced from the point 2 to the point 1, then the field reversal circles will be displaces from the position of the circle (2) to the position of the circle (1).

Fig. 34



(+-)
(++)
(--)
P2
P1
20km
50km
60km
8km
(2) Inner field
reversal circle
(1) Outer field reversal circle
0
10
20km
km
5
0
2
1
Eertks surface
Q

a range roughly covering 20 - 60 km, really comes into the field reversal region. Hence, let us assume that the lightning dipoles which each have a constant inclination and a constant horizontal separation of dipole charges, both identical with those of the lightning dipole illustrated to the left lowerside of Fig. 34, take any azimuth with equal probability, and further that the occurrence probability of lightning discharges per unit area is everywhere constant, then the probability that the atmospheric waveforms recorded in a certain region of the observation distances actually fall into a certain type of ES pulse polarity variations, will be proportional to the area which is cut from the region* relating to a certain polarity variation type and included in a certain range of the observation distances. Therefore the statisticl tendencies, which the four types of ES pulse polarity variations would represent in connection with the change in the observation distances, may be determined from the measurement of area of the individual regions which correspond each to a certain polarity variation type and to a certain range of the observation distances at the same time. The result of this measurement is given in Table 34.

A remarkable characteristic of this table is that the polarity variation types + - and - + of ES pulses do not represent any maxmum in the range of medium distances in contrast to what the same types in Table 33 indicate. Another remarkable point is that the spaces in Table 34, which correspond to the respective spaces in the Table 33, which are included in the rows representing the polarity variation types + + and - - and indicate the value 1.6 %, really give the values appreciably larger than this. Hence, it is evident that Table 34 really gives a result somewhat nearer to the observational result represented in Table 22 than what Table 33 indicates. Comparing the theoretical expectation indicated in Table 34 with the observational results given in Table 22 regarding the above point, it becomes possible to conclude that so long as Table 22 being concerned, the cloud discharges which produce the atmospheric waveforms falling into the polarity variation type + - of the ES pulses may be interpreted with the discharge mechanism of a positive dipole developed by a positive complex streamer, and the ground discharges which produce the waveforms falling into the polsairty variation type + - of the ES pulses may be

---

* One region out of the three, i.e., the inward region inside the inner field reversal circle, the outward region outside the outer field reversal circle, and the field reversal region placed between the outer and the inner field reversal circles.

Table 34.

Polarity of complex streamer	Distance / ES pulse polarity variation type	Positive dipole 0-8km	Positive dipole 8-20km	Positive dipole 20-60 km	Negative dipole 0-8km	Negative dipole 8-20km	Negative dipole 20-60 km
(a) Positive	+ +	45.8%	42.6%	14.4%	31.8%	51.2%	80.0%
	+ −	22.4%	6.2%	5.6%	22.4%	6.2%	5.6%
	− +	0%	0%	0%	0%	0%	0%
	− −	31.8%	51.2%	80.0%	45.8%	42.6%	14.4%
(b) Negative	+ +	45.8%	42.6%	14.4%	31.8%	51.2%	80.0%
	+ −	0%	0%	0%	0%	0%	0%
	− +	22.4%	6.2%	5.6%	22.4%	6.2%	5.6%
	− −	31.8%	51.2%	80.0%	45.8%	42.6%	14.4%

interpreted with the discharge mechanism of a negative dipole developed by a positive complex streamer.

The statistical tendency which the polarity variation type − + given in Table 22 represents concerning the cloud discharges, however, represent a somewhat complicated character in contrast to other types. Hence, the difficulty of interpreting this tendency may not to the removed unless a dipole discharge to assume a more complicated structure. Concerning the polarity variation type− + which the cloud discharges represent, Table 22 give the percentage valued which are increased with the increase in the observation distances. Therefore to make the theoretical percentage values to approach to the observed statistical tendency, it become necessary to give the inner and the outer field reversal circles such relative positions that the partial area, which is cut from the field reversal region and included in a certain range of the observation distances, may be increased as the observation distances corresponding to the above range increase. This would mean that the difference between the radii of the two field reversal circles should be considerable. The first relation of the formulae(8) clearly indicates the two possible ways to give large R value, i.e., the one is to obtain a large R by making h large, and the other is to obtain a large R by increasing the inclination γ of a local dipole. Following the former idea, let us attempt to increase R by increasing h under the assumption that the inclination γ is kept at a constant value equal to that illustrated in Fig. 34. In this case, however, we are obliged to assume an unreasonably large h value which can not be applied to an actual thunderstrom. Therefore the reasonable way to obtain the two remarkably different R values will be to give the inclination of the two local dipoles, which correspond respectively to the outer and the inner reversal circles, the considerably different values with each other. Hence let us assume a complex streamer that developes a cloud discharge, to change its direction once on half way of it, and to become more parallel to the horizontal direction in the second half period of the discharge Further we shall assume that the altitude of this doubly inclined dipole may be given by $H_- = 6$ km, $H_+ = 6.9$ km, and the horizontal separation of the dipole electrodes by 2 km, and the inclinations inthe first half and the second half periods of the discharge by $tg\gamma_1 = 3.75$ and $tg\gamma_2 = 1.5$, respectively then the outer and the inner field reversal circles relating to this dipole discharge will take the relative positions illustrated in the Fig. 35. In this case, it is shown clearly that the field reversal region held between the two circles is remarkably wider than that illustrated in Fig. 34. The measurement of the areas on Fig. 35 has been made in the same way as before, and the statistical result of it is represented in Table 35 that corresponds to Table 34. Comparing the rows which represent the variation type $-+$in this table with the row which represents the same variation type $-+$and is included in the column of cloud discharge in Table 22, we may arrive at the conclusion that this type of ES pulse polarity variations, which the cloud discharges produce, should statistically be attributed to the discharge process that can be represented by a dipole discharge developed by a negative complex streamer.

Following an attmpt to interpret the statistical results given in Table 22, of the observations, without assuming an aggregation of lightning discharges represented by a mixture of positive and negative dipoles, we have postulated, in the above discussions, the possible discharge mechanisms appearing in thunderclouds. The knowledges about the possible structures of lightning discharges in thundercloud, thus obtained, are sammarized in Table 36.

Following what the table indicates, it is evident that the cloud discharges statistically have the character which can be interpreted with the assumption of a negative dipole in

Fig. 35

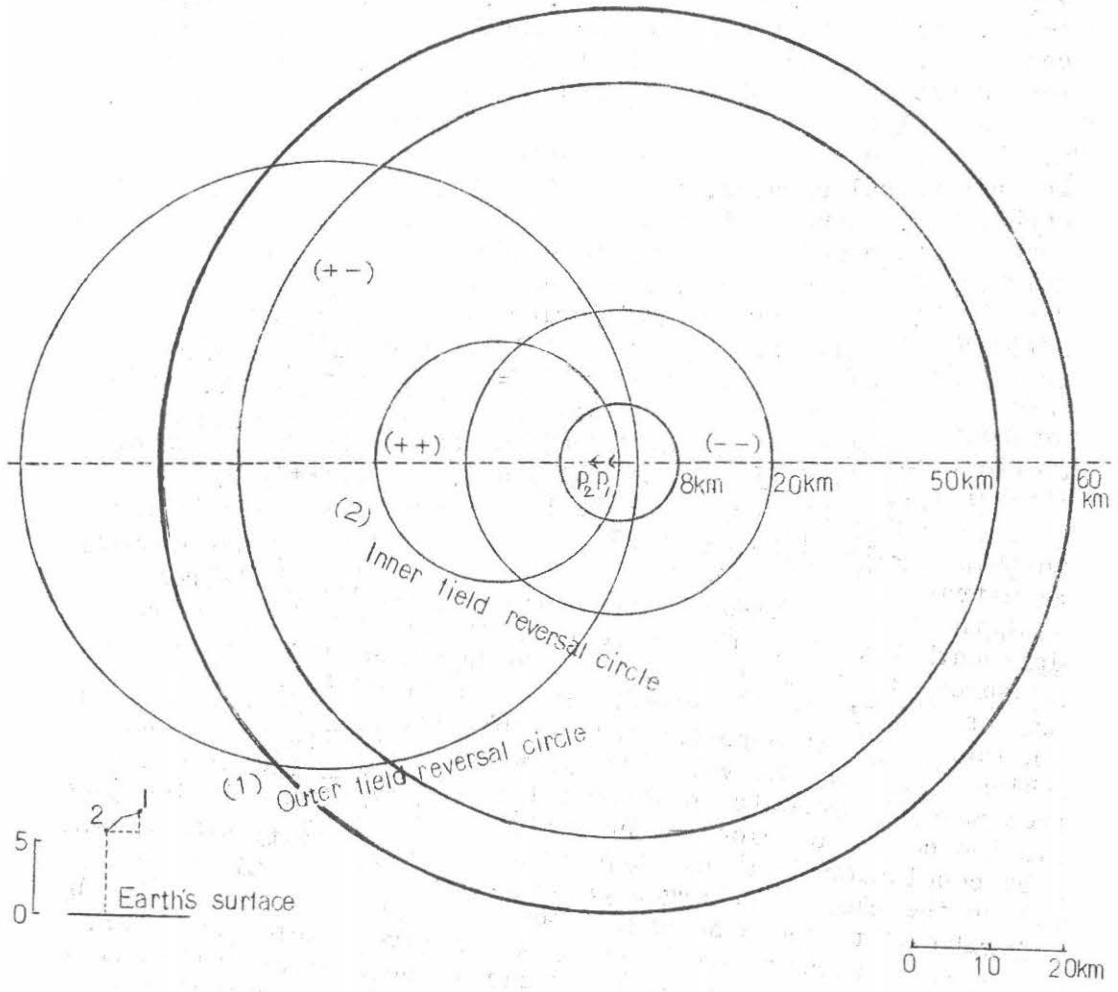

(+−)
(++)
(−−)
P_2 P_1
8km
20km
50km
60 km
(2)
Inner field reversal circle
(1) Outer field reversal circle
2
1
5
0
Earth's surface
0
10
20km

Table 35

		Positive dipole			Negative dipole		
Polarity of complex streamer	Distance / ES pulse polarity variation type	0-8km	8-20 km	20-60 km	0-8km	8-20 km	20-60 km
(a) Positive	+ +	54.3%	37.3%	2.1%	34.0%	49.6%	72.2%
	+ −	11.7%	13.1%	25.7%	11.7%	13.1%	25.7%
	− +	0%	0%	0%	0%	0%	0%
	− −	34.0%	49.6%	72.2%	54.3%	37.3%	2.1%
(b) Negative	+ +	54.3%	37.3%	2.1%	34.0%	49.6%	72.2%
	+ −	0%	0%	0%	0%	0%	0%
	− +	11.7%	13.1%	25.7%	11.7%	13.1%	25.7%
	− −	34.0%	49.6%	72.2%	54.3%	37.3%	2.1%

thundercloud, while the ground discharges have the character which can be interpreted with the assumption of a positive dipole existing in the cloud, and further, that both these dipoles may be inferred, in some cases, as being developed each by a positive complex streamer, while in the other cases, they must be posutulated as being developed each by a negative complex streamer. Concerning this point, Table 32 already has given the occurring percentage of positive dipoles each developed by a positive complex streamer, the percentage of the same polarity dipoles each developed by a negative complex streamer, the percentage of negative dipoles each developed by a positive complex streamer, and the percentage of the same polarity dipoles each developed by a negative compex streamer and from this, we have arrived at the conclusion that the greater part of cloud discharges and junction processes of ground discharges must be inferred as being developed by positive complex streamers. However, it would be difficult to obtain the exact values of

Table 36

Sort of lightning discharge	Polarity of dipole	Polarity of complex streamer	Character of lighning dipole
Cloud discharge	Positive	Positive	Singly inclined
		Negative	Doubly inclined
Ground discharge	Negative	Positive	Singly inclined
		Negative	Vertically directed

these occurrence percentages, unless we would use a sufficient number of relaible data obtained from the direct measurement of a certain nature of a complex streamer, e.g., the electrostatic field change measurement, instead of the data obtained from the indirect method of ES pulse polarity measurement. This is the point that has already been pointed out in the discussion of Table 32.

Concerning the inclination of a dishcarge channel, the only one case which can be interpreted with a vertical dipole model is the ground discharge developed by a negative complex streamer, and accordingly the other three cases must be onsidered statistically more or less being inclined from the vertical axis, and in some cases, the inclin tions will become considerable in accordance with the degree of horizontal shift of the two opposite charge centers in a thundercloud relative to each other. Further the table shows the point that the cloud discharges generally are more inclined from the vertical axis toward the horizontal direction than the ground discharges do it.

As to points whether some of the cloud discharges statistically can be represented by a negative dipole model, and whether some of the ground discharges statistically can be represented by positive dipoles model, it will be difficult to expect some definite conclusion from the indirect method of ES pulse measurements on the records atmospheric waveforms whose propagation distances could not be estimated anyhow in a exact way. In this connection, a number of reliable data of electrostatic field changes due to lightning discharges will be the key point to solve the question, provided that the estimation of discharge distances will be made exactly.

(b) Fine structure of a local discharge:

Following the results obtained in the previous paragraph, a complex streamer developing a lightning discharge in thundercloud always takes the direction roughly identical with those of local discharges occurring in association with the complex streamer. If we use a more theroetical expression, a dipole representing a lightning discharge in thundercloud and the local dipoles associated with the former always have a common direction, but the senses which they have always are reversed with each other. Therefore the advancing direction of a positive complex streamer always coincide with the sense, as well as the direction of the local dipoles, while the advancing direction of a negative complex streamer always is in a reversed relation with respect to the sense, as well as the direction of the local dipoles.

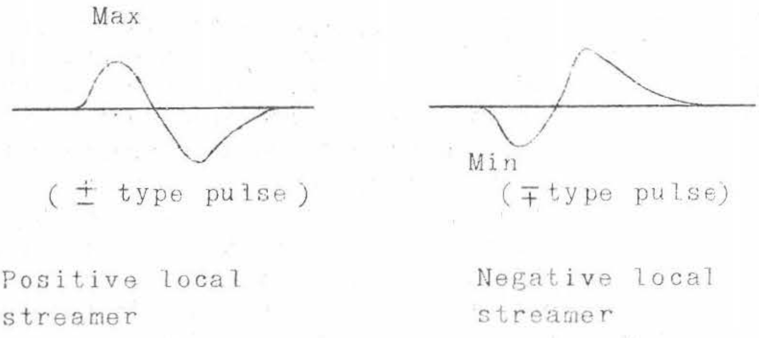
We shall describe in this paragraph few problems, which have not been described in the previous paragraphs concerning the character of a local discharge, for example, the polarity of the streamer* developing a local discharge. We have already obtained several observational results concerning the nature of a local discharge through the statistical measurements of ER pulses, as well as of ES pulses on the atmospheric waveforms due to lightning discharges, from which we have derived the conslusion that a local discharge must be a discharge which has a considerably large discharging rate, however, whose scale is relatively small, so that appreciably limited in a small locality. A local discharge, through appreciably small in its scale, would be a type more or less associated with a complicated group of minor streamers, as the discharge breaks out in the atmosphere within a thundercloud under a barometric pressure not largely different from one atmosphere. Therefore if we succeeded to record the electrostatic field change due to a local discharge at a postion located on the earth's surface near to the field reversal circle relating to the local dipole discharge, the record of it should have a maximum or a minimum in accordnace with the local discharge being developed respectively by a positive streamer or by a negative streamer, where the corception of the above streamer has been introduced to explain the resultant effect of the probable processes developing an actual local discharge, so that it may be the one which really includes so called streamer processes as well as non-streamer processes. We shall call this sort of a streamer representing the resultant effect of a local discharge " the local streamer " in the following discussions. As the short range waveform recorder of atmospherics we have adopted in our thunderstorm observations includes the main amplifier system with a relatively short time constant (for

---

* An assumed streamer representing the resultant effect of a local discharge.

example, 300 micro sec.), so it will be difficult to record with our waveform recorder, the electrostatic field change due to a local discharge without any distortion because of the relatively slow speed of the stepwise field change. Consequently the stepwise electrostatic field change due to a local dipole discharge will be deformed appreciably so as to take the form of an ES pulse as illustrated in Fig. 22 (a) in Section 5 of this chapter. Moreover, if the ture field change due to a local discharge exhibits an extreme value on the record of it, and, if the magnitude of the net field change recorded in the first half period before the occurrence of the extreme value is smaller than the magnitude of the net field change recorded in second half period after the occurrence of the extreme value, then the ES pulse appearing on the atmospheric waveforms will take the shape illustrated in Fig. 36 (cf. the explanation of Fig. 8 given in Section 3A, Chapter II). Hence, the ES pulse will fall into the $\pm$ type or into the $\mp$ type according

Fig. 36



as the corresponding electrostatic field change really exhibits a maximum or a minimum respectively. As we have already investigated, the local discharges included in a lightning discharge in thundercloud have statistically the directions which are held roughly parallel to that of the complex streamer throughout the process of the discharge. However, if we investigate the details of variation of the ES pulse polarities on the atmospheric waveforms of a lightning discharge, nearly half of the recorded lightning discharges really represent more or less some fluctuations in the ES pulse polarities (refer to Table 27). This indicates the fact that the directions of the individual local discharges included in a lightning discharge exhibit each a certain deviation from the mean direction. If the fluctuation in the direction of an individual local dipole discharge is adequate, the field reversal circle corresponding to the local dipole will pass a point on the earth's furface very close to the observation point. In this case the probability that the electrostatic field change due to the local discharge may exhibits a maximum or a minimum will be increased considerably, and hence, the number of ES pulses which take the shape illustrated in Fig. 36 will be increased on the records of atmospheric waveforms. We have classified the fluctuation characteristics of ES pulse polarities into the following three types: the type which has no polarity fluctuation, the type in which the fluctuations performed between + and - types of ES pulses and involve neither ± type nor ∓ type of ES pulses, and the type in which the polarity fluctuations really include either ± type ∓ type, or both these types of ES pulses.

Table 37 represents the percentage number of the recorded discharges which fall into the above three categories. The remarkable point of this table is that more than half of the lightning discharges which give the atmospheric waveforms each exhibiting some polarity fluctuations of ES pulses, actually involve either ± type or ∓ type of ES pulses; hence the lightning discharges which give the atmospheric waveforms whose polarity fluctuations are executed thoroughly between + and - ES pulses, really construct only a minority group of the recorded lightning discharges. The fact that a large part of the ES pulse fluctuations usually contain either ± type or ∓ type ES pulse in themselves seems to indicate the point that in the case of a lightning discharge which accompanies remarkable fluctuations in the directions of local discharges, the fluctuations of their directions are performed usually in rather a continuous way. Therefore the probability will become appreciable in many cases that the field reversal circle corresponding to a certain local discharge comes to pass the neighborhood of the observation point during the period of the lightning discharge concerned. This sort of remarkable fluctuations in the directions of individual local discharges executed in a nearly continuous way may be attributed, for example, to gradual but rather complicated changes in the advancing direction of a complex streamer developing a lightning discharge or to the branchings, with small angles, of local discharges from the advancing head of the mother complex-streamer channel. On the contrary to this, the minority group of ES pulse polarity fluctuations which involve neither ± type nore ∓ type ES pulse in themselves must be attributed to abrupt and large fluctuations of the local discharge directions, if it is desired to interpret the polarity fluctuations of ES pulses by the fluctuations in local discharge directions. So that it will be more reasonable to consider, in this case, such mechanism as the branching, with a large angle, of a local discharge from the advancing head of the mother complex-streamer channel,

Table 37

Sort of discharge	ES pulse polarity variation type	Polarity fluctuation of ES pulses			No. of record
		No. fluctuation	Fluctuation not involving ±, ∓ types	Fluctuation involving ±, ∓ types	
Cloud discharge	+ +	44.2 %	22.1 %	34.7 %	326
	+ −	24.5 %		75.5 %	192
	− +	44.5 %		55.5 %	126
	− −	39.7 %	23.8 %	36.5 %	247
Ground discharge	+ +	56.8 %	17.3 %	25.9 %	116
	+ −	24.5 %		75.5 %	49
	− +	53.1 %		46.9 %	32
	− −	19.7 %	18.2 %	62.1 %	66

than to consider the gradual changes in the advancing direction of the streamer. If we compare the occurrence percentages of the ES pulse polarity fluctuations involving either ± type or ∓ type ES pulse in themselves between the ES pulse polarity variation type + +, or - - and the polarity variation type + - or - +, given in Table 37, it will be evident that the case of the polarity variation type + -, or - +, generally gives larger occurrence percentages concerning the polarity fluctuations involving either ± type or ∓ type ES pulse, than in the case of the polarity variation type + +, or - -, except for the case of the polarity variation type - - arising in the ground discharges. Because the lightning discharges which produce atmospheric waveforms falling into the polarity variation type + -, or - +, will statistically make the peripheries of field reversal circles each corresponding to a local discharge to pass through the points placed nearer to the observation point, compared with the lightning discharges producing atmospheric waveforms falling into the polarity variation type + +, or - -, therefore the evidence above described must be inferred to indicate the point that a small fluctuation in the direction of a local dipole will be sufficient to cause a displacement of a field reversal circle in such a way that its circular periphery really comes to pass through the nighborhood of the observation point. According to the above idea, the ES pulse polarity flucutations which involves $\pm$ type or $\mp$ type ES pulse must be expected to become recordable when the field reversal circle corresponding to a certain ES pulse really passes through the neighborhood of an observation point. Let us consider a lightning discharge that gives the atmospheric waveforms falling into the ES pulse polarity variation type + - or - + , and assume that the magnitudes of directional fluctuations of the individual local discharges from the mean direction are all equivalent with each other, then the occurrence probability of an ES pulse polarity fluctuation must very with the development of the concerning complex streamer and will reach a maximum when the development of the streamer will enter into the transitional period, in which the corresponding atmospheric waveforms will produce the ES pulse polarity variation from positive to negative, or from negative to positive. To see this point, we have investigated on the records of atmospheric waveforms resulting from a lightning discharge, and falling into the ES pulse polarity variation type + - or - +, the point how frequently the $\pm$ type or $\mp$ type ES pulse may be detected in the transitional period of ES pulse polarity variations from + to - or from - to + on the waveforms. The result of these investigations is represented in Table 38. This is the result which really coincides with our expectation

Table 38

Sort of dis-charge	ES pulse polarity variation type	Position of occurrence of $\pm$ or $\mp$ type ES pulse on atmospheric waveforms		Number of data
		Inside the transition period	Outside the transition period	
All light-ning dis-charge	+ -	90.5 %	9.5 %	116
	- +	91.2 %	8.8 %	46

described previously, and supports our interpretation of the meanings of the $\pm$ or $\mp$ type ES pulse. Following this interpretation the $\pm$ type or the $\mp$ type of ES pulse must correspond respectively to a maximum type or a minimum type of electrostatic field change, in other words, it has its origin respectively in a positive or a negative local streamer developing a local discharge.

Therefore if we know the occurrence percentages of the waveform sections indicating the polarity fluctuations each containing ± type or ∓ type ES pulse on the records of atmospheric waveforms due to lightning discharges, we can make the statistical aspects of the polarities of the local streamers clear. The table 39 represents the result of this investigation, According to this the occurrence percentages of

Table 39

ES pulse polarity fluctuation / Sort of discharge	Type of ES pulse polarity fluctuations			Number of data
	±	∓	±, ∓ mixed	
Cloud discharge	27.0 %	61.9 %	11.1 %	656
Ground discharge	38.1 %	51.4 %	10.5 %	247
Polarity of a local streamer	Positive	Negative	Complex	

the cases in which the local discharges are developed by negative local streamers are 61.9 % for the case of cloud discharges, and 51.4 % for the case of ground discharges, while the occurrence percentages of the cases in which the local discharges are developed by positive local streamers are only 27.0 % for the case of cloud discharges and 38.1 % for the case of ground discharges. Hence, it is clear that the case in which the local discharges are developed by negative local streamers occupies the majority group for the both sort of lightning discharges. Concering this point, the statistical nature of the complex streamer polarities has already been whown in Table 32., Following this roughly 60 % of the cloud discharges as well as the ground discharges are developed by positive complex streamers, while the lightning discharges developed by negative complex streamers occupy roughly 40 % of all the recorded lightning discharges. Therefore it is evident that in this case the positive polarity occupies the majority group. So that if we consider the possible combinations of the polarities of local streamer with those of complex streamers, it will be needless to mention that the combination of the majority group of local streamers with the majority group of complex streamers, i.e., the combination of negative local streamers with a positive complex streamer, must have considerably a larger occurrence probability than other streamer polarity combinations do it. To see more exactly the statistical relations between individual combinations of complex streamer polarities and local streamer polarities, it becomes necessary to investigate the occurrence percentages of $\pm$ or $\mp$ type ES pulses on the atmospheric waveform which give the ES pulse polarity variations of the type + - or - +, which probably corresponds to a positive or a negative complex streamer respectively. For this purpose, attentions were paid to the lightning discharges which produced the atmospheric waveforms each falling into the ES pulse polarity variation type + - or into the type - +, and each representing the polarity fluctuations involving $\pm$ type, or $\mp$ type ES pulses, and then the percentage number of lightning discharges giving the waveforms involving the $\pm$ type ES pulses, and that of the discharges giving the waveforms involving the $\mp$ type ES pulses were investigated on the waveform records of the above noticed type of lightning discharges, the result of which is represented in Table 40.

Table 40

Sort of discharge	ES pulse polarity variation type	Character of ES pulse polarity fluctuation		Number of data
		Involving type ES pulse*	Involving type ES pulse*	
Cloud discharge	+ -	32.7 %	67.3 %	136
	- +	43.6 %	56.4 %	70
Ground discharge	+ -	33.8 %	66.2 %	37
	- +	46.7 %	53.3 %	15

* A lightning discharge which gave the waveforms involving both the $\pm$ and $\mp$ types of ES pulses, were evaluated as $\frac{1}{2}$ in each of these two categories.

If the percentage number of waveforms which involve $\pm$ type ES pulses is compared with that of waveforms which involve $\mp$ type ES pulse on Table 40, it will be clear that the waveforms involving $\mp$ type ES pulses really predominate over the waveforms involving $\pm$ type ES pulses, independent of the waveforms being produced by cloud discharges, or ground discharges. This is just the same tendency as that given in Table 39. But if we compare the percentage number of the discharges producing waveforms which involve $\pm$ type, or $\mp$ type ES pulses between the discharges giving waveforms falling into the ES pulse polarity variation type + - and those giving waveforms falling into the ES pulse polarity variation type - + , given in Table 40, it will be evident that the occurrence percentage of lightning discharges giving waveforms which involve $\pm$ type ES pulses and fall into the - + type polarity variation, statistically predominates over the occurrence percentage of lightning discharges giving waveforms which involve the same type ES pulses and fall into the + - type polarity variation, disregarding whether they are, cloud discharges or ground discharges, while the occurrence percentage of lightning discharges giving waveforms which involve $\mp$ type ES pulses and fall into the + - type polarity variation, statistically predominates over the occurrence percentage of lightning discharges giving waveforms which involve the same type ES pulses and fall into the - + type polarity variation, independent of they being cloud discharges or ground discharges. On the other hand, the occurrence percentage of the lightning discharges producing the waveforms falling into the + - type variation and that of the discharges producing the waveforms falling into the - + type variation has already been given in Table 32 referring to the case of cloud discharges and to the case of ground discharges. Therefore, if the numerical values given in the spaces of Table 40 are multiplied respectively by the numerical values given in the corresponding spaces of Table 32, then we can get the occurrence probability of combination of a complex streamer polarity with a polarity of the local discharges concerned referring to the two sort of lightning discharges. Table 41 indicates the result of this calculation.

Table 41

Probability of polarity combination between a complex streamer and the local streamers concerned

Sort of discharges	Polarity of complex streamer	Polarity of local streamer	
		Positive	Negative
Cloud discharge	Positive	19.7 %	40.6 %
	Negative	17.3 %	22.4 %
Ground discharge	Positive	20.4 %	40.1 %
	Negative	18.4 %	21.1 %

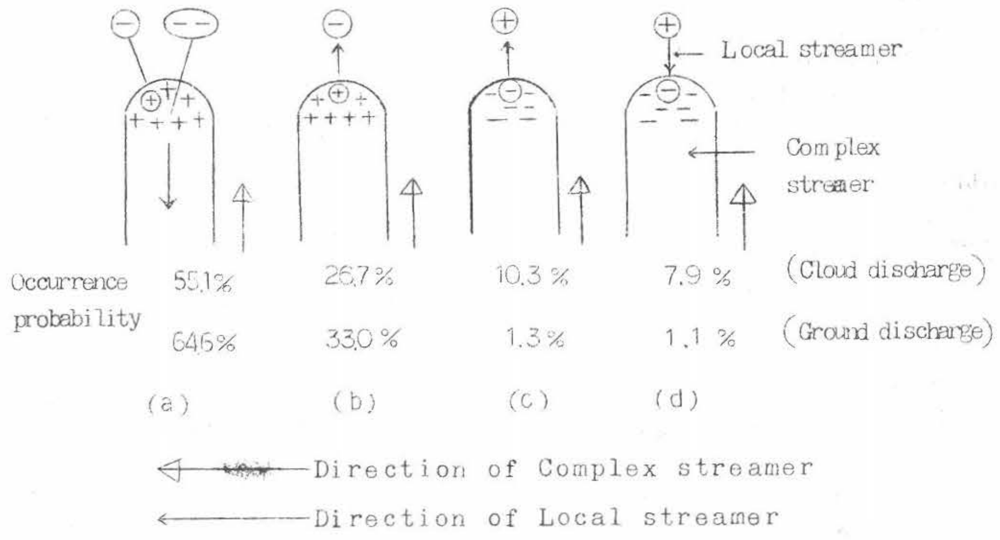
We have already investigated that the method of directly measuring the electromagnetic effect of a complex streamer, e.g., the electrostatic field-meter method, really has advantages over the method of indirectly measuring the same effect of the complex streamer, e.g., the ES pulse polarity variation method, when it is desired to obtain the exact knowleges about the occurrence percentages of the positive and the negative complex streamers. So that if we use the statistical results (Table 18, Section 6A, Chapter IV) obtained with the electrostatic field-meter method instead of Table 32 obtained with the ES pulse method, and carry the same calculation which we have adopted to obtain Table 41, then the probability of the polarity combinations between a complex streamer and the local streamers concerned will be obtained on the basis of the records obtained with the electrostatic field-meter. The result is indicated in Table 42
The comparison of these two Tables 41 and 42 clearly indicates

Table 42

Probability of polarity combinations between a complex streamer and the local streamers concerned			
Sort of discharges	Polarity of complex streamer	Polarity of local streamer	
		Positive	Negative
Cloud discharge	Positive	26.7 %	55.1 %
	Negative	7.9 %	10.3 %
Ground discharge	Positive	33.0 %	64.6 %
	Negative	1.1 %	1.3 %

that the probability tendency that the cloud discharges indicate and what the ground discharges indicate do not differ from each other in both of these two tables. This seems to indicate the fact that any appreciable difference can not be found to exist between the discharge mechanisms of a cloud discharge and those of a ground discharge, so long as we take into account only the discharge processes which break out within a thundercloud. There are some differences existing between the percentage value given by a certain polarity combination in Table 41 and that given by the same polarity combination that given in Table 42, when the same sort of discharges is compared between the two tables. Concerning this point we shall give a preference to Table 42 over Table 41, because the former is based on the more direct method of measurement than the latter. Fig 37 represents the generalized figures of these four combinations of streamer polarities in the order of the occurrence probability values represented in Table 42.

Fig. 37



The table shows that 81.8 % of cloud discharges and 97.6 % of ground discharges are developed each by a positive complex streamer, and if we limit the lightning discharges to those which are developed each by a positive complex streamer, 67.3 % of the cloud discharges, and 66.2 % of the ground discharges include negative local streamers. Out of these four cases, the combination of a positive complex streamer and the negative local streamers concerned (see Fig. 37 (a)), occupies the largest group, and represents the most usually observable type of a discharge mechanism in a thundercloud.

This is the mechanism which coincides with the local discharge mechanism having been deduced from the junction streamer process of a ground discharge. Following this idea, when a positive complex streamer having broken out from the inward periphery of a charged electrode composing a predominant positive center of electricity, will progresse through the cloud-body at a velocity of the order of 10^6 cm/sec toward the opposite negative charge center to develop a lightning discharge in a thundercloud, the advancing head of the complex streamer will sometimes reach the immediate neighborhood of a remarkable but small local accumulation of negative electricity scattered along a vertical columnar distribution of negative electricity in a thundercloud (refer to Fig. 1 Section 1 Chapter II). At this moment a number of minute negative streamers will break out from the negative local charge center, directing toward the head of the positive complex streamer that has advnaced in the reverse direction, and will progress toward the inner portion of the complex streamer head. The small discharge process which involves a number of minute negative streamers in it, may compose a local discharge as a whole, and will produce a small stepwise electrostatic field change that results in an ES pulse on the atmospheric waveform due to a lightning discharge. Accoridng to circumstances some of the numerous minute streamers will have the chance to grow to a large scaled negative streamer, i.e., a dart leader streamer, and may progress along the discharge channel previously prepared by the positive complex streamer as long as several hundred meters toward the direction of the opposite charge center. At this moment the progressing velocities of dart leaders may reach the values larger than 10^9 cm/sec and emit a strong atmospheric radiation pulses. This must be the origin of a ER pulse appearing on the atmospheric waveforms having propagated at a long distance. Follwoing our estimation, the number of these relatively small sized dart leaders per local discharge is two in the median value. It will be very probable that the vertical columnar distribution of negative electricity resulting from the charge separating action of a strong upwards air stream developing a thundercloud, really has an appreciable number of fluctuations in the electric charge density along the axial direction of the negative column in accordance with the possible micro-structure of the upwards air stream, e.g., presumably the sub-cell structures, suggested by J. Küttner(19), which probably be arranged in the vert cal direction along a negative column. If the contribution of the micro-structure of the upwards air stream to the separation of electricity is appreciable, the fluctuation in the electricity distribution along the vertical column will become appreciable and may result in vertically arranged local charge centers. Further it will probable that the strong action of charge separation due to remarkably violent micro-structures existing at several points along the upward air stream being combined with the stong charge separating action of the general upward air stream will make it possible some of the local charge centers to accumulate remarkably larger magnitude of negative electricity than other local charge centers. Therefore, when the advancing of a positive complex streamer reaches to one of these local charge centers involving a remarkable megnitude of negative electricity, the local discharge thus produced will become very strong. And thus, some of the large number of minute streamers will have the chance to grow to the huge scale negative dart leaders, in this case, and travel along the discharge channel previously tapped by the positive complex streamer so as to reach a sufficiently distant point away from the head of the complex streamer.

One of the large number of minute streamers grown up to a large scaled dart leader will not be enclosed inside a thundercloud and the probability the leader developing through the outer boundary of the cloud, or spreading out from the cloud-body will be increased considerably according to the electrical conditions in and around a thundercloud body. The dart leaders which develop from the respective local charge centers involving remarkable charge accumulations, may compose a multiple intercloud discharge. When a positve complex streamer constructs the junction process of a ground discharge, a dart leader produced by the above process will reach the ground and lead the succeeding return stroke. Therefore it becomes evident that no essential differences seem to exist between the discharge mechanism which produces a local discharge and that which produces a dart leader leading a succeeding return ground stroke, except for the difference existing in their scales. This is just the same conclusion already obtained through the interpretation of Fig. 23 in Section 5 of this chapter.

Concerning the other three polarity oombinations of the two streamers, however, we have, at present, only a little knowledges about the lightning discharge mechanisms which can be applied for the interpretation of these three, so that it will be difficult to make clear the physical meanings of these three combinations and to determin the electrical conditions under which these three will become possible. According to what we have hitherto investigated in this paragraph, the head of a positive complex streamer probably advances through a columnar negative charge distribution which contains an appreciable number of negative local charge centers*, therefore a vertical dipole discharge model which replaces the tow opposite volume charge accumulations relating to an actual discharge in thundercloud with the two opposite point charge electrodes, can not be a high degree of approximation in any way. So that it becomes necessary to assume a volume electrode which has a certain spatial spread and a non-uniform distribution of electricity, if we take the existence of local discharges into account.

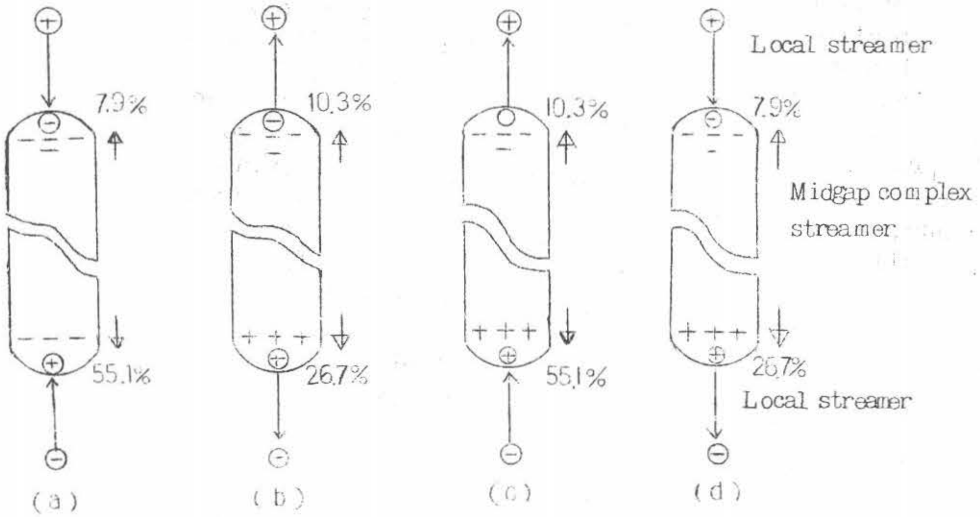
H. Hatakeyama pointed out in his paper(20) that a discharge

* According to Table 26 in Section 7B, Chapter IV, number of local charge centers per lightning discharge will be roughly 21.5 in the median value.

in a thundercloud at Maebashi may be interpreted by assuming a vertical dipole whose electrodes are composed of the two horizontal rings located respectively at two different altitudes along a common vertical axis, as well as by assuming a vertical dipole whose electrodes are composed of the two vertical cylinders located respectively at two different altitudes on a common vertical axis. Concerning this point, it will be evident that we should assume the electrodes which have each a vertical spread, if we consider the mechanism of charge separation taking place along a violent upward air stream in a thundercloud, and the junction process involved in a ground discharge. Following H. Hatakeyama let us assume a negatively charged cylinder extending vertically from the altitude 4 km to the altitude 8 km, and a positively charged cylinder extending vertically from the altitude 8 km to the altitude 12 km on a common vertical axis. Then a discharge will be produced at first between the two opposing edges of the two cylindercal electricity distributions, and thus a complex streamer will be built up in the gap space held between the two electrodes. The analogy of the experimental spark discharges leads us to the following deduction that a complex streamer breaking out in the inter-electrode space will gorw up to a midgap streamer, the lower erd of which will be streached downwards into the negative cylinderical electrode and form a positive complex streamer, and upper end of which will be streached upwards into the positive cylinderical electrode and form a negative complex streamer(21).
The midgap complex streamer thus produced in a thundercloud will have the structure which will be interpreted with the appropriate combinations of the complex streamer given in Fig. 37. Fig. 38 represents the four possible structures of midgap complex streamers constructed from the streamers illustrated in Fig. 37.
According to what the figure indicates, it is clear that the most probable structure of a midgap complex streamer in a thundercloud will have the details represented by the streamer model (c) in the figure. In this case, the local discharges appearing on both heads of the midgap streamer, will be developed each with a negative local streamer directing upwards. Next let us assume a case in which the electrostatic field change due to the development of one of the four midgap streamer models illustrated in Fig. 38 is recorded at an observation point located in the area on the earth's surface, which excludes the field reversal region*

* Let the horizontal distance of the midgap streamer from the observation point be expressed with D, the altitude of the positive and the negative dipole electrodes of the concerned cloud discharge respectively with H and H_-, then the field reversal region given by the midgap streamer will be represented as $\sqrt{2}H_- \leq D \leq \sqrt{2}H_+$.

Fig. 38



←— Direction of complex streamer
←— Direction of local streamer

given by the related midgap streamer. Then the field change a midgap complex streamer would produce, must be expected to have similar characteristics as those of the field change which would be produced by a positive or a negative single sided complex streamer occupying a position respectively corresponding to the lower head or the upper head of the concerned midgap streamer and advancing respectively downwards or upwards. However, if the field change due to a midgap complex streamer is recorded at an observation point included in the area of the field reversal region, the field change will become to have different characteristics from those of the field change due to a single sided complex streamer. If the lower positive head of a midgap streamer develops earlier than the upper negative head of it, the field change due to the midgap streamer would represent a minimum on itself, or take the form of a ± types complex field change, i.e., a maximum followed by a minimum type field change. In the former minismum type, we can not discriminate a midgap complex streamer from a negative single sided complex streamer on a record of electrostatic field changes, and this may increase the precentage value of the minimum type field changes due to cloud discharges indicated in Table 18, Section 6A, of this chapter. If the lower positive head of a midgap streamer develops later than the upper negative head of it, the field change due

to the midgap streamer would represent a maximum on itself, or take the form of a $\mp$ type complex field change, i.e., a minimum followed by a maximum type field change.
In the former maximum type, we have no means to discriminate a midgap streamer from a positive single sided complex streamer on the record of electrostatic field changes, and this may result in the increase in the percentage value of the maximum type field changes due to cloud discharges indicated in Table 18.
As it is well known that a positive streamer generally develops more easily than a negative streamer, so it is expected that the lower positive head of a midgap streamer generally develops earlier than the upper negative head of it, and therefore, that statistically the $\pm$ type complex electrostatic field changes due to cloud discharges must predominate over the $\mp$ type.
The existence of a cloud discharge which produces the complex electrostatic field changes, and likely corresponds to a cloud discharge developed by a midgap streamer, may be recognized by the fact that the data corresponding to the grouping of "complex change" given in Table 18 in Section 6A of this chapter occupies as much as 25.5 % of all the investigated cloud discharges.
If the rapid electrostatic fielc changes due to individual local discharges accompanied by one of the four midgap complex streamer models in Fig. 38, are recorded with a short range waveform recorder of atmospherics located in a area on the earth's surface excluding the field reversal region given by the concerned midgap streamer discharge, the ES pulses thus recorded will have the characteristics similar to those of the ES pulses which would be produced by the local discharges associated with a positive or a negative single sided complex streamer occupying a position respectively corresponding to the lower head or the upper head of the midgap streamer, and advancing respectively downwards or upwards. However, if the ES pulses due to local discharges are recorded at an observation point included in the area of the field reversal region given by the related complex streamer discharge, then they will become to indicate different characteristics from those of the ES pulses due to local discharges associated with a single sided complex streamer. If the lower positive head of a midgap streamer develops earlier than the upper negative head of it, the ES pulse polarity variations which would be produced in association with the development of any one of the four midgap streamer models in Fig. 38, will fall into alternative one of the three ES polarity variation types represented respectively with (- +), (- + -), and (+ - +).
If the lower positive head of a midgap streamer develops later than the upper negative head of it, the ES pulse polarity variations which would be produced in association

with the development of any one of the four midgap streamer models in Fig. 38, will fall into alternative one of the three ES polarity variation types represented respectively with (+ -), (- + -) and (+ - +). As the ES pulse polarity variation type (- +) and (+ -) are also interpreted respectively with negative and positive single sided complex streamers, moving along vertical axes, it will be impossible, in this case, to discriminate a midgap streamer from a single sided streamer.
As to the ES pulse polarity variation types (- + -) and (+ - +), it will be reasonable to consider that the cloud discharges which contributed to the group of complex variation type given in Table 22, Section 7B of this chapter, must partly involve in themselves the discharges developed by the midgap streamer process. If a midgap streamer channel is appreciably curved horizontally and inclined from the vertical axis, a cloud discharge waveform recorded at an observation point included in the area of the field reversal region corresponding to itself, will have an appreciable possibility to represented ± type or ∓ type ES pulses on itself. Concerning this point, the midgap streamer models(a) and (b) in Fig. 38 each equally involve a positive and a negative local streamers, while the model (c) and (d) of the same figure involve two negative and two positive local streamers respectively. So that it is very probable that the electromagnetic waveforms due to a cloud discharge developed with a midgap streamer of the type given by the mode (a) or (b) in Fig. 38, will indicate both ± type and ∓ type of ES pulses or alternative one of these two types on themselves, while the waveforms due to a cloud discharge developed with a midgap streamer of the type given by the model (c) or (d) in the same figure, will represent respectively either ∓ type or ± type ES pulses on themselves. Hence, the model (c) and (d) are not suited for the interpretation of a cloud discharge waveform which involves both ± type and ∓ type ES pulses on itself.
Concerning this point, the percentages of the observed lightning discharges which produced the atmospheric waveforms carrying both ± type and ∓ type ES pulses on themselves, have also been represented in Table 43.
Following this, it is evident that we can not neglet the existence of the atmospheric waveforms involving both ± type and ∓ type ES pulses. Corresponding to this point, the investigation of the moving flash photographs of cloud discharges clearly has shown that in some cases, the investigated multiple intercloud discharges actually were composed each of a group of several dart leaders, the both ends of which were streached outwards more and more with increase in the order of the dart leaders. These are probably the intercloud discharges which can be interpreted

Table 43

Sort of discharges	ES pulse polarity variation type	Character of polarity fluctuation of ES pulses			Number of data
		Including ± type ES pulse	Including ∓ type ES pulse	Including ± type and ∓ type ES pulses	
Cloud discharges	+ −	15.4 %	50.0 %	34.6 %	136
	− +	25.7 %	38.6 %	35.7 %	70
Cloud discharges	+ −	16.2 %	48.6 %	35.2 %	37
	− +	26.6 %	33.4 %	40.0 %	15

with the mechanism of the midgap complex streamer above described. We shall next consider the distribution of electricity inside a vertical colmnar electrode along its axis. According to Table 26, the number of ES pulses appearing in the atmospheric waveforms due to a lightning discharge may be given 21.5 in the median value. Concerning this point, the statistical number of ER pulses per lightning discharge is indicated in Table 44, which includes merely the results obtained from the data due to all lightning discharges occurring within thunderclouds, because the results will not differe in any amount between cloud discharges and ground discharges. Following this, the number of ER pulses per lightning discharge may be given by 19 in the median value, if we take small amplitude ER pulses as well as medium and large amplitude ER pulses into account. This is the value roughly comparable with the above described value 21.5, the number of ES pulses per lightning discharge.
However, if we neglect small amplitude ER pulses, the median value will reduce to 16, and further if we merely consider large amplitude ER pulses, the median value will become only to 10. Considering these points, we may assume that the number of local discharges appearing in a lightning discharge statistically are given by 16, so long as we neglect the existence of the local discharges of small scales. Following the cloud discharge model of a dipole with pair of cylindrical electrodes, the avaerage separation of the two electrodes may be assumed to take the value 4.0 km. If we assume that a complex streamer produce 16 local discharges while the streamer advances the

Table 44

Amplitude of ER pulse / ER pulse group	Including small amplitude ER pulses	Excluding small amplitude ER pulses	Excluding small amplitude, as well as large amplitude ER pulses
Number of ER pulses per lightning discharge (Median Value)	19	16	10
Number of data	727	321	88

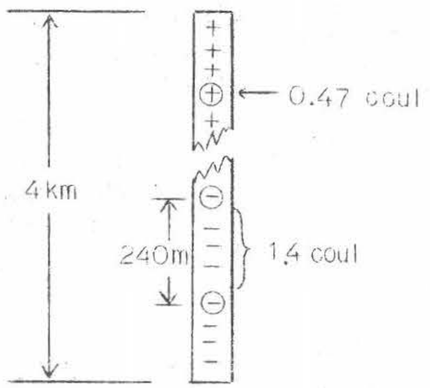
distance 4 km, the mean electrode separation, then the mean distance between two successive local discharge centers distributed through the mean electrode separation, will be given by 4/17 = 0.24 km i.e., inaverage, 16 local charge **centers** are **arranged along a portion of the electrode axis given by the mean** dlectrode separation, at an average interval 0.24 km. To estimate the magnitude of the electrical charge involved in a local charge center, let us make an assumption that the electric charge quantity involved in a local charge center is roughly proportional to the mean length of dart leaders produced in association with a local discharge. Following the measurement of length of a dart leader made on the moving flash photographs of intercloud discharges, the mean of the 11 measurements give the value 2.6 km, and they spr ead from 1.4 to 4.0 km. Taking this point into account, let us as ume that the average length of a dart leader contributing to a intercloud discharge would be 3.0 km, because the both end of a dart leader would more or less be hidden in cloud bodies in many cases. Further, if we follow Table 6 in Section 4 of this chapter, and adopt the average value 0.5 km, given in the table, of length of a dart leader involved in a local discharge, then the ratio of lengths of the two dart leaders will be 0.5/3.0. In the mean while, the mean of the electric charge quantities each discharged by one of the ground strokes, following to the first, have already been given in Table 26 (a) in Section 5B, Chapter II, according which it is given by $\bar{Q}_{ni}$ = 2.8

coul.* So that the mean electric charge per local charge center will be given by $2.8 \times 0.5/3.0 \doteq 0.47$ coul, accordingly the total electric charge accumulated in all local charge centers inside the columnar electrodes will be $0.47 \times 16 \doteq 7.5$ coul. According to what Table 23 in Section 5B of Chapter II indicates, statistically 32 coul of electricity are dissipated by a cloud discharge, hence, the electricity discharged by a complex streamer process contributing to a cloud discharge may be given by

$$\bar{Q}_{complex} = 32 - 7.5 = 24.5 \text{ coul.}$$

If the electricity is distributed uniformly throughout the mean separation 4 km of the two opposite electrodes, the electric charge which is distributed between two successive local charge centers, and contributes to the process of a complex streamer will be given by $24.5/17 \doteq 1.4$ coul. Fig. 39 illustrates a model showing the above electricity distribution inside the two opposite columnar electrodes composing a vertical dipole. For the purpose to know the scale of a local discharge, it is necessary to estimate the value of a local dipole moment by measuring the

Fig. 39



* The distribution of electricity inside the two opposite columnar electrodes will not differ appreciably between a cloud discharge and a ground discharge. Therefore, it will be reasonable to consider that the degree of electricity accumulation inside a local discharge center would be comparable with the accumulation of electricity inside a charge center leading a ground stroke, if a local discharge included in a intercloud discharge could produce a huge dart leader.

electrostatic field change due to a local discharge on the electromagnetic waveforms of a lightning discharge. Concerning the point, our waveform recorder can not register the correct electrostatic field change due to a local discharge because of the too short time constant of its amplifier system, therefore the amplitude measurement of a ES pulse on the waveforms of a lightning discharge will not give a correct estimation of the electrostatic field change due to the local discharge concerned.

Nevertheless, to estimate the magnitude of a local dipole moment in the first approximation, we have measured the amplitudes ΔE_{Ret} of a radiation pulse corresponding to a return ground stroke and the amplitude E_{Loc} of each ES pulse on the same record of atmospheric waveforms due to a ground discharge. Then we have calculated, for each ΔE_{Loc} value, the ratio of ΔE_{Loc} to $\overline{\Delta E}_{Ret}$, the mean of the ΔE_{Ret} values, where ΔE_{Loc} and ΔE_{Ret} are the values measured on the same record of waveforms due to a ground discharge. In this way we have obtained the ratio values $\Delta E_{Loc}/\overline{\Delta E}_{Ret}$ for each ΔE_{Loc} appearing on the waveforms due to scores of ground discharges caught at appropriate distances from the observation station, and investigated the statistical character of them, the result of which is indicated in Table 45.

	Median value	Number of data	Observation distance
$\Delta E_{Loc}/\overline{\Delta E}_{Ret}$	0.069	369	20~40 km

Let us consider the first approxmation and assume that the possible errors in the ΔE_{Loc} measurements, may be neglected in this order of approximation. If we assume that the mean altitude $\overline{H}_R$ of ground strokes and the altitude H_{Loc} of an individual local discharge are sufficiently small in comparison with the mean distance $\overline{D}$ of the discharges from the observation station, so as to satisfy the relation $\overline{D} \gg \overline{H}_R$, H_{Loc}, then a simple approximate caluation will show that the ratio $\Delta E_{Loc}/\overline{\Delta E}_{Ret}$ must be given by

$$\Delta E_{Loc} / \overline{\Delta E}_{Ret} \doteqdot q.dl/\overline{Q}_R.\overline{H}_R \qquad (12)$$

where $\overline{Q}_R$ and q.dl respectively represent the mean electric charge transferred by a return ground stroke from a thundercloud to the earth, and the local dipole moment. Here, $\overline{H}_R$ will be given by the mean of the individual H_i values represented in Table 21 in Section 5A, Chapter II, and $\overline{Q}_R$ by the mean of the individual Q_{Ri} values represented in Table 21 in Section 5A, Chapter II, and in Table 26(b) in Section 5B, Chapter II, according to whose results the estimated mean values are $\overline{H}_R = 3.8$ km and $\overline{Q}_R = 1.5$ coul respectively. Putting these values into the relation (12), we can get

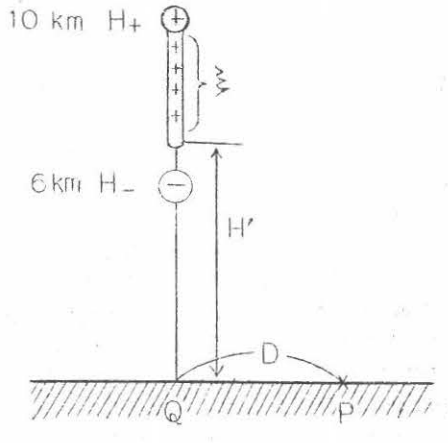
$$q.dl = 0.69 \times 1.5 \times 8.3 \doteqdot 0.39 \text{ coul. km}$$

If we adopt the q value obtained in the above discussion, i. e., $q = 0.47$ coul, $d.l = 0.84$ km will be concluded. This is the result which suggests that the length of the columnar domain, in which a local discharge takes place, is roughly comparable with the mean length of small dart leaders breaking out in connection with a local discharge, and further, appreciably larger than the estimated mean distance between two successive local charge centers.

Following the observational evidences, the electrostatic fielch charges due to a cloud discharge, recorded with our fieldmeter, always do not represent any structure which may be interpreted by the process of a local discharge, but are completely composed of gradual variations corresponding to the spatial slow movement of a complex streamer. This means that the inffluence of a local discharge on the electrostatic field changes due to a cloud discharge is always remarkably smaller than the ilffuence of a complex stream on the field changes. Therefore, if the above distribution model of electricity inside the vertical columnar electrodes, illustrated in Fig. 39, has some importance as an approximation of an actual cloud discharge, the rapid electrostatic field change ΔE_{Loc} produced by the discharge of a local dipole with the moment $q.dl = 0.39$ coul. km. must be sufficiently smaller than the slow electrostatic field change ΔE_{Comp} produced by the movement of a complex streamer through the mean distance 0.24 km between two successively arrange local charge centers. To see this point, we shall consider a dipole discharge representing a cloud discharge, as illustrated in Fig. 40, in which the positive and negative point electrodes of an assumed vertical dipole are located respectively at the mean altitudes H_+ and H_- of the columnar electrodes of the dipole above discussed, and the assumed dipole has been half discharged by a positive complex streamer extended from the upper positive electrode as for as ξ downwards. If we assume that a local discharge breaks out at this instance, the altitude of this local discharge must be given by $H' = H_+ - \xi$. Let the mean linear electric charge density of the complex streamer be $\overline{q}$, then the electrostatic field change produced by the progress of the complex streamer from ξ_1 to ξ_2 and recorded at the observation point P on the earth's surface, by the distance D apart from the discharge will be given by

$$\Delta E_{Comp} = E_{Comp}(\xi_2) - E_{Comp}(\xi_1) \qquad (13)$$

Fig 40



where $E_{Comp}(\xi) = \frac{2\bar{q}}{D}\left[\frac{1}{\{1+(H_+-\xi)^2/D^2\}^{\frac{1}{2}}} - \frac{1}{\{1+(H_+/D)^2\}^{\frac{1}{2}}} - \frac{(H_+/D)(\xi/D)}{\{1+(H_+/D)^2\}^{3/2}}\right]$

and $\xi_1 < \xi_2$ are the altitudes f two successive local charge centers. In the meanwhile, a rapid electrostatic field change produced by the discharge of a downwardly directing local dipole located at the altitude H', and recorded at the observation point P, will be obtained by using the formula (3) given in Section 7B of this chapter as follows.

$$\Delta E_{Loc} = -\frac{-2q.dl}{D^3} \frac{1-2(H'/D)^2}{\{1-(H'/D)^2\}^{5/2}} \qquad (14)$$

Further we shall consider the case, in which the observation distance is so large that the relations $H_+/D \ll 1$, $H'/D \ll 1$. are satisfied, and make the approximate estimation of the formula (13) and (14) taking the second order terms $(H_+/D)^2$, $(H'/D)^2$ into account. The results of this approximation are respectively given by

$$\Delta E_{Comp} = \frac{\bar{q}}{D^3}(\xi_2 - \xi_1)\left\{H_+^3/D^2 - (\xi_2 + \xi_1)\right\} = \frac{\bar{Q}}{D^3}\left\{H_+^3/D^2 - (\xi_2 + \xi_1)\right\} \qquad (13')$$

$$E_{Loc} = \frac{2qdl}{D^3} \left\{ 9/2(H'/D)^2 - 1 \right\} \qquad (14')$$

where $\bar{Q} = \bar{q}(\xi_2 - \xi_1)$ is the total electrical charge distributed along the space between two successively arranged local charge centers. Then $\Delta E_{Loc}/\Delta E_{comp}$ can be obtained by dividing (14') by (13'), which results in

$$\frac{\Delta E_{Loc}}{\Delta E_{Comp}} = \frac{2qdl}{QH} \; \frac{9/2(H'/D)^2 - 1}{(H/D)^2 - (\xi_2 - \xi_1)/H} \qquad (15)$$

Let us consider the instant when the complex streamer has extended half the mean separation of the columnar electrodes. In this moment the following value must be expected.

$\xi_1 + \xi_2 \doteq 4$ km, $H + = 10$ km, $H' = 8$ km,

$\bar{Q} = 1.5$ coul $q.dl = 0.39$ coul.

Taking the result of Table 45 into account, the relation(15) has been numerically calculated for the two values of the observation distances, $D = 20$ km, $D = \infty$, whose results are represented in Table 46.

Table 46

Distance. D	20 km	∞
$\Delta E_{Loc}/\Delta E_{Comp}$	0.10	0.13

We can clearly see that the numerical evaluation of the ratio $\Delta E_{Loc}/\Delta E_{Comp}$ obtained here, roughly statisfies our expectation $\Delta E_{Loc}/\Delta E_{Comp} \ll 1$, which also seems to support the point that the model which has been discribed in this paragraph concerning the non-uniform distribution of electricity inside the volume electrodes, actually interpret the probable structure of the volume charge accumulations which are developed in a thundercloud, and produce a lightning discharge.

References (IV)

(1) B.F.J. Schonland, D.J.Malan and H. Collens: Proc. Roy. Soc. A, 168, 455 (1938)

(2) M.Sourdillon: Ann. Geophys 8, 349 - 364 (1952)

(3) A.Cravath and L.B. Loeb: Physics, 6, 125 (1953)

(4) B.F.J. Schonland: Handbuchd. Phys. XXII Gasentladungen II Springer (1956)

(5) H. Isikawa and M. Takagi: Bull. Res. Inst. Atmosph. 5, 19 - 26 (1956)

(6) J.M. Meek and J. D. Craggs: Electrical Breakdown of Gases p. 25, Oxford (1953)

(7) Ross Gunn: J. Geophys. Res, 55, 171 (1950)

(8) R.B. Morrison: Phil. Mag. 44, 980 - 986 (1953)

(9) A.J.W. Sommerfeld: Partial Differential Equations in Physics, p. 237 (Acad. Press 1949)

(10) M.Kotani : Electricity and magnetism (II) p.227 Lectures on physics, (Iwanami, 1940)

(11) C.E.R. Bruce and H. R. Golde: J.I.E. E. 88, 487 (1950)

(12) A.Kimpara: Bull. Res. Inst. Atmosph. 1, 6 (1950)

(13) T. Issiki J. Power and Weather Coord. Comm. No. 16, 31 (1956)

(14) E.J. Workman, R.E. Holzer and G.T. Pelsor: Tech. Note Nat. Adv. Comm. Aeron. No. 864 (1942)

(15) K. Honda: J. Phys. Soc. Japan: 12, 1403 - 1412 (1957)

(16) H. Ishikawa and T. Takeuti: Bull. Res. Inst. Atmosph. 6, 1 (1956)

(17) D.J. Malan and B.F.J. Schonland: Proc. Roy. Soc. A, 206, 145 (1951)

(18) L.G. Smith: Q. J. Roy. Met. Soc. 83, 103 - 111 (1957)

(19) J. Küttner: J. Met. 7, 322 (1950)

(20) H. Hatakeyama: Bull. Train. Inst. Met.Observ. 1, No. 1 - 2 (1946)

(21) L.B. Loeb and J.M. Meek: The Mechanism of the Electric Spark pp. 59 - 60 and 83 (Standford Univ. Press 1941)

Photo. 1 (a)

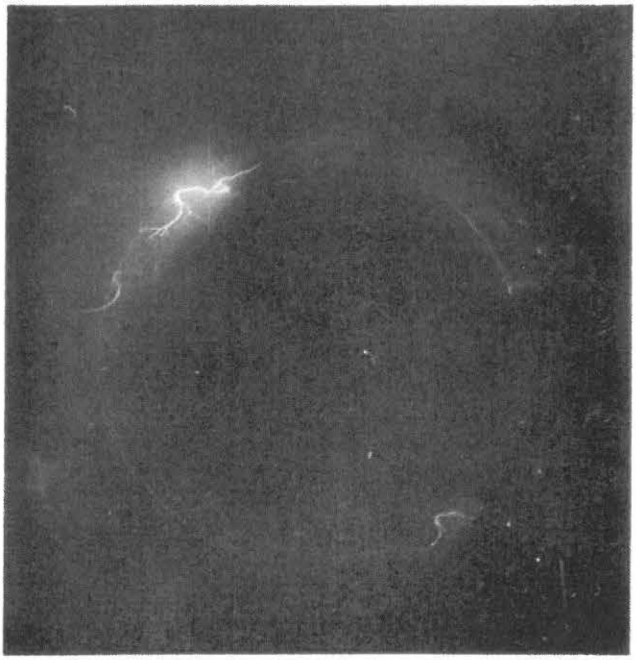


Photo. 1. (b)

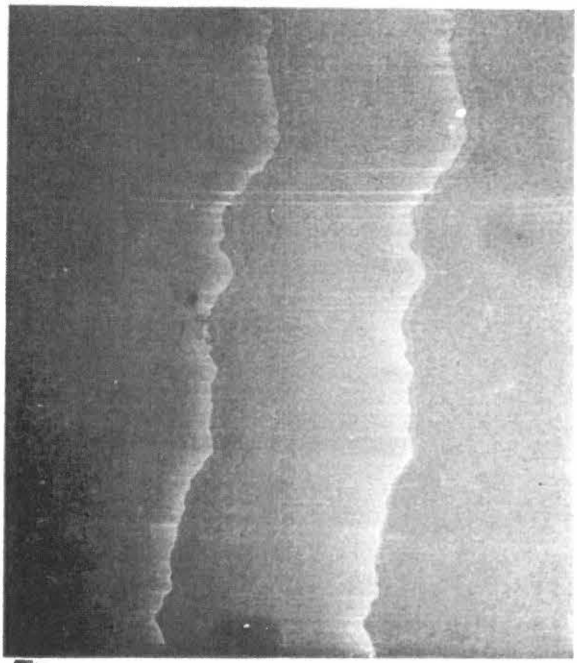


Photo. 2

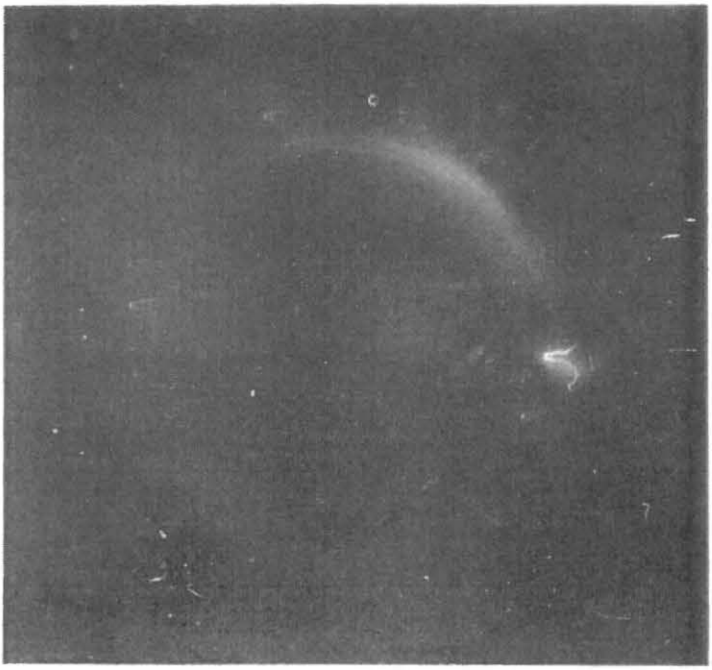


Photo. 3

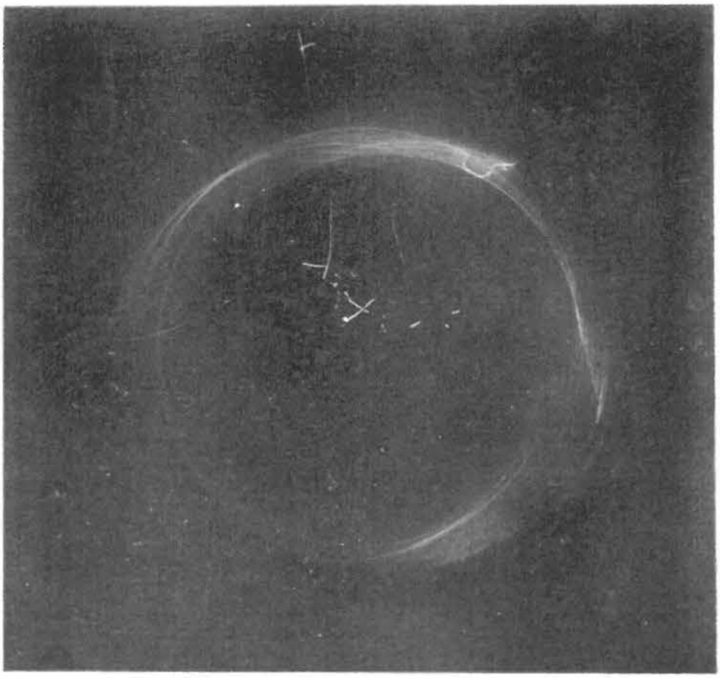


Photo. 4

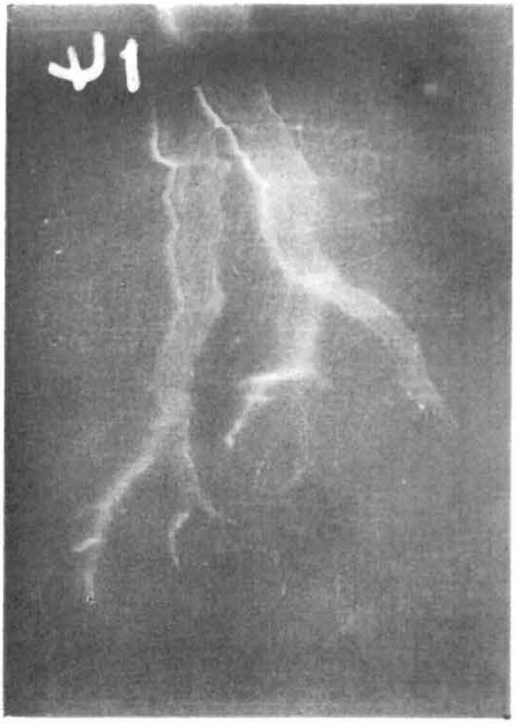


Photo. 5

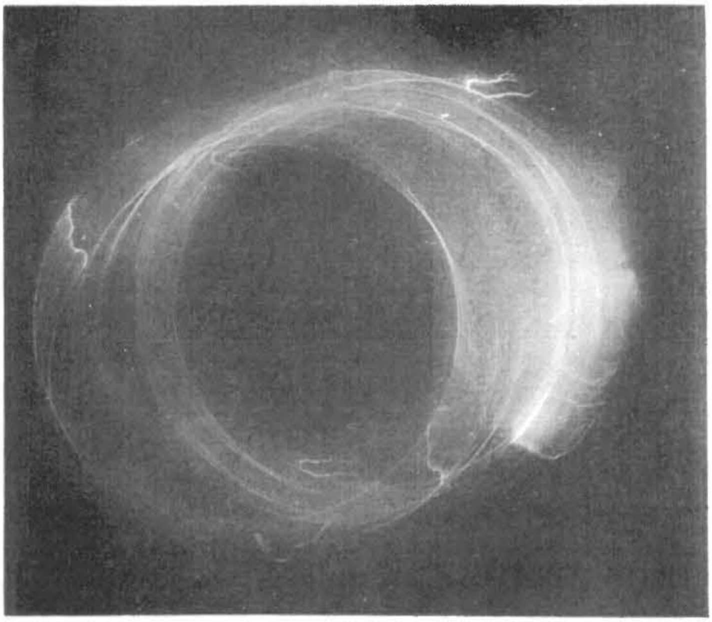


Photo. 6

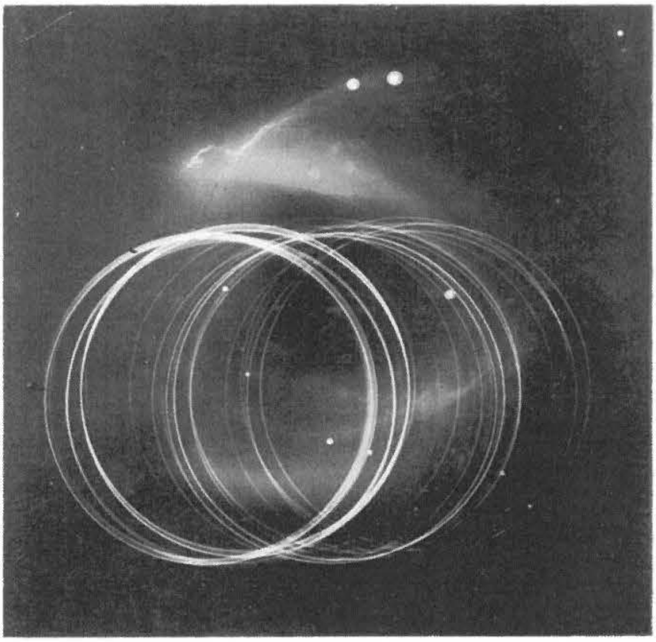


Photo. 7