Chapter III Positive Ground Discharge

1. Introduction

As we have already investigated in Section 1 and 3, Chapter II, a negative ground discharge is generally initiated with an igniting discharge taking place between the lowermost portion of the vertical negatively charged column n inside a thundercloud and the small positive charge concentration p (see Fig. 1 Section 1, Chapter II) and then grows to a huge discharge between n and the earth(1), as a result of which the negative electrical charge distributed in a vertical columnar volume is lowered successively from its lower and toward the earth's surface(2). In contrast to this, there are few ground discharges by which a positive electrical charge is lowered from thundercloud toward the earth, that is the ground discahrge with a reversed polarity. These positive ground discharges may usually be considered being a discharge taking place between the earth's surface and the small positive electrical charge connentration p grown up to an appreciable degree in the vicinity of the cloud base. Our statistical investigation of the polarity of a ground discharge has shown that the ground discharge with a positive polarity usually does not present itself except for a very special case. It depends on this reason that the fine structure of a positive ground discharge could not have been made clear. However, at present we have arrived at a stage, in which the number of measurable electromagnetic waveforms of ground discharges have increased to as much as 440 through thunderstorm observations in several summers. We have investigated the polarity of these 440 ground discharge waveforms and found that there are few ground discharges which really have a positive polarity. We shall describe in this chapter the general aspect of a positive ground discharge by investigating these few records of positive ground discharge waveforms.

2. Occurrence probability of positive ground discharges

As we have already investigated in Section 1 Chapter II, about 76% of lightning discharges are the cloud discharges taking place independent of the earth's surface, so the ground discharges occupy only 24% of all the lightning discharges. Of these 24% ground discharges, how much percentages will be occupied by the positive ones? To see this point we have investigated CW records of ground discharges as well as the electrostatic field changes recorded on magnetic tapes with our field-meter, both obtained through two summers out of 1956 - 1959. The result is represented in Table 1.

Table 1.

	Method of recording	Polarity of ground discharge		Number of data
		Negative	Positive	
Occurrence Probability	Electromagnetic Waveform	99.2%	0.8%	262
	Electrostatic field-meter	96.6%	3.4%	176

* Except for the data involved in this 0.8% there are two other electromagnetic waveforms obtained by us, likely corresponding to cloud discharges, even though they have the similar nature as that of a ground discharge waveform. These waveforms, however, have been excluded from this table.

The distances of lightning discharges giving the results of the table have been inferred to be roughly less than 100 km and 15 km respectively for the case of electromagnetic waveforms and records of electrostatic field-meter. Follwoing the table, it is evident that the percentages of the positive ground discharges do not amount to a value large than 3.4% even when we consider the electrostatic field-meter record which indicates the higher percentage value. So the proportion of positive ground discharges relative to all the recorded lightning discharges is only 24 x 0.034 = 0.82 %. Further the fact that the investigation of electromagnetic waveforms indicates the existence of the positive ground discharges only of 0.8 %, while the investigation of records of the electrostatic field-meter give the percentage of positive ground discharges as much as 3.4 % seems to be interpreted as follows: former method records the field change in the frequency range 0.5 - 100 kc/sec correctly. whereas the latter method records that in the frequency range 0 - 700 c/sec, therefore the latter can not register the fine structure of field change due to a lightning discharge as the former can do, and the decision of polarity of a ground discharge will become more severe for the electromagnetic method than for the electrostatic method.

3. Multiple ground discharge involving a positive ground stroke

As we have investigated in Section 1, a positive ground stroke is conceivable to be a discharge taking place between the earth's surface and the minor positive charge concentration p grown up to a sufficient degree in the vicinity of a thundercloud base. The results described in Section 5 Chapter II has shown that two opposite electrical charges composing the negative dipole pn_1 (see Section 4 A Chapter II) respectively amount to $Qp = 2.9$ coul., and $Qnl \fallingdotseq 8.0$ coul. for the case of a negative ground discharge. If we assume that the relation is reversed for the case of a positive ground discharge, i.e., $Qp \fallingdotseq 8.0$ coul. and $Qnl \fallingdotseq 2.9$ coul., the positive electrical charge p of this magnitude may be expected being dissipated only by one ground stroke process. This will be very conceivable when we consider the electrical charge dissipated by a ground stroke process involved in a negative multiple ground discharge. So that, if a positive ground discharge is really produced by the minor positive charge p, the positive ground stroke involved in it will not have a multiple structure, but will be limited only to the first stroke. To make this point clear, we have investigated on four records of electrostatic field changes the polarity of each of the ground strokes composing a multiple ground discharge which includes at least one positive stroke. The result of this investigation is represented in the Table 2., which indicates in accordance with the above expectation that all of the postitive ground strokes recorded by us always present themselves as the first stroke of a ground discharge, and when the ground discharge is of multiple structure, the strokes following the first are all of negative polarity. The difference between the positive and negative ground discharges, therefore, consists, at the utmost, in the polarity of the first stroke being reversed, and there is no other differences existing between the two, so long as the succeeding strokes are concerned. This indicates that the minor positive charge p is completely

Table 2.

	Symbol indicating a discharge	Order of strokes				
		I	II	III	IV	V
polarity of component strokes	A	+	-	-	*	*
	B	+	-	-	-	-
	C	+	*	*	*	*
	D	+	*	*	*	*.

neutralized by a ground stroke process, and the discharge after the first stroke is performed between the earth and the negatively charged column n remaining after the first stroke.

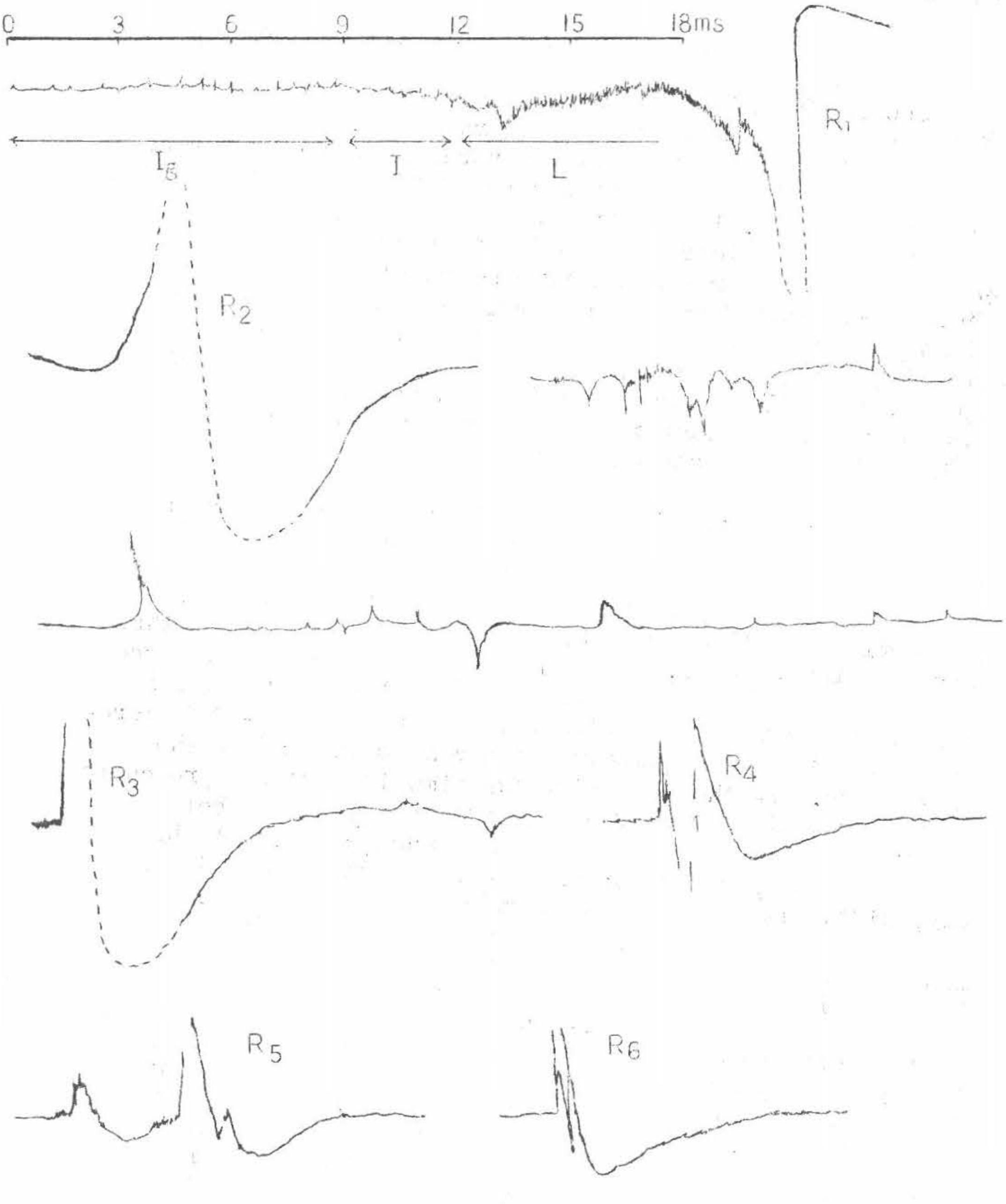
4. Structure of a positive stroke

One of the effective way to know the structure of a lightning stroke is to record the rapid field changes due to a lightning stroke with several short range waveform recorders simultaneously at several different distances from the stroke. Fig. 1 illustrates the waveform of the electromagnetic field changes due to a ground discharge composed of six strokes having appeard at a distance 20 - 30 km apart from the station. It is very clear in the figure that the first stroke R_1 is the only one that has a positive polarity and the successive strokes $R_2 \sim R_6$ are all of negative polarity, so that we shall investigate the structure of electromagnetic waveforms only of this first strokes.

(A) Structure of the preliminary discharge leading a positive ground stroke

The positive ground discharge illustrated in Fig. 1 is initiated with a preliminary discharge composed of three sections Ig. I and L, which are followed by a positive ground stroke R_1. In the Ig section a group of positive pulses builds up a pulse train with time intervals 200 - 900 micro-sec., which reduce themselves towards to the end of the Ig section. I_n the I section the time intervals approach to a value roughly 200 micro-sec. and the pulses of both polarities are recorded mixing with each other. In the L section the pulse intervals become so small that it is very difficult to separate individual leader pulses. But it represents an appreciable slow field change from the moment about 4 ms before the occurrence of R_1 The fact that the leader occurring at a distance 20 ~30 km apart from the station really produces a negative field change, must be attributed to the downward movement of a positive leader from cloud to earth(3) If we consider the point that L section of the first leader in Fig. 1 is composed of a high frequency pulse train of just the same characteristics as those of the L section of the first leader involved in an ordinary negative ground discharge, it will be very clear that the L section in Fig. 1 is really produced by a positive stepped leader traveling downwards from cloud to earth. In general, if we record the electromagnetic field change, produced by negative vertical stepped leader mvoing downwards, with a waveform recorder located outside the field reversal distance from the discharge, the radiation field produced by each of the

Fig. 1.



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step streamers will take the form of a differential type pulse with positive polarity (4). This principle applied to the case of a positive stepped leader will result in the negative differential type pulses being produced by individual step streamers outside the field reversal distance. Because of the time sweep 3 ms of the waveforms and the large ratio of contraction photography 1/8.8 caused by the necessity to record the waveforms reproduced on a C.R.T. screen with a continuous 16 mm cine camera, it is very difficult to know the polarity of individual radiation pulses on the waveform in Fig. 1. However, the radiation pulses which have a positive polarity in the Ig section seems gradually to change its polarity from positive to negative as they pass through the I section. Taking this point into account, it will be natural to presume that the polarity of the pulses appearing on the L section of the waveform in Fig. 1 will be negative. In the Ig section of the waveform illustrated in Fig. 1, on the other hand, the positive pulses of the differential type are repeated with mean time intervals about 270 micro-sec., so it is evident that the pulse train characteristics of this Ig section is just the same as those in the Ig section of an ordinary negative ground discharge so long as the polarity and the time intervals of the radiation pulses are concerned. Therefore we may conclude that the discharge producing the field change of the Ig section of a ground discharge must have the structure similar to α type stepped leader independent of the polarity of the Ig discharge.

(B) Initiation of the first ground stroke

Considered from a statistical stand point of view, the negative first ground stroke is usually ignited by the discharge of a vertical dipole composed of a negative charge concentration nl located at the lower and of a negatively charge column and a positive charge concentration p located at the cloud base. (see Fig. 16 Section 4 B Chapter II) In this case, the igniting discharge is performed mostly by a negative streamer, with the nature of a stepped leader, traveling downwards from nl towards p, as it has already been described in Section 3 of Chapter II. Following to what we have investigated in paragraph A, a positive ground discharge also initiated, like negative one, by a igniting discharge with the nature of a stepped leader. The point whether the igniting discharge Ig is performed in this case, by a streamer starting from p or by a streamer developing from nl, the point must be determind from the electrostatic field change produced by an Ig discharge. However, at the present stage where the record of a positive ground discharge suited for this investigation has not yet been obtained in any amount, the only way left for us is to make some deductions from our imperfect data. As we shall see later in Paragraph D, if the Ig discharge is to be initiated from p, the probability of occurrence of the streamer that travels from p to n_1 may be inferred being identical with the probability of occurrence of the streamer that travels from p toward to the earth. According to this presumption the actual electromagnetic waveforms due to a positive ground discharge should be initiated by the Ig section corresponding to a discharge developing from p toward nl, or by the L section corresponding to a discharge developing from p toward the earth, or by a section of Ig, L mixed type corresponding to the discharge developing from p toward the both sides, i.e., upward and downward simultaneously. These three cases may be expected to be realized each in certain proportions.

The investigation of a few electromagnetic waveforms* of the positive ground discharges which have been recorded up to the present has indicated the point that the recorded positive ground discharges were all initiated each with an Ig process. This fact seems at least not to support the above latter two interpretations positively but to suggest the Ig discharge developing downwards from n_1 to p. Generally a positive ground discharge may be expected likely to break out when the positive electrical charge concentration p predominates the negative charge concentration nl appreciably. Despite of this, to let a positive ground discharge to start from nl, the electrical charge density at nl in this case must be at least 1.6 times as large as the charge density at nl in the case of a negative ground discharge, the point of which will be discussed in Paragraph D. As it would be difficult statistically to find some serious differences in the process of negative charge accumulation in a thundercloud, to exist between positive and negative discharges it can not be expected that the charge density at n_1 Statistically attains to an appreciably high value especially for the case of a positive ground discharge. Nevertheless if a positive ground discharge is actually initiated with an igniting discharge developing from nl, it must be attributed to rather an unusally high concentration of electricity at nl, which can not be interpreted with the general mechanism of charge separation within a thundercloud, but thoroughly results from an accidental factor relating to the charge separation. In contrast to this, if the electrical charge density of p is comparable with that of nl, the electrical break down will start from p accumulating larger amount of electricity. Theoretically, the latter interpretation will

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* One reliable waveform of the positive ground discharge and two somewhat less reliable waveforms of the positive ground discharge.

be more plausible than the former. If it is so, an appreciable portion of the recorded positive ground discharges must each have the preliminary discharge without an Ig section. However, it is the problem of the furture observation to investigate which of these three interpretations are the most probable.
As to the problem, which will be observed more frequent, the positive streamer or the negative streamer, being concerned with the Ig discharge that takes place between p and n_1, it should be inferred, as a general view, as follows.
Following Honda's (5) paper the progressive velocities of a negative and a positive stepped leaders may be given by 4×10^7 cm/sec and 8×10^7 cm/sec respectively, while the results of our investigation shows that the time duration T_{Ig} of an Ig discharge amount to 6.0 ms, as represented in Table 14 given in Section 4 A, Chapter II.*
So that the distances traveled by the negative, and the positive stepped leader will be $4 \times 10^7 \times 6 \times 10^{-3} = 2.4 \times 10^5$ cm and $8 \times 10^7 \times 6 \times 10^{-3} = 4.8 \times 10^5$ cm respectively. As we have already investigated, it is probable that the discharge taking place between p and n_1 is usually inclined from the vertical axis considerably, so let us assume (H/L) Ig $\doteq 0.5$**; where H is the vertical distance between p and n_1, L is the length of the Ig discharge channel. Then the altitude difference between p and n_1 will be given by $2.4 \times 0.5 = 1.2$ km and $4.8 \times 0.5 = 2.4$ km respectively. Comparing these values with those illustrated in the Table 16 given in Section 4 A, Chapter II, we can see that the negative streamer has the advantage of interpreting the observational result. For this reason, the positive ground stroke should statistically be considered as being initiated by a negative streamer.
From time to time the waveforms of cloud discharges recorded by us each included one section or seldom more than one section of the same characteristics as those of the Ig section of waveform of the first ground stroke. To know the polarities of the streamers producing Ig like discharges, we have investigated statistically the polarities of the radiation pulses appearing in the Ig like, section of the above type cloud discharge waveforms. The results are given in Table 3

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* Exactly speaking, the Table 14 represents the statistics of the data of negative ground discharges. However, it is not unplausible that the positive discharges will give the same result as well, because of the similarity of the preliminary discharge durations existing between the positive ground discharge waveforms (see Fig. 1 Section 4) and the negative ground discharge waveforms (see Fig. 2 (b) and (c), Section 1, Chapter II)

** See Section 4 A, Chapter II.

indicating the point that a great portion of the Ig like discharges appearing in some of the cloud discharges are developed each with a negative streamer.

Table 3

Polarity of stepped leaders producing the Ig like section of a cloud discharge waveform			
Positive streamer	Negative streamer	Complex streamer	Number of data
17.4 %	57.9 %	24.7 %	19

This observational fact as well seems to support the interpretation that the igniting process of a positive ground discharge is developed, as a cloud discharge, usually with a negative streamer. Therefore the results we have hitherto obtained in this chapter seem to indicate the fact that a ground discharge generally is initiated by a negative stepped leader traveling downwards from n_1 to p independent of the polarity of a ground discharge. After the discharge gap p n1 has been bridged once with a streamer of the nature of a stepped leader, a preliminary discharge changes its nature and enters into the stage which represents the tendency of a continuous discharge with the slower rate of development. At this stage, the preliminary discharge becomes does not to emit any remarkable radiation pulse, but to produce the I section with the intermediate characteristics between the Ig and the L sections on the waveform of the discharge. Therefore it will not be unreasonable to conclude that the discharge producing the I section of the waveform is a discharge of the continuous character with a slow discharging rate, hence it lacks a clear stepwise structure. The quantity of electricity discharged by an I process must, of course, be inferred to be very small compared with the total electricity discharged by the whole preliminary process. The I discharge will be continued till to the moment when either of the electricity involved in the charge concentrations n1 and p being dissipated thoroughly.

In the case of a negative discharge the quantity of positive electricity p must usually be inferred to be smaller than that of the negative electricity n1, therefore the former must be dissipated earlier than the latter. At the end of an I process, there exist negative residual electricity remaining at n_1 and a discharge channel streaching downwards from n_1 to p. As the negative electricity distributing in a columnar form from n1 upward prevent the streamer channel, which has bridged the distance between n1 and p, to develop further upwards, once after the positive electricity at p has been dissipated by the Ig and I discharges, so the lower end of the Ig streamer will stretch downward under the influence of the self field as well as the electrostatic field* built up instantaneously between the columnar distribution n of the negative charge and the earth's surface. Then the streamer will grow to a stepped leader by the influence of the negative charge left at nl behind the Ig and I discharges and will lead the discharge to the first return stroke. Honda $^{(5)}$ assumed that the mean electrostatic field $E_m = 5 \times 10^3$ v/cm must be needed to exist in the space of a long lightning spark gap to enable the lower end of the streamer to develop downwards with a high velocity further.. This value is roughly only 1/10 of the field intensity $E_B = 6 \times 10^4$ v/cm $^{(6)}$ necessary for a electrical breakdown to take place in the a thundercloud. This point also suggests that and I portions having been after the Ig

completed, the start of a preliminary discharge is performed by the further downward development of the lower end of the completed I_g channel under the influence of an appreciably low mean electrical field about 5×10^3 v/cm existing round the dissipated positive electricity p.

In the case of a positive ground discharge, the positive electricity p predominates the negative electricity nl, so n_1 will be dissipated faster than p. Therefore at the stage of a preliminary discharge corresponding to the end of I section of the waveform, we may expect the existences of a positive electricity remaining at p and a discharge channel stretching from p toward n_1. In this case the remaining discharge channel is subjected to

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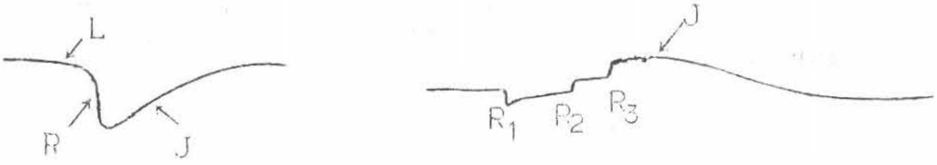
* Let the mean electrostatic field streangth built up between the earth's surface and the cloud base be 5×10^3 v/m, and further the altitude of p be 2.3 km, then the electrical voltage at p relrtive to the earth will be $5 \times 10^3 \times 2.3 \times 10^5 = 12 \times 10^8$ volt. Assuming a negative discharge, let the electrical charge p be 3 coul., then the electrostatic capacity between p and the earth's surface will be $C = 3/12 \times 10^8 = 2.5 \times 10^{-9}$ farad. If we estimate the effective electrical resistance between the area of the earth's surface just beneath p and that surrounding the former being of the order of 10^5 ohm. The relaxation time of the CR circuit built up the earth's surface will be $2.5 \times 10^{-9} \times 10^5 = 2.5 \times 10^{-4} = 0.25$ ms, which is very short compared with the time duration of the Ig or I section of the electromagnetic waveform. Therefore the variation in the induced electrical charge along the earth's surface, which results from the cloud discharge between p and n_1, can, as a first approximation, follow the discharge development without any serious time delay.

an electrostatic field built up between the residual positive electricity at p and the negative electricity $Q_{n'} = Q_{n2} + Q_{n3} + \ldots\ldots\ldots$ (see Fig. 18 Section 4B, Chapter II) contributing to the strokes later than the first. If the electricity $Q_{n'}$ is predominant and if the mean electrostatic field $\bar{E}_{pn'}$ acting between p and n' larger than that $\bar{E}_{pe}$ acting between p and the earth, so that $\bar{E}_{pe} < \bar{E}_m < \bar{E}_{pn'}$, the discharge channel completed by the Ig and I process will develop the upper end, and the discharge will take place between the two electrodes p and n_2, the lowermost part of n'. Then the discharge will not construct a ground discharge but end itself as a cloud discharge. However, if the electricity $Q_{n'}$ does not exist in the thundercloud, or the amount of it is not appreciable, so that the relation $\bar{E}_{pn} < \bar{E}_m < \bar{E}_{pe}$ is satisfied, the electrical situation surrounding the lowermost portion of the discharge channel that bridges the two charge centers p and n_1 would be as follows. At the end the I process, the lower head of the discharge channel should be inferred to be of a very complex structure, if we attach importances to the result of discussions in Section 4 A, Chapter II, Few of the numerous photo-electrons emitted from the assumed many minor element streamers, which compose a complex streamer head, may have a chance to enter into the region of the electrostatic field E_{pe} active between p and the earth under a very favorable condition. If at least one of these few photo-electrons has the ability to grow to an electron avalanche, a positive stepped leader will result in. Therefore in this case, a positive stepped leader travels downwards from p to the earth's surface, and then leads a negative return stroke developing upwards from the earth. This will be the structure of a positive ground stroke.

(C) Discharge following to a positive ground stroke

As illustrated in Fig. 1 in Section 4, the electromagnetic waveform of a positive multiple ground discharge clearly indicates that each ground stroke following to the first always has a negative polarity. To investigate the nature of the discharge performed by the so called junction process$^{(2)}$ appearing in the time interval between two successive strokes of a positive multiple ground discharge, let us investigate two examples of the record of electrostatic field-meter illustrated in the Fig. 2, (a), (b), which represent the two cases of electrostatic field changes due to ground discharges each with a positive first stroke and were recorded outside and at the field reversal distances respectively. In the Fig. 2, L, R and J represent the field changes due to the first leader, the return stroke and the junction process respectively.

Fig. 2



(a) $D < 5 \sim 8$ km (b) $D \doteqdot 5 \sim 10$ km

(a) represents a single ground discharge and (b) a triple ground discharge. In the case of (a) the electrostatic field change due to the leader L is recorded with an appreciable amplitude, so that it is very easy to see that the leader really has a positive polarity. We shall next investigate the electrostatic J-field change following to R_1 in the Fig 2. Concerning this point, the example (a) shows that the electrostatic J-field change recorded at a distance, which is appreciably nearer than the case of (b), but longer than the relalted field-reversal distance because of the low altitude of the stroke, has a positive polarity, so the field change, in this case, must be produced by a vertical upward movement of a positive electricity or by a downward movement of a negative electricity. In the case of (b), on the other hand, it is clear that the J-field change recorded has a maximum, so the field change must be attributed to a vertical movement of positive electricity.*

Combining these observational facts, we may conclude that the J-field change appearing in the stroke intervals of a positive ground discharge is developed by an upward movement of positive electricity.

This is just the same electrical process as the junction process(2) of an ordinary negative ground discharge. If we summarize the results of the above investigations, the following conclusions will be obtained. The difference between a positive and a negative ground discharges

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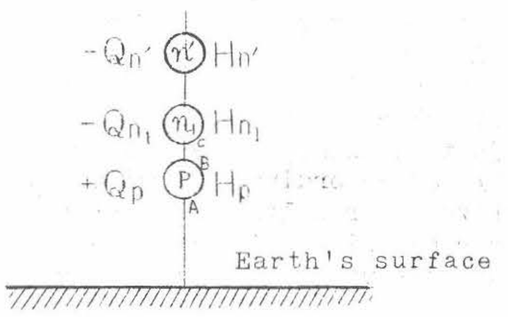
* In all, there are six records of positive ground discharges caught by our electrostatic field-meter, three of which are classifiable as the type that has a miximum on the section of a J-field change as illustrated in Fig. 2 (b) and the remaining three are classifiable as the type that has no maximum on the J-field change as illustrated in Fig. 2(a).

generally consists in no other point than the stepped leader and the following return stroke, composing the first stroke, therefore the electrical processes, which follow the first return stroke, i.e., the successive ground strokes and the junction process in the stroke intervals, are thoroughly the same between these two ground discharges with opposite polarities.

(D) Electrical breakdown of the dipole composing a igniting discharge

As we have already investigated in Section 4 B, the first stroke of a ground discharge is always initiated with a discharge of a negative dipole existing in the vicinity of a thunder-cloud base independent of the polarity of a ground discharge. If we assume the distribution of electricity in a thundercloud to have the structure illustrated in the Fig. 1 of Section 1, Chapter II, which portion of a thundercloud will produce an electrical breakdown to initiate a ground discharge? To investigate this point, let us replace the electrical charge distribution relating to individual strokes of a ground discharge with several spherical distribution of electricity arranged along a vertical axis in such a way as illustrated in Fig. 3. This simplification, of course, results in the neglection of the diversity of individual lightning discharges. However, the slow electrostatic field change due to a lightning discharge recorded with an electrostatic field-meter with a vertical antenna attached to its head at a distance within the range distributing

Fig 3



10 - 30 km* from the discharge is usually of a very simple character independent of being a ground discharge or a cloud discharge. Table 4 is the statistical result representing this point. It is well known that the greater part of lightning discharges occurring within thunderclouds have each a structure which make it possible to simplify their mechanisms by replacing themselves with a vertical dipole discharge performed with a process similar to a junction process.

Table 4

	Types of slow electrostatic field-changes*	Lightning discharges	
		Ground discharge	Cloud discharge
Number of data	Simple change	12	22
	Complex change	2	3

* Measurement of records of electrostatic field changes obtained at distances lying within the range of distances 10 - 30 km from the discharges.

Considering this point, we can conclude that the simplification of the charge distribution inside a thundercloud illustrated in Fig. 3 gives a model suited for the investigation to know the general character of a lightning discharge. In the figure, p and nl represent respectively the positive and the negative electrical charge centers composing a negative dipole relating to the first ground stroke. Following the result obtained in Section 4 A and Section 5 A of Chapter II, the mean altitudes and the mean electrical charges of the igniting dipole of a negative ground discharge may be estimaded as Hp = 2.3 km,

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* If we record the electrostatic field-changes of a lightning discharge at distances like those described here, the field changes due to small secondary discharge processes involved in the main part of it will tend to attenuate themselves completely, which makes it possible to simplify the structure of a lightning discharge, and makes it easy to know the general character of a lightning discharge.

H_{n1} = 3.5 km and Qp = 2.9 coul, Q_{n1} = 8.0 coul respectively. In the case of a positive ground discharge, we have no quantitative data concerning the dipole at present, therefore, let us assume the mean altitude of the dipole being given by Hp = 1.5 km, H_{n1} = 3.5 km for the reasons which will be described in section 4E (b), and the mean electrical charge of it being given by Qp = 8.0 coul, Q_{n1} = 2.9 coul, i.e., the relation which is the reverse of a negative ground discharge. Qn' represents the total charge concerned with the strokes following to the first*. According to the result obtained from the discussion in Section 4B Chapter II, it is clear that the vertical development of a thundercloud in the Maebasi district is by no means so active, as it is in the district surrounding Johanesburg in South Africa, so that the altitudes of successive strokes of a ground discharge at Mawbasi are statistically lying in the range 4 - 6 km, and generally lower than those at Johanesburg, and they do not increase appreciably with the increase in the order of ground strokes. As we are going to consider the electrostatic field change produced by a vertical movement of electricity concerned with the first ground stroke, the simplified model will not have any important defect, even though the electrical charges (Q_{n2}, Q_{n3}, ...) contributing to ground strokes following to the first are replaced by the total electrical charge Qn' located at an effective altitude Hn' . The mean altitude of successive ground strokes given in the Table 19 in Section 4 B Chapter II is Hn' = 4.5 km, the mean electrical charge of each of the strokes given by the estimation of Workman and his colleagues(7)

Table 5

Polarity of ground discharge	Hp	H_{n1}	Hn'	Qp	Qn1	Qn'
Positive discharge	1.5	3.5	4.5 km	8.0	2.9	13.0 coul
Negative discharge	2.3	3.5	4.5	2.9	8.0	19.5

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* If we follow the model illustrated in Fig. 18, Section 4 B, Chapter I, Qn' will be represented as

$$Qn' = Qn2 + Q_{n3} + Q_{n4} + \cdots\cdots$$

is Q_{n1} = 6.5 coul*, and the mean multiplicity of a ground discharge given in Table 17 of Section 4 B, Chapter II is 3 for the case of a positive multiple ground discharge and 4 for the case of a negative one. Therefore the total electrical charge $Q_{n'}$ will be $Q_{n'}$ = 6.5 x 2 = 13 coul for a positive discharge and $Q_{n'}$ = 6.5 x 3 = 19.5 coul for a negative discharge. Table 5 represents the results of estimation of altitudes and the electrical charges of the charge centers p, n_1 and n'. Let us assume in Fig. 3 that' the radii of the spherical distributions of electricity at p, n_1, n' are r_p, r_{n1}, $r_{n'}$ respectively and further the distributions of electricity in each sphere are of uniform densities respectively given by N_p, N_{n1}, $N_{n'}$, then the electrostatic field intenstities at the three points A, B, C on the surface of the charged spheres p and n_1 (see Fig. 3), where the field intensities attain the extreme values, will be obtained as follows:

$$\left.\begin{aligned}
E_A &= 90Q_p\left\{\frac{1}{r_p^2}+\frac{1}{(2H_p-r_p)^2}\right\} - 90Q_{n_1}\left\{\frac{1}{(H_{n_1}-H_p+r_p)^2}\right.\\
&\qquad \left.+\frac{1}{(H_{n_1}+H_p-r_p)^2}\right\} - 90Q_{n^1}\left\{\frac{1}{H_{n^1}-H_p+r_p)^2}+\frac{1}{(H_{n^1}+H_p+r_p)^2}\right\}\\
E_B &= 90Q_p\left\{\frac{-1}{\gamma_p^2}+\frac{1}{(2H_p+\gamma_p)^2}\right\} - 90Q_{n_1}\left\{\frac{1}{(H_{n_1}-H_p+\gamma_p)^2}+\frac{1}{(H_{n_1}+H_p+\gamma_p)^2}\right.\\
&\qquad -90Q_{n^1}\left\{\frac{1}{(H_{n^1}-H_p-\gamma_p)^2}+\frac{1}{(H_{n^1}+H_p+\gamma_p)^2}\right\}\\
E_C &= 90Q_p\left\{\frac{-1}{(H_{n_1}-H_p-\gamma_{n_1})^2}+\frac{1}{(H_{n_1}+H_p-\gamma_{n_1})^2}\right\} - 90Q_{n_1}\left\{\frac{1}{\gamma_{n_1}^2}+\frac{1}{(2H_{n_1}-\gamma_{n_1})^2}\right.\\
&\qquad -90Q_{n^1}\left\{\frac{1}{(H_{n^1}-H_{n_1}+\gamma_{n_1})^2}+\frac{1}{(H_{n^1}+H_{n_1}-\gamma_{n_1})^2}\right\}
\end{aligned}\right\}(1)$$

Where Q, H, r, and E are expressed in coul, km, v/cm respectively. If the extent of each spherical charge distribution is sufficiently smaller than the altitude of the respective sphere, so that $H \gg r$, then the following approximations will be allowed

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* This results in the adoption of a larger value than what has been estimated through the discussion in Section 5 B Chapter II. However, these alternative values will give the same theoretical conclusion.
The condition of the transition from Ig to L will become more severe, if we give n_1 a larger value.

$$\left.\begin{aligned}
E_A &\doteqdot 90Q_p\left\{\frac{1}{\gamma_p{}^2}+\frac{1}{(2H_p)^2}\right\}-90Q_{n_1}\left\{\frac{1}{(H_{n_1}-H_p)^2}+\frac{1}{(H_{n_1}+H_p)^2}\right\}\\
&\quad -90Q_{n^1}\left\{\frac{1}{(H_{n^1}-H_p)^2}+\frac{1}{(H_{n^1}+H_p)^2}\right\}\\
E_B &\doteqdot 90Q_p\left\{\frac{-1}{\gamma_p^2}+\frac{1}{(2H_p)^2}\right\}-90Q_{n_1}\left\{\frac{1}{(H_{n_1}-H_p)^2}+\frac{1}{(H_{n_1}+H_p)^2}\right\}\\
&\quad -90Q_{n^1}\left\{\frac{1}{(H_{n^1}-H_p)^2}+\frac{1}{(H_{n^1}+H_p)^2}\right\}\\
E_C &\doteqdot 90Q_p\left\{\frac{-1}{(H_{n_1}-H_p)^2}+\frac{1}{(H_{n^1}+H_p)^2}\right\}-90Q_{n_1}\left\{\frac{1}{\gamma_{n_1}^2}+\frac{1}{(2H_{n_1})^2}\right\}\\
&\quad -90Q_{n^1}\left\{\frac{1}{(H_{n^1}-H_{n_1})^2}+\frac{1}{(H_{n^1}+H_{n_1})^2}\right\}
\end{aligned}\right\}\quad (2)$$

To estimate the order of magnitude of the radius of a spherical charge distribution, at which the negative dipole begins to break-down under the given H and Q values, let us put the H, Q values represented in Table 5 into for the case of the negative ground discharge, into the third relation of the formulae (1), then we can get Table 6 shows the result

$$E_C = 261\left\{\frac{-1}{(1{,}2-\gamma_{n_1})^2}+\frac{1}{(5{,}8-\gamma_{n_1})^2}\right\}-720\left\{\frac{1}{\gamma_{n_1}^2}+\frac{1}{(7{,}0-\gamma_{n_1})^2}\right\}$$

$$-1775\left\{\frac{1}{(1{,}0+\gamma_{n_1})^2}+\frac{1}{(8{,}0-\gamma_{n_1})^2}\right\}$$

of calculation of the above relation under several given rn1 values.

Honda (6) pointed out that the electrical field intensity necessary for producing the break-down in the air under an atmospheric pressure in and around the lower portion of a

Table 6

r_{n1}	E_c(kv/cm)
0.1	-73.3
0.2	-23.0
0.3	- 9.2
0.5	- 3.8

thundercloud must be 60 kv/cm, therefore it will be evident from the Table 6 that radius r_{n1} of the charged sphere n_1 must attain the value 0.1 - 0.2 km to produce an electrical break-down at the point C in Fig. 3 under the given values of Q_p' Q_{n1}, Q_n', and H_p, H_{n1}, h_n'. This relation is roughly unchanged also for the cases of E_A and E_B, so that the condition $r \ll H$ is really satisfied for all E's. This enables us to adopt the approximate formulae (2). Putting the H, Q values values in Table 5 into the approximate formulae (2), we can obtain the following relations:
For a positive discharge

$$\left.\begin{aligned} E_A &= -847{,}4 + 720/{r_p}^2 \\ E_B &= -126{,}1 - 720/{r_p}^2 \\ E_C &= -969{,}9 - 261/{r_{n1}}^2 \end{aligned}\right\} (3)$$

For a negative discharge

$$\left.\begin{aligned} E_A &= -847{,}4 + 261/{r_p}^2 \\ E_B &= -847{,}4 - 261/{r_p}^2 \\ E_C &= -1431{,}6 - 720/{r_{n1}}^2 \end{aligned}\right\} (4)$$

As the condition $|E_B|>|E_A|$ is satisfied for both of these cases, so theoretically the electrical breakdown must be produced at B or C. Let us calculate the respective radii of the spherical charge distributions, when the electrical breakdown is produced at B or C. If we put $E_B = E_C = -60$ kv/cm into the formulae (3) and (4), the values r_p, r_{n1} represented in the Table 7 will be obtained, in which the ion-densities of the spherical distributions when the radii of the spheres attain the table values are tabulated along with the radius values.

Table 7

Polarity of discharge		Positive discharge	Negative discharge
Radius of dipole electrode	rp	0.11 km	0.066 km
	r_{n1}	0.067 km	0.111 km
Ion density of dipole electrode	Np	9.00 x 10^6ion/cc	14.7 x 10^6 ion/cc
	N_{n1}	14.4 x 10^6ion/cc	8.75 x 10^6ion/cc

Let us investigate here the break-down of the dipole p_{n1} for the two cases, i.e., a negative discharge and a positive discharge.

(a) Negative discharge: The Table 7 tells that to produce an electrical breakdown from the electrode p the ion density of this electrode must attain the volue no less than 14.7 x 10^6 ion/cc, whereas to produce it from the electrode n, the ion density needed is no more than 8.7 x 10^6 ion/cc. As we have already investigated the greater part of ground discharges appearing in Maebasi district have always a negative polarity. Whether a negative discharge of this statistical character is generally initiated from p or from n, it must depend on the fact that which of these two electrical accumulations statistically attains first the value necessary for the initiation of an electrical break-down. Considered from the statistical stand point of view, the mechanism of charge separation, necessary for the accumulation of positive electricity Qp that must attain the ion-density of the order of 10^6 ion/cc in order to result in an electrical break-down, can not be interpreted satisfactorily,* so long as the theories other than the Simpson's water drop-breaking process (8) are not taken into account. Therefore it is necessary at least, to consider a more violent process of positive ion production caused, for example, by point discharges along the earth's surface subjected to a strong electrostatic field built up in the space between a thundercloud and the earth's surface beneath it, and to consider the capture and the accumulation of produced positive ions by cloud particles at the base of the cloud.** Because the positive point discharges occurring along the earth's surface are generally produced by the influence of a strong electro-static field of the order of 300 v/cm built up in the space between the earth's surface and the negative electricity N (see Fig. 1 Section 1, Chapter II) accumulated in the lower part of a thundercloud, it will be reasonable to infer that the accumulation of electricity at the negative electrode nl will statistically be completed earlier than that at the positive electrode p. If we consider point, it is evident that nl must first attain the situation capable of an electrical breakdown, and the igniting must start from the point C indicated in Fig. 3. This point really seems to be supported by the observational facts described in Section 3 Chapter II. If we assume the charge accumulation at p and nl being performed in such a

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* Simpson showed that the electricity created in a water droplet by one drop-breaking process is 2.3×10^{-2} esu/cc and further, according to our investigations, the water content of a thundercloud in the neighbourhood of Maebasi estimated from the rainfall area detected with PPI radar indications and from the quantity of rain fall accompanied by a thundercloud is 5×10^{-6} g/cc. If we assume that the density of water is 1, the mean electrical charge density of a thundercloud composed of water droplets which have been subjected to one drop-breaking process will be 1.15×10^{-7} esu/cc, which gives the ion density $1.15 \times 10^{-7} / 8 \times 10^{-10} = 2.4 \times 10^{3}$ ion/cc. In a thundercloud it is expected that water droplets will repeat the following processes: drop-breaking, upward movement of the broken pieces, gathering of the broken pieces and falling of the gathered droplet in a strong ascending air stream with a mean velocity more than 30 km/sec. It may be reasonable to think that, at least, a time length of the order of 1 min will be needed to repeat these processes, so that if we assume that the life time of a thundercloud cell is no more than 50 min, the possible maximum number of the repetitions must be 50. Therefore the ion density of a thundercloud composed of water droplets subjected to 50 times of breaking processes will be 1.2×10^{5} ion/cc which gives the possible maximum ion density produced by the water drop-breaking process. However, this is much smaller than the ion density 107 ion/cc necessary for the electrical breakdown.

way that the charge densities at the both electrodes being kept identical with each other, the following results will be obtained.

$r_p \doteq 0.0791$ km $EA = 40.9$ kv/cm $E_B = 42.5$ kv/cm

$r_{n1} = 0.111$ km $E_C = -60.0$ kv/cm

$N_p \doteq N_{n1} \doteq 8.75 \times 10^6$ ion/cc

From these results, we can get the relation $|E_C| \gg |E_B| > |E_A|$, which means that the electrical breakdown must start from the point C and therefore can interpret the observational facts. As the above nummerical values give $(|E_B| - |E_A|)/E_B \fallingdotseq 0.04$, so that we must notice the difference between $|E_A|$ and $|E_B|$ being only 4%.

(b) Positive discharge: As described in Section 2, this is the discharge which we can find only 0.82 times out of 100 records of the electromagnetic waveforms of lightning discharges, an must be inferred to break out under a very special electrical condition. Therefore it will not be appropriate, as a method of explanation, to attempt to interpret the start of a positive discharge from the general statistical characters of the separation, and the accumulation of electrical charges at p and n_1.

If the electrical charge accumulations at p and n_1 are performed in such a way that the ion densities at p and n_1 are always kept identical with each other, the electrical breakdown should start from the electrode p which, in the case of a positive discharge, accumulates much more electricity than n_1. This condition of equal ion density gives the following results.

$r_p > 0.11$ km $E_A \doteq 59.9$ kv/cm $E_B = -60$ kv/cm

$r_{n1} = 0.074$ km $E_C \doteq -48.3$ kv/cm

** If we assume the point discharge current from the earth's surface being 3.2×10^{-8} amp/m^2, the value given by Schonland, and the duration of the cumulus stage of a thundercloud being 15 min, the electrical charge accumulation per m^2 in this period will be $3.2 \times 10^{-8} \times 9 \times 10 = 2.88 \times 10^{-5}$ coul/m^2. So that the area of point discharge along the earht's surface needed for the electricity accumulation at p of the magnitude 2.9 coul (for a negative discharge) or 8 coul (for a positive discharge) will be 1×10^5 m^2 or 2.78×10^5 m^2 respectively. If the areas are represented with circles, the radii of these circlues are 358 m and 594 m respectively. As these values are only about 2.2 times larger than the respective raii of the spherical charge distributions 158 m and 320 m., the reduction of the area of this magnitude will be interpreted by the convergence of the upward stream of the air from the earth's surface toward the lower part of a thundercloud.

$$N_p = N_{n1} = 9.0 \times 10^6 \text{ ion/cc}$$

This results in $|E_B| > |E_A| \gg |E_C|$, therefore it will be reasonable to think that the positive discharge theoretically starts from the point C represented in Fig. 3. But $(|E_B| - |E_A|) / |E_B|$ 0.013, that is, the difference between $|E_B|$ and $|E_A|$ is only 1.3 %. This small theoretical difference 1.3% seems not to have practically an important statistical meanings concerning the relative magnitudes of E_B and E_A, because certain special electro-meteorological conditons must be satisfied to produce a positve discharge.
So, if the charge accumulations at p and nl are peformed under the conditon of equal ion density, it would depend on the fine structure of electrical charge distribution at p, whether the positive discharge starts from A or from B. The probabilities of occurrence of these two cases would then roughly be identical with each other.

As we have already investigated in Section 4 B Chapter III, there are several observational facts which seem to indicate that some of the Ig discharges leading positive discharges are really initiated from the electrode nl, like the case of a negative ground discharge. In this case, the electrical breakdown must be initiated from nl with minor electricity, so the ion density of n_1 must inevitably higher than that of p. We can estimate in this case, the upper limit of the ion density of p, from the conditon that the **beakdown** does not start from p. The calculation gives:

$$r_p > 0.11 \text{ km} \quad |E_A| < |E_B| \ll 60 \text{ kv/cm}$$
$$r_{n1} = 0.067 \text{ km} \quad E_C = -60 \text{ kv/cm}$$
$$N_p < 9.0 \times 10^6 \text{ ion/cc} \quad N_{n1} = 14.4 \times 10^6 \text{ ion/cc}$$

If we take $r_p = 0.16$ km, because of the reason that will be described in Section 4 E (b), we can get

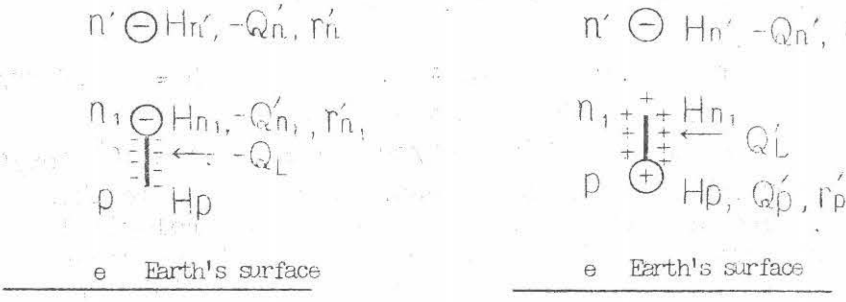
$$r_p = 0.16 \text{ km} \quad E_A = 2.80 \text{ kv/cm} \quad E_B = -28.2 \text{ kv/cm}$$
$$r_{n1} = 0.067 \text{ km} \quad E_C = -60 \text{ kv/cm}$$
$$N_p = 2.92 \times 10^6 \text{ ion/cc} \quad N_{n1} = 14.4 \times 10^6 \text{ ion/cc}$$

The conditon $|E_C| \gg |EB| > |EA|$ is, of course, satisfied in this case too. Because certain special electro meterological conditions must be satisfied to produce a positive ground discharge, it is very difficult, at present, to interprete the reason why the ion density at the electrode n_1 in the case of a positive discharge reaches a value, at least, 1.6 times larger than that of the case of a negative discharge. However, in the theory of the next paragraph, we shall assume that the electrical breakdown of a positive ground discharge will be initiated at the point C, because some of the observational facts seem to support this point.

(E) Transition from igniting discharge to leader pcoress

As we have already investigated in Section 4 B the electrical charge distributions around p and n_1 at the moment just before the initiation of a leader process after the end of an igniting discharge, will represented by a discharge channel bridging the distance from p to n_1 or from n_1 to p according to the polarity of the ground discharge. In order that the lower end of a bridging discharge channel will be able to progress further towards the earth's surface as a stepped leader in the next stage, it is needed that the upper end of the bridging channel is subjected to a smaller electrostatic field than the critical mean field E_m necessary for the maintenance of a streamer advance, and at the same time, the lower end of the channel is subjected to a larger electrostatic field than E_m. In the followings we shall investigate whether the above conditions about the critical mean field can really be satisfied for the case of the spherical distribution model of lightning discharge electricity described in Paragraph D. Let us assume the electrical charge distribution at the moment just before the start of a L discharge being just like as illustrated in Fig. 4, in which (a) and (b) represent the cases of a negative ground discharge and a positive ground discharge respectively. In both of these, let us assume that the bridging discharge channel pn_1 has a uniform distribution of electricity with a mean linear ion density equal to that of a stepped leader, and the polarity of the distributed electricity being negative for the case (a), and positive for the case (b). The inter-electrode mean electrostatic field intensity $\bar{E}_{n'n1}$ and $\bar{E}_{n1e}$ acting

Fig. 4



(a) (b)

respectively between n'n1 and between n can be obtained for the case of a negative ground discharge as follows. If we assume the electrical charge distribution illustrated in Fig. 4 (a) representing the case of a negative discharge $\bar{E}_{n'n1}$ and $\bar{E}_{n1e}$ will be given by

$$\left.\begin{aligned}
\bar{E}_{n'n_1} = {} & \frac{90Q_{n'}}{H_{n'}-H_{n_1}}\left\{\left(\frac{-1}{r_{n'}}+\frac{1}{2H_{n'}}\right)+\left(\frac{1}{H_{n'}-H_{n_1}}-\frac{1}{H_{n'}+H_{n_1}}\right)\right\} \\
& + \frac{90Q'_{n_1}}{H_{n'}-H_{n_1}}\left\{\left(\frac{+1}{r'_{n_1}}-\frac{1}{2H_{n_1}}\right)+\left(\frac{-1}{H_{n'}-H_{n_1}}+\frac{1}{H_{n'}-H_{n_1}}\right)\right\} \\
& + \frac{90Q'_L}{(H_{n'}-H_{n_1})(H_{n_1}-H_p)}\log\left|\frac{H_{n_1}-H_p}{\varepsilon}\cdot\frac{H_{n_1}-H_p}{2H_{n_1}}\cdot\frac{H_{n'}-H_n}{H_{n'}-H_p}\cdot\frac{H_{n'}+H_{n_1}}{H_{n'}+H_p}\right| \\
\bar{E}_{n_1e} = {} & \frac{90Q_{n'}}{H_n}\left(\frac{-1}{H_{n'}-H_{n_1}}+\frac{1}{H_{n'}+H_{n_1}}\right)+\frac{90Q'_{n_1}}{H_{n_1}}\left(\frac{-1}{r'_{n_1}}+\frac{1}{2H_{n_1}}\right) \\
& + \frac{90Q'_L}{H_{n_1}(H_{n_1}-H_p)}\log\left|\frac{\varepsilon}{2H_p}\cdot\frac{H_{n_1}-H_p}{H_{n_1}-H_p}\right|
\end{aligned}\right\}(1)$$

$\bar{E}_{n'p}$ and $\bar{E}_{pe}$ for a positive ground discharge can also be obtained in a similar way

$$\left.\begin{aligned}
\bar{E}_{n'p} = {} & \frac{90Q_{n'}}{H_{n'}-H_p}\left\{\left(\frac{-1}{r_n}+\frac{1}{2H_n}\right)+\left(\frac{1}{H_{n'}-H_p}-\frac{1}{H_{n'}+H_p}\right)\right\} \\
& + \frac{90Q'_p}{H_{n'}-H_p}\left\{\left(\frac{-1}{r'_p}+\frac{1}{2H_p}\right)+\left(\frac{1}{H_{n'}-H_p}-\frac{1}{H_{n'}+H_p}\right)\right\} \\
& + \frac{90Q'_L}{(H_{n'}-H_p)(H_{n_1}-H_p)}\log\left|\frac{\varepsilon}{H_{n_1}-H_p}\cdot\frac{2H_{n_1}}{H_{n_1}+H_p}\cdot\frac{H_{n'}-H_p}{H_{n'}-H_{n_1}}\cdot\frac{H_{n'}+H_p}{H_{n'}+H_p}\right| \\
\bar{E}_{pe} = {} & +\frac{90Q_{n'}}{H_p}\left(\frac{-1}{H_{n'}-H_p}+\frac{1}{H_{n'}+H_p}\right)+\frac{90Q'_p}{H_p}\left(\frac{+1}{r'_p}-\frac{1}{2H_p}\right) \\
& + \frac{90Q'_L}{H_p(H_{n_1}-H_p)}\log\left|\frac{2H_p}{\varepsilon}\cdot\frac{H_{n_1}-H_p}{H_{n_1}+H_p}\right|
\end{aligned}\right\}(2)$$

Where $(\bar{E}, Q)$ and (H, r, ε) are represented in v/cm, coul and km respectively, and

$$\left.\begin{aligned} Q'_L &= \left\{(H_{n1} - H_p)/H_{n1}\right\} Q_L \qquad \text{(see Formulae (2) (*) Section 5 A, Chapter II)} \\ Q'_{n1} &= Q_{n1} - (Q_p + Q'_L), \quad Q'_p = Q_p - (Q_{n1} + Q'_L) \end{aligned}\right\} (3)$$

ε represents the radius of the bridging discharge channel, and r_n', r'_{n1}, r'_p the radii of the respective spherical electricity distributions at the moment of start of a L process.

(a) Nagative discharge:

Put the H values represented in Table 5 in Section 4 D, Chapter III, and the Q_L value represented in Table 21 in Section 5 A, Chapter II into the first relation of the formulae (3), then Q'_L will be obtained. This Q'_L value together with Q values represented in Table 5 being put into the second relation of the formulae (3) will give Q'_{n1} value. The result is summarized in the following table.

H_p	H_{n1}	$N_{n'}$	Q'_L	Q'_{n1}	$Q_{n'}$
2.3 km	3.5 km	4.5 km	0.9 coul	4.2 coul	19.5 coul

As to the ε value, let us consider the Honda's theory (5) of a stepped leader mechanism and assume the interelectrode length to be 1 km, which results in $\varepsilon = 0.005$ km. It is difficult to estimate the value of r'_{n1} representing the radius of the electrode n_1 at the moment, when the electrical charge as much as $(Q_p + Q'_L)$ haveing been dissipated. The time length necessary for the dissipation of $(Q_p\ Q'_L)$ may be given by $T_{Ig} = T_{IgL} - T_L = 27 - 14 = 13$ ms in the median value (see Table 14, Section 4 A Chapter II). If we assume the mobilities of ions composing the both spherical charge distributions p, n1 being of the order of 1.0 (cm/sec)/(v/cm), (11) the ions of the both polarities existing in an electrostatic field of the order of 10^4 v/cm can move only 130 cm in 13 ms. Therefore the dissipation of the charge $(Q_p + Q'_L)$ inside the electrode n1 must be performed almost by the movement of the electrons created

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(*) For the case of a negative discharge

$$Q_{n1} = Q_p + Q_L + Q_R$$

For the case of a positive discharge

$$Q_p = Q_{n1} + Q_L + Q_R$$

in it. Comsidering the high mobility of electrons, we may assume the uniform distribution of electricity throughtout the electrode n_1 before and after the dissipation of $(Q_p + Q'_L)$. If this is the cace, the radius r_{n1} of the electrode n_1 will not be changed appreciably before and after the dissipation of $(Q_p + Q'_L)$. So that let us assume $r'_{n1} \doteqdot r_{n1} = 0.111$ km adopting the result given in Section 4 D (a). As to the value $r_{n'}$, this will be given by the following relation

$$r_{n'} = (Q_{n'} / \ 4/3 \ \pi \quad)^{1/3}$$

where and $Q_{n'}$ are the electrical charge density and the total charge inside the electrode n' respectively. The electrical charge density inside a thundercloud cell measured by Ross Gunn using an aircraft gives the value

$$= (1/3) \times 10^{-4} \text{ coul/cc } (12).$$

This value, together with $Q_{n'} = 19.5$ coul represented in Table 5, being put into the above relation will give $r'_n = 0.519$ km. If we put these values thus obtained into the formulae (1), we can obtain the inter-electrode mean electrostatic field intensities, which are represented in the following table.

Inter-electrode mean electrostatic field intensity*	
$E_{n'n1}$	1213 v/cm
E_{n1e}	-1377 v/cm

As the table indicates, the upper-end n_1 of the bridging discharge channel is under the influence of a downward directing self-field. So that the discharge channel, of course, will grow further upwards, if the self field is sufficiently strong. The upward progress of the discharge channel, however, must be stoped, after it has developed some distances because of the influence of the negative electrode n' existing above n_1. In contrast to this, as the lower end of the bridging discharge channel is subjected to an upward electrostatic field, so it is possible that the discharge channel really develops further downwards under the influence of the upward field, provided the field being sufficiently strong. Honda(6) considered that the critical electric field intensity E_m needed to maintain the progress of a streamer in the air under an atmospheric pressure would be $E_m = 5 \times 10^3$ v/cm. This value is about 3.6 time larger

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* The vertical upward direction has been selected as the direction of a negative field.

than $|\bar{E}_{n1e}| = 1.4 \times 10^3$ v/cm, which has been estimated by us concerning a negative ground discharge. In the actual case, however, the L process must be considered really to develop despite of this small $|\bar{E}_{n1}|$ value, so that the reason of this discrepancy must be attributed to the inapplicability of the model of spherical charge distributions to the real electricity distributions relating to a ground discharge. But, so long as we consider the model of spherical charge distributions, the critical mean electric field E_m must be considered not to take a large value like 5×10^3 v/cm, but to take a value given by $|\bar{E}_{n'n1}| < E_m < |\bar{E}_{n1e}|$, i.e.,

$$1213 \text{ v/cm} < E_m < 1377 \text{ v/cm} \qquad (4)$$

Hence the E_m value thus determined must be considered to represent an equivalent critical mean electric field concerning the streamer advance in the above model.
Then if we assume a E_m value satisfying the relation(4), we shall reach the conclusion that the bridging discharge channel leading a negative discharge will not develop its upper end further, but advance its lower end downwards, and the discharge will enter the L discharge.

(b) Positive discharge:

The distribution of electricity just before the start of a L process in the case of a positive discharge has already been illustrated in the Fig. 4 (b). A linear distribution of positive electrical charge n_{1p} is seen to exist between the lower negative charge distribution forming the image of n_{1p} with respect to the earth's surface, and the upper negative charge at n'. If we simply assume that the electrical quantities at p and n_1 of a positive discharges are in a reversed relation to those of a negative discharge, the inter-electrode mean electric field intensitites calculated for a positive discharge will give the relation $|\bar{E}_{pe}| < |\bar{E}_{n'p}.|$ This means that the upper-end of the bridging discharge channel must develope further upwards and the discharge should grow to a cloud discharge. Therefore to prevent an igniting discharge ending itself as a cloud discharge, and to let it to grow to a ground discharge, the altitude Hp of the positive electrode p of a positive ground discharge must be inferred being lower than the Hp of negative ground discharge, so long as the electrical quantities at p and n_1 do not differ so much with each other from a positive ground discharge to a negative ground discharge. For this reason let us assume that the altitude of a negative dipole will be given by $H_p = 1.5$ km, and $H_{n1} = 3.5$ km taking the Table 16 given in Section 4 A, Chapter II into account. Putting Q's and H's values represented in Table 21, Section 5 A, Chapter II and in Table 5, Section 4 D, Chapter III, into the formulae (3), we can get individual H and Q values represented in the following table similar to those described in Paragraph (a). As to the value $r_{n''}$, the same calculation as described in Paragraph (a) gives $r_{n'}$ = 0.453 km.

H_p	H_{nl}	$H_{n'}$	Q'_L	Q'_p	$Q_{n'}$
1.5 km	3.5km	4.5 km	1.5 coul	3.6 coul	13.0 coul

Concerning the value r'_p we shall assume $r'_p = r_p$ as before. But in this case it is not possible to estimate r_p directly, therefore we shall estimate r'_p indirectly. To do this, the value r'_p must be determined so as the E_m value given by the relation (4) simultaneously to satisfy the relation $|\overline{E}_{n'p}| < E_m < |\overline{E}_{pe}|$ with respect to a positive discharge. If we take r'_p to be the only one unknown quantity in the formulae (2) and put the above given numerical values into the formulae, we can obtaine the following relations

$$\left.\begin{array}{ll} \overline{E}_{n'p} & = -(744.1+98.2/r'_p) \\ \overline{E}_{pe} & = 42.8+216/r'_p \end{array}\right\} (5)$$

To determine r'_p so as the $\overline{E}$'s values represented by the formulae (5) to satisfy the relation $|\overline{E}_{n'p}| < E_m < |\overline{E}_{pe}|$, r'_p must satisfy

$$774.1+98.2/r'_p < E_m < 42.8+216/r'_p \qquad (6)$$

Let us seek the r'_p which simultaneously satisfied the both relations (4) and (6), by assuming several values of r'_p. The following table represents $\overline{E}$ values calculated from the formulae (5) for several given values of r'_p.

r'_p	$-E_{n'p}$	
0.14 km	1445 v/cm	< 1585 v/cm
0.15	1399	< 1483
0.16	1358	< 1393
0.17	1322	> 1313
0.18	1290	> 1243

The table clearly indicates the r'_p values that simultaneously satisfies the both relations (4) and (6) is about 0.16 km. Therefore, if we assume r'_p being equal to 0.16 km, $\overline{E}$ values corresponding to this r'_p value will be obtained from the above table as follows:

Inter-electrode mean electrostatic field intensity	
$\overline{E}_{n'p}$	-1358 v/cm
$\overline{E}_{pe}$	1393 v/cm

Therefore the E_m value will be given by the relation $1358 < E_m < 1377$ v/cm resulting from the relations (4) and (6). If the equivalent critical mean electric field E_m of an actual thundercloud has a value given by the above relation, the bridging discharge channel, independent of its polarity, will not develop upward, but grow downward, and transform into a downward stepped leader, which will lead a return stroke, when the electrical charge distribution in a thundercloud would be favorable for the development of a positive ground discharge.

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