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THE MECHANISM OF DISCHARGES IN A THUNDERCLOUD

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CONTENTS

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I. Electric Field Changes Produced by Discharges in a Thundercloud

Abstract -- A cloud discharge usually takes place between the upper positive and the lower negative charged portions of a thundercloud. According to the author's statistical investigations they are located respectively at the altitudes about $7 \sim 11$ and $3 \sim 6$ km, and the mean inclination of the axis connecting them is generally smaller than $30°$. The main process of a cloud discharge involves a branched positive streamer which proceeds downward through the negative charged portion with the velocity of the order of 10^6 cm/sec. When a tip of the slow main process arrives at a local accumulation of negative electricity, a rapid negative streamer with the velocity of the order of 10^8 cm/sec ascends the main channel previously ionized by the slow main process. The rapid streamer processes are repeated more than ten times through the slow process of a cloud discharge, and they each transfer the electricity about 1 coul extending over the distance 1 km on the average.

The intracloud discharge occurring in association with a ground discharge is likewise constructed of a slow positive streamer moving upward and many rapid negative streamers moving downward. The rapid streamer caused by a larger local accumulation of negative electricity may be expected to extend further downward and to reach the ground. This will result in a dart leader guiding the immediatly following return stroke.

1. Introduction

The electric field change produced by a lightning discharge has been measured comprehensively by many research workers using the apparatuses located on the earth's surface till to the present. To know the effective positions respectively of the positive and the negative charged portions of a thundercloud and to know the amount of electricity which is involved in themselves and neutralized by the process of a cloud discharge, it is necessary to make the coincident and absolute measurement of the field changes at least at seven points located on the earth's surface. This sort of an observation was executed first by Workman and his colleagues.(1) The coincident observations at several stations, however, will require a considerable accuracy of time measurement at each station, if the time resolving accuracy needed in the record is comparatively high. In this case the procedure of multipoint observation and the analysis of the observational data will become in any way an uneasy one. In this respect, Workman did not record the fine structure of a lightning discharge. In the present paper the author will make an attempt to interpret the mechanism of a cloud discharge from the statistical investigation of many records of the field changes due to lightning discharges having appeared in a few different ranges of distances.

The apparatus applied to our observation of lightning discharges is capable of recording faithfully the electric field change with the duration ranging from several seconds to nearly 10 μsec. It has been found from the analysis of our data that the electrical process which plays the most important role to neutralize the cloud electricity is composed of a slow positive streamer with the velocity of the order of 10^6 cm/sec and that the slow streamer usually accompanies many rapid negative streamers with the velocity of the order of 10^8 cm/sec. The rapid streamers, however, transfer each a comparatively small amount of electricity.

2. Observation method

Two observation systems have been employed to record the field changes of two different time rates. The one is to record the electrostatic field changes whose frequency spectrum chiefly spreads from 0 c/sec to 1 kc/sec. The other is to record the frequency spectrum range spreading from 200 c/sec to 100 kc/sec. In the latter case the predominant slow component of the field change is inevitably cut off and only the rapid component becomes to be emphasized. Our thunderstorm observations were carried out in every summer season from 1952 to 1960 at Maebashi, north-west and about 100 km from Tokyo.

The apparatus was annually modified and supplemented. (2)(3) A brief description of the apparatus in the present stage will be given at this place. Fig. 1 shows the general construction.

A) Recording of the rapidly changing electric field

A vertical antenna is adopted to catch up the rapid electric field changes. An alminium ball of 80 mm in diameter is installed on the top of the antenna to protect it from point discharges resulting from a very strong electric field.

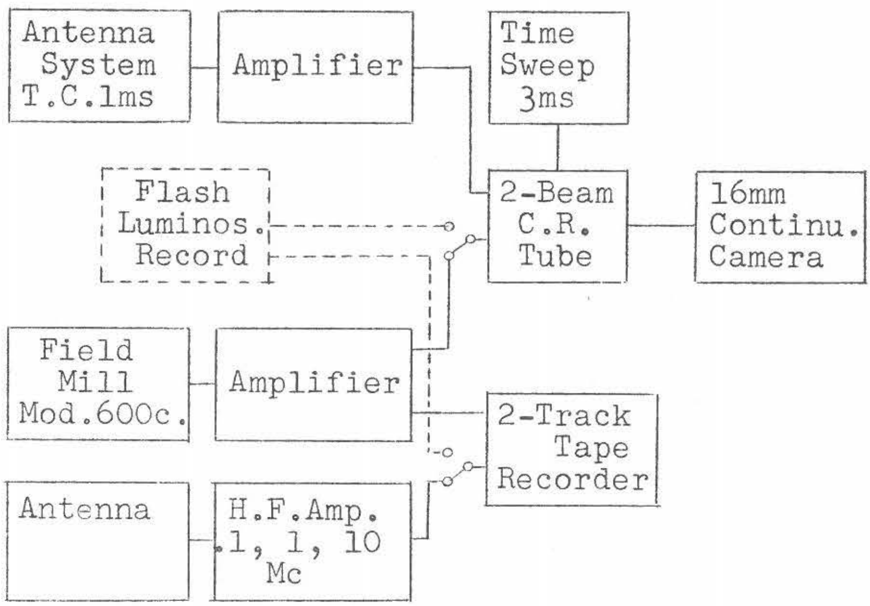

Fig. 1. The construction of the electric field change recorder.

Since the vertical antenna is almost capacitive in the frequency range up to 100 kc, the gain of the antenna system is determined by the ratio of the self capacity of antenna to the earth capacity. The self capacity of the antenna is 40 pF in this apparatus, and the earth capacity is designed to be selected out of the five element capacitors by a telephone dial and relays. As the five capacitor elements have the values 0.001, 0.003, 0.01, 0.03 and 0.1 μF respectively, the gain of the antenna system can be varied in 10 db step from about -28 db to -68 db. Resistors connected in parallel to the earth capacitors are also selected out of the values from 10 k-ohms to 1 M-ohms, through which the time constant of the antenna system can be kept at a constant value 1 msec at every adjustable gain. The antenna coupling part contains a cathode follower, the output from which is fed to the main amplifier arranged inside the observation room through a feeder of 20 m in length. The main amplifier is of a flat response capable of reproducing correctly the antenna input.

The recorder is constructed of a dual beam cathode ray tube and a continuously running 16 mm cine camera. The time axis of the record is constructed from two different relative motions of the bright spot on the C.R.T. screen to 16 mm cine film, i.e., the vertical sweep of the bright spot produced on the C.R.T. screen by a repeated saw-tooth waveform voltage and the horizontal continuous movement of 16 mm cine film. The time resolving power is affected by the sweep velocity and is about 30 μsec when we use the time sweep of 3 msec. As the film speed is about 10 cm/sec, the cine film of 100 feet in length mounted on a reel will be consumed in about 5 min continuously. As it is very expensive to record continuously the whole period of a thunderstorm, the recordings were made interruptedly with appropriate intervals throughout the activity of a thundercloud. We have obtained the records of 8800 feet under 17 thunderstorms in five summers from 1956 to 1960. The number of continuous recordings per one storm is about 5 on the average.

The other element of the dual beam C.R.T. is utilized to record simultaneously the flash luminosity changes caught with a photo-multiplier tube or the electrostatic field changes which will be described in the following paragraph B).

B) Recording of the electrostatic field change

To record the electrostatic field change due to a lightning discharge we adopted an equipment of a so-called mill type field meter. This is constructed from the same principle as the electrostatic flux meter developed by Malan and Schonland.(4) By rotating an earthed disk with many holes disposed on a circular periphery at equal intervals, the terminals in the similar disposition to the holes are alternately exposed to and shielded from an external electrostatic field, and then the alternative voltage proportional to the external field is produced between both ends of the earthed resistance. Since the equipment has 24 holes and terminals and the disk rotates at the speed of 1500 rpm, the output will be amplitude-modulated with 600 c/sec. The time resolving power is therefore about 2 msec. The determination of the polarity of the field changes can be made through the output from a synchronous detection circuit employing the photoelectric method,(3) or the systematic deformation in the modulated output waveform which has a very close relation to the polarity of the electrostatic field to be measured.

The electrostatic field changes are recorded on a track of a double track magnetic tape recorder. The other track is used to obtain the simultaneous record of the flash luminosity changes or the high frequency radio noises radiated from lightning discharges. The electrostatic field changes are also recorded together with the rapidly changing electric field in a 16 mm cine film driven continuously, but in this case the time sweep is not added on to the modulated electrostatic field output, because it does not promote the time resolving power in any amount.

In the season of thunderstorm observation in 1960, we adopted the field change oscillogram equipped with a vertical antenna which had a large time constant of the order of 1 sec. This apparatus also follows after the same principle that has been described in the paragraph A), and the principal differences between the two consist in the antenna time constant and the amplitude modulation of the output. To record the output from the antenna on a magnetic tape, the output of the gradual electrostatic variation is needed to be modulated with some appropriate procedure. Since the duration of a lightning discharge usually does not exceed 1 sec, the record obtained with this apparatus will give a representation of an actual field change without any serious error.

3. Types of the observed electrostatic field changes

On the record of electrostatic field change due to a ground discharge, we can always recognize some rapid stepwise field changes with the duration of the order of 100 μsec to appear intermittently, and it is not always difficult to see these stepwise field changes each to correspond to the rapid and large amount of charge transfer resulting from the individual return stroke. It is also not seldom that a long spark which bridges two separate thunderclouds actually produces a stepwise field change with the duration of the order of 1000 μsec. In the case of intracloud discharges which occupy the greater part of actually occurring lightning discharges, however, we can not usually recognize this kind of stepwise field changes on the record of their field changes, which always indicate only slow smooth variations.(5) These observational facts clearly indicate that the main process to neutralize the thundercloud electricity is nothing but a slow process of discharge with an effective velocity of progression of the order of 10^6 cm/sec.

The electrostatic field changes produced by cloud discharges can be divided into the following 5 types, if we neglect relatively small variations as well as stepwise field changes which probably correspond to the rapid and large strokes bridging across the intercloud spaces.

i) + type: the electrostatic field change indicates only a simple increase.

ii) - type: the electrostatic field change indicates only a simple decrease.

iii) +→- type: the electrostatic field change indicates a maximum.

iv) −→+ type: the electrostatic field change indicates a minimum.

v) complex type: the electrostatic field change indicates a maximum and a minimum.

The above denomination follows after the sign of the differential coefficient of the time variation of the electrostatic fields. In the cases of iii), iv) and v), each is subdivided into two cases according to the sign of the net field change, the point of which is indicated by parentheses as shown in Table 1. So far as our investigation is concerned, all complex type field changes are of the −→+→− type, in which a minimum precedes a maximum on the field change.*

Table 1. Occurrence percentages of the five types of electrostatic field changes due to cloud discharges.

Distance (km)	Type								Number of data
	+	−	+→− (+)	+→− (−)	−→+ (+)	−→+ (−)	−→+→− (+)	−→+→− (−)	
0 − 5	77		14	9				%	44
5 − 10	53	3	20	18	2	1	2	1	106
10 − 15	13	38	7	23	9	6	1	3	143
15 − 25		84		4	4	8			25

Table 1 shows the percentage of occurrence of each type in the four ranges of propagation distances. This is the summarized results of 10 thunderstorms recorded through the summers from 1958 to 1960. The horizontal distance from a lightning discharge to the observation station has been estimated from the lightning-thunder time interval, the structure and the amplitude of the rapid electric field change, or the thunderstorm map kindly submitted from the meteorological agency. The table, however, really includes the small number of data whose estimated distances are probably too rough to withstand the following discussions. Nevertheless this defect will not lead to a serious error, so far as we investigate the results statistically.

* There is no obvious basis in deciding how small variations may be neglected. If the smaller variations, which have been neglected in Table 1 from case to case according to their magnitudes and durations, are further taken into account to some extent, the occurrence percentage of the complex type will be increased more than what is indicated in the table. And in this case the +→−→+ type or the other types indicating several extreme values will be included in the complex type.

4. Altitude and inclination of a cloud discharge and net electrostatic field change

The positive and the negative electricities neutralized by a cloud discharge perhaps occupy the considerably large portions of a thundercloud respectively. However, it is a well known fact that the earth's electrostatic field change due to a lightning discharge inside a thundercloud can be interpreted, as the first approximation, from the mechanism of a dipole discharge appearing in the cloud. Let us denote the positions of the respective charge centers with P and N and put the coordinate origin at the point where the axial line of the dipole PN intersects the earth's surface. The distances to P and N from the origin will be denoted with s_1 and s_2 respectively, and the inclination of PN relative to the vertical line will be denoted with θ ($0 \leqq \theta \leqq \pi/2$). Then the altitudes of the points P and N will be given by $h_1 = s_1 \cos\theta$ and $h_2 = s_2 \cos\theta$ respectively. Let us denote the position of the observation point with (ρ, ϕ) in the polar coordinates expression, where ρ is the distance of the point from the origin and ϕ is the azimuthal angle from the horizontal projection of the line PN. The two point charges Q and $-Q$, respectively located at the points P and N, will produce the following electrostatic fields at the observation point respectively:

$$F_P = 2Q s_1 \cos\theta / (\rho^2 - 2\rho s_1 \sin\theta\cos\phi + s_1^2)^{3/2} ,$$
$$F_N = -2Q s_2 \cos\theta / (\rho^2 - 2\rho s_2 \sin\theta\cos\phi + s_2^2)^{3/2} . \tag{1}$$

Since the electrostatic field composed of F_P and F_N will disappear by a lightning discharge, the net field change must be represented by

$$F = -(F_P + F_N) . \tag{2}$$

The sign of the net field change will be reversed if the observation point is moved across the locus of $F = 0$, which may be transformed as follows,

$$\rho^2 + 2a\rho\tan\theta\cos\phi - b^2\mathrm{sce}^2\theta = 0, \qquad (3)$$

where $a = h_1^{2/3} h_2^{2/3} (h_1^{1/3} + h_2^{1/3})^{-1}$, $b = h_1^{1/3} h_2^{1/3} (h_1^{2/3} + h_2^{2/3})^{1/2}$.

This equation gives the expression of a circle, whose center is given by $(a.\tan\theta, \pi)$ and the radius is given by $\{b^2 + (a^2+b^2)\tan^2\theta\}^{1/2}$.

According as the observation point is located inside or outside the circle, the sign of the net field change produced by the lightning discharge will be reversed. Thus the circle will be designated as a reversal circle hereafter. If P is located at an altitude higher than N, i.e., if the dipole polarity is positive, the conclusion will be $F>0$ in the circle and $F<0$ out of it. When Table 1 is rearranged in accordance with the sign of the net field change, Table 2 will be obtained. Table 2 shows the point that the net field changes are usually positive when they are measured in the neighbourhood of lightning discharges and become negative when the distances are increased. Therefore it is evident that a cloud discharge generally can be represented by the disappearance of a positive dipole located in a thundercloud, i.e., a dipole composed of a positive charge in the upper portion of the cloud and a negative charge in the lower portion of it. This polarity of a lightning dipole is in accord with the polarities observed in various parts of the world. (1,6,7,8)

Table 2 . Occurrence percentages of positive and negative net field changes produced by cloud discharges

Distance (km)	Net field change +	Net field change −	Number of data
0 − 5	91	9%	44
5 − 10	77	23	106
10 − 15	30	70	143
15 − 25	4	96	25

If the dipole axis PN were perfectly vertical and the altitudes of P and N were both constant, the reversal distance of the sign of net field change would be the same for all discharges, and the range of distances which contained both positive and negative net field changes in Table 2 would be limited to the only one range including the reversal distance. Table 2 shows, however, all ranges contain the both signs although the degrees of mixing are different from a range to another. This may not be explained unless we take account of the dispersion in the altitudes of both point charges or the inclinations of PN axes, although the existence of a small number of negative dipole discharges is quite expected. Because of the minority of negative dipoles, however, it is quite natural that the observed occurrence percentages of positive and negative net field changes will give us some knowledges about the dispersion in the altitude values and the inclinations of the observed dipoles.

A) Altitude

If all the dipoles observed have a common vertical direction and the positive polarity, the dispersion in the altitudes of dipoles necessary to explain the values given in Table 2 will be as follows.

The center of the reversal circle is of course placed just under the points P and N in this case, and the radius of it is given by b in equation(3). Statistically speaking, the probability distribution of the values b must reach a maximum at a certain b value and decrease to both sides of the maximum. However, for the sake of brevity it will be assumed here that the distribution of b values is constant (not zero) between b_1 and b_2 ($b_1 > b_2$) and equal to zero outside this section. Then the probability that the observation point located at the horizontal distance r from the discharge will be included in the reversal circle, i.e., the observed net field change will be positive, can be represented as follows.

$$p = 1 \qquad r \leqq b_2$$
$$p = (b_1 - r) / (b_1 - b_2) \qquad b_2 < r < b_1 \qquad (4)$$
$$p = 0 \qquad r \geqq b_1$$

If we follow what Table 2 indicates, it will be reasonable to assume that the probability p will take a value between 0.77 and 0.91 at r = 5 km, and a value between 0.30 and 0.77 at r = 10 km, and a value between 0.04 and 0.30 at r = 15 km respectively. Therefore the b values to satisfy the conditions given by equation (4) may be estimated to have the values b_1 = 18 km and b_2 = 3km respectively. If we assume the relation $h_1/h_2=2$, the results will be given by $h_1 = 3\sim18$ km and $h_2 = 1.5\sim9$ km. These distribution ranges of the positive and the negative point charges are somewhat too broad to be compared with our knowledges about the electrical structure of a thundercloud. This seems to indicate the point that the inclination of the dipole to the vertical line must be taken into account.

B) Inclination of dipole

In the case of an inclined dipole discharge, the center of the reversal circle does not coincide with the point located just beneath the point P or N. When the value of θ or h_1/h_2 exceeds a certain limit, the point just beneath the point P or, according to circumstances, even the point just beneath any point on the line PN will be placed outside the reversal circle.*

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* For instance, if $h_1/h_2 = 2$, the point just beneath P will be displaced out of the reversal circle for $\theta > 51°$, and the point just beneath the center of PN will also be displaced out of the circle for $\theta > 76°$. However, the point just beneath the point N is always included in the circle.

Therefore, it will not always be rigorous to represent the horizontal distance between the discharge and the observation point with ρ given in equation (3), and the more reasonable way to define the position of the dipole discharge to have a considerable extent is to fix the center of the dipole PN.* For this purpose let us displace the coordinate origin to the point just beneath the dipole discharge, then the reversal circle will become to be represented as follows:

$$r^2 + 2r\ (a+c)\ \tan\theta\cos\psi - b^2 + \{c\ (2a+c) - b^2\}\tan^2\theta = 0, \qquad (5)$$

where c is the altitude of a dipole discharge,

$$c = (h_1 + h_2)/2,$$

and (r, ψ) is the position of the observation point represented with the new coordinates.
Let us introduce here the quantity k defined by the following equation:

$$k = \frac{-r^2 + b^2 - \{c\ (2a+c) - b^2\}\tan^2\theta}{2r\ (a+c)\ \tan\theta} \qquad (6)$$

If the values of h_1, h_2 and θ are given, the quantity k becomes a function of r. Taking these two equations into account, it is easy to arrive at the following results: If $k > 1$, the observation point, the distance r apart from a dipole discharge, will always be included in the related reversal circle, while if $k < -1$, it will always be excluded from the circle. If $-1 < k < 1$, the situation depends on the value of ψ as follows; if $k > \cos\psi$, the observation point comes into the reversal circle, and if $k < \cos\psi$, it goes out of the circle. Fig. 2 illustrates the above relation with respect to the values θ and r.

* If the value h_1/h_2 is in any way not so large, it will become unimportant which point on the line connecting P and N is regarded as the indication of the position of a dipole.

The two boundary distances r_1 and $r_2(r_1 > r_2)$, between which both signs of net field changes can be observed, are determined from the following equations:

$$k(r_2) = 1, \quad \text{and} \quad k(r_1) = -1.* \qquad (7)$$

If we limit our observation to a fractional period of a thunderstorm, the locations of the individual dipoles, i.e., the positions of P's and N's will be comparatively definite in a thundercloud. However, if the occurrence rate of lightning discharges is averaged between the sufficient number of thunderstorms, it will be probable that the azimuth of a

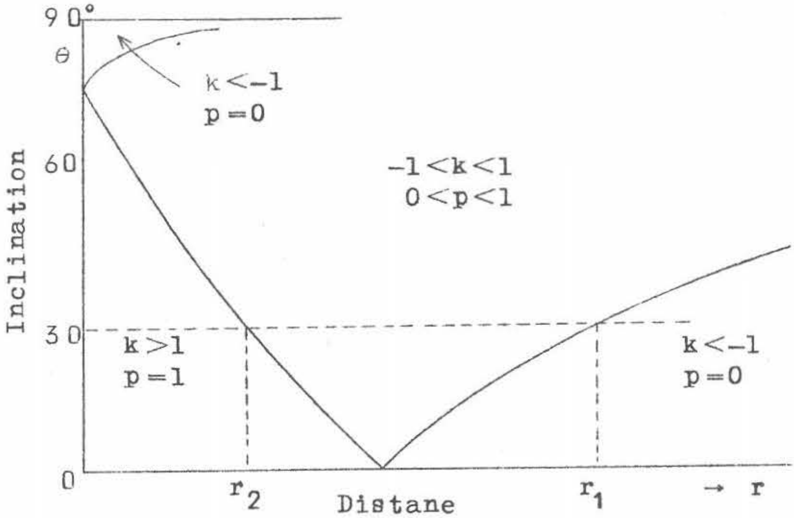

Fig. 2. The axial inclination of a discharge dipole and the ranges of distances divided in accordance with characteristics of the net field changes.

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* If $\tan^2\theta > b^2 / \{c(2a+c) - b^2\}$, then $k<1$ is always satisfied irrespective of the r value, and the point just beneath the center of PN is placed outside the reversal circle. In this case, r_1 and r_2 are given by the two roots of the equation $k(r) = -1$, in which the roots are both positive.

discharged dipole axis relative to the direction toward the observation point, in other words, the azimuth ψ of the observation point relative to the horizontal projection of the diple axis takes any value with an equal probability. In this case, we can consider the probability that the observation point is included in the reversal circle, i.e., the net field change is of the same polarity as that of the dipole , for any given value r. This probability can be given by the following relations.

$$\begin{aligned} p &= 1 && k \geqq 1 \\ p &= 1 - (\cos^{-1} k)/\pi && -1 < k < 1 \\ p &= 0 && k \leqq -1 \end{aligned} \tag{8}$$

We can determine statistically the occurrence rate of the field changes which indicate the same sign as that of the discharged dipoles. If the dipoles are assumed to be distributed only in narrow ranges of h and θ values, it becomes possible to infer the respective values of h and θ.

The extents of probable p values at the distances 5, 10 and 15 km from the dipoles have already been estimated from Table 2 in the previous paragraph. Fig. 3 shows the result of the h and θ value estimation which has been obtained from equations (6) and (8). The hatched area represents the portion which satisfy the conditions. The curves which define this area are somewhat variable with the h_1/h_2 value. Fig. 3 shows the case of $h_1/h_2 = 1$. In this case, equation (6) will take the somewhat simpler expression as follows:

$$k = (2h^2 - r^2) / 3hr \,.\, \tan\theta \ . \tag{9}$$

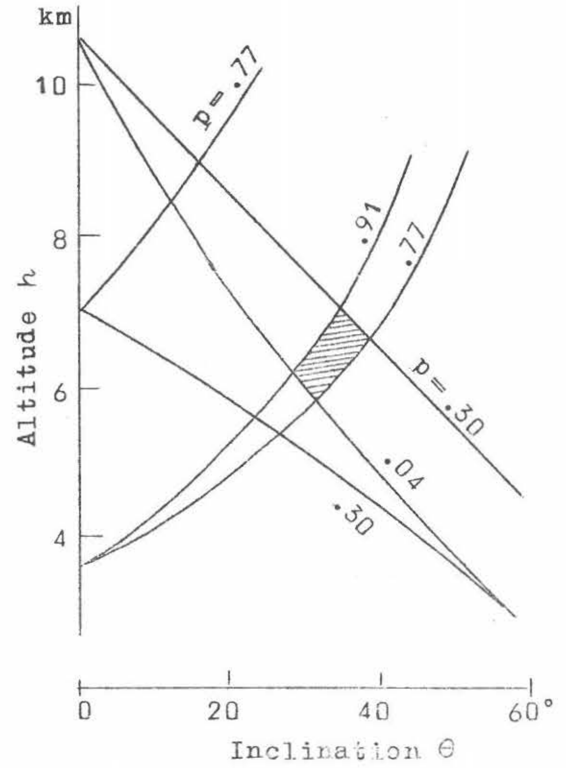

Fig. 3. The average altitude and the axial inclination of a discharge dipole in a thundercloud. The hatched area satisfies the conditions assigned from the observed occurrence rates of positive and negative field changes.

The area will be displaced only a few hundred meters toward the lower level and very slightly moved to the direction of θ, even if we increase the h_1/h_2 value from 1 to 2. Therefore it is evident that the value h_1/h_2 will not have an important role in fixing the above area, if we take the accuracy in the estimation of the distance r into account. The area covers the ranges of h and θ values $6 \sim 7$ km and $30 \sim 40°$ respectively. It is evident that the errors in the estimation of distances in Table 1 will broaden the extent of the p value distribution, and that the area which satisfies the above conditions will also be extended. However, the central portion of the area itself will not be displaced appreciably from the position just described.

The estimation of θ so far has been made on the assumptions that h and θ can be regarded as constant in all discharges and that ψ takes any value with an equal probability. In an actual case, however, h and θ will be subjected to considerable fluctuations, and this will make the distance range which mixes both signs to broaden considerably. This leads to the result that the actual occurrence percentages of the opposite sign field changes will approach nearer to each other in a related range of distances than they would be subjected to when the values h and θ would be constant. Therefore, if the discharge dipoles are distributed in limited narrow ranges of h and θ values surrounding their average values, the difference between the occurrence percentage values of the opposite signs will become more considerable than what is indicated in Table 2. In this case, all the curves illustrated in Fig. 3 will be moved more or less toward the smaller value direction of θ. Therefore the conclusion is that the estimated value θ, using Table 2 and equations (6) and (8), is in any way not larger than the average of the actual inclinations of the dipoles.

Since the accuracy of the estimations of the distances r is by no means so high, the value θ obtained from the above discussion is of course not highly reliable. Nevertheless there seems some contradictory to exist between the value less than 30~40° obtained by the author and the value reported by Workman and his colleagues.(1) According to their report the horizontal separation of a discharge dipole is statistically a few times larger than the vertical separation of it. However, they estimated this value once more afterwards(9) and derived the value about 25° which agreed fairly well with our expectation.

5. Movement of electric charges contributing to a lightning discharge and types of electrostatic field changes

The waveform of an electrostatic field change represents the process of a neutralization of electricity, i.e., the process of a lightning discharge. Let us first assume a simple model of dipole discharge, in which the process is completed by a streamer advancing from either of the two poles to the other pole. So far as the electrostatic field change due to a dipole discharge is concerned, the above simple streamer process of a discharge can be replaced by a movement of either of the two point charges toward the other of the dipole. We shall limit our discussion only to the case of positive dipole hereafter.

A) Discharge produced by a descending positive point charge.

As the negative point charge composing the lower pole of a dipole does not move in this case, the electrostatic field change due to this process of a discharge must thoroughly result from the movement of the positive point charge to descend from s_1 to s_2. If the time t is measured from the moment of start of the point charge movement, and if the position of the positive point charge P at the time t is denoted with s, the electrostatic field produced by the positive charge Q at the time t will be

$$F_P(s) = 2Qs\cdot\cos\theta / (\rho^2 - 2\rho s\cdot\sin\theta\cos\phi + s^2)^{3/2}, \qquad (10)$$

where we use the same notation as that of the previous section. The net field change at this moment will be

$$F(s) = F_P(s) - F_P(s_1) . \tag{11}$$

Let us assume at first the positive point charge P to move along the initial dipole axis with a constant velocity v. Then the position of P is given by

$$s = s_1 - vt. \tag{12}$$

Hence the time differential of the electrostatic field produced in this case is as follows.

$$dF/dt = dF_p(s)/ds \cdot ds/dt$$
$$= \frac{-2Qv \cdot \cos\theta\,(\rho^2 + \rho s \cdot \sin\theta\cos\phi - 2s^2)}{(\rho^2 - 2\rho s \cdot \sin\theta\cos\phi + s^2)^{5/2}} \tag{13}$$

We shall introduce here the value s_0 defined from the following equation.

$$\rho^2 + \rho s_0 \sin\theta\cos\phi - 2s_0^2 = 0 \tag{14}$$

Here the value s_0 represents the position of the positive point charge P, where the charge P affects the strongest field onto the observation point throughout its advancement. This can clearly be seen in the following relations:

$dF/dt = 0 \quad s = s_0, \; dF/dt > 0 \quad s > s_0,$

$dF/dt < 0 \quad s < s_0 .$

The position represented by s_0 will often be called hereafter as the transition point on a dipole axis. In accordance with the value s_0 relative to the values s_1 and s_2, the following three types of field changes will be produced.

i) If $s_1 > s_2 > s_0$, it follows $dF/dt > 0$ and the field F falls into the + type.

ii) If $s_1 > s_0 > s_2$, it follows $dF/dt > 0$ for the variable s to change from s_1 to s_0, and $dF/dt < 0$ for the variable s to change from s_0 to s_2, and so F falls into the $+ \rightarrow -$ type.

iii) If $s_0 > s_1 > s_2$, it follows $dF/dt < 0$ and F falls into the - type.

The position of the transition point s_0 thoroughly depends on the position of the observation point, in other words, the position of the observation point which gives a constant s_0 value can be fixed by **equation** (14) for each discharge. Equation (14) also represents a circle with the radius $s_0(2+\sin^2\theta/4)^{1/2}$, whose center is located at $(s_0 \sin\theta/2\pi)$.

If the observation point is located within a region limited between the two critical circles which will be obtained by putting $s_0 = s_1$ and $s_0 = s_2$ into equation (14), the value s_0 which can be fixed from the position of the observation point will take a value between s_1 and s_2. In this case the field change will fall into the $+ \rightarrow -$ type. The reversal circle given by equation (3) must of course take a position between these two critical circles above described and does not cross with them. An example of the circle is illustrated in Fig. 4. The field changes observed in the four regions limited by these three circles fall respectively into the +, $+ \rightarrow -(+)$, $+ \rightarrow -(-)$ and - types from inside to outside.

B) Discharge produced by an ascending negative point charge.

In this case we assume that the negative charge will advance from s_2 to s_1 and that the positive charge will not move. If the position of the negative point charge is represented with s at the time t, then it follows

$$F_N(s) = -2Qs\cdot\cos\theta/(\rho^2 - 2\rho s\cdot\sin\theta\cos\phi + s^2)^{3/2}, \tag{15}$$

$$F(s) = F_N(s) - F_N(s_2), \tag{16}$$

and

$$s = s_2 + vt. \tag{17}$$

Hence dF/dt in this case is given in the very same expression as equation (13). If the position s_0 is given by the same equation (14), the following three types are to be produced according as s_1 and s_2 are larger or smaller than s_0.

i) If $s_1 > s_2 > s_0$, it follows $dF/dt > 0$, and F falls into the + type.

ii) If $s_1 > s_0 > s_2$, it follows $dF/dt < 0$ for the variable **s** to change from s_2 to s_0, and $dF/dt > 0$ for the variable s to change from s_0 to s_1, and so in this case F falls into the $- \rightarrow +$ type.

iii) If $s_0 > s_1 > s_2$, it follows $dF/dt < 0$, and F falls into the - type.

Although the area is divided into the four regions similar to the case A) shown in Fig. 4, the types of field changes observed in the respective regions are respectively the +, $- \rightarrow +(+)$, $- \rightarrow +(-)$, and - types from the inside to the outside regions in this case.

Table 3. Occurrence percentages of the two transitional types.

Distance (Km)	Type $+ \rightarrow -$	$- \rightarrow +$	Number of data
0 - 5	100	0 %	10
5 - 10	93	7	43
10 - 15	67	33	66
15 - 25	25	75	4
Total	77	23 %	123

As it is expected from the above two cases, the rates of occurrence of the simple field change types, i.e., + and - types, are seen being relatively low in the intermediate range of distances in Table 1. As to the transitional types of field changes which are found in the regions II and III in Fig. 4, it is easy to see that the field change with a maximum, i.e., the $+ \rightarrow -$ type, must be produced by the movement of a positive electric charge, while

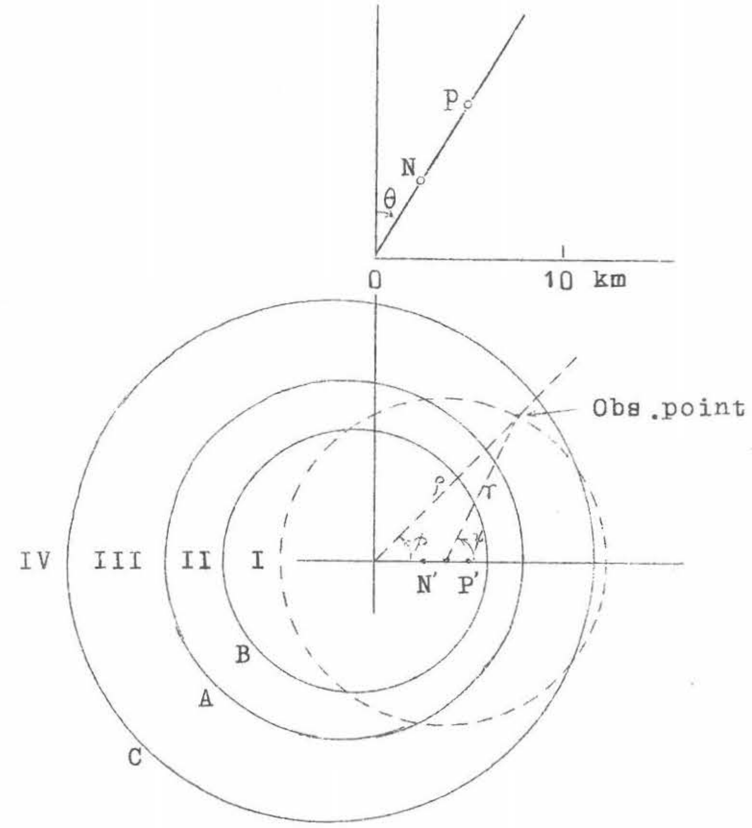

Fig. 4. An example of reversal and critical circles. The altitudes of P and N are 8 and 4 km respectively, and the inclination of PN is 30°.

A. Reversal circle.

B. Inner critical circle.

C. Outer critical circle.

the field change with a minimum, i.e., the $- \rightarrow +$ type, must be produced by the movement of a negative electric charge. The situation would not be changed, if the polarity of a dipole was reversed. Therefore, the occurrence rates of the two transitional types of field changes, the $+ \rightarrow -$ type and the $- \rightarrow +$ type, must give the information about the polarity of the moved electric charge. Table 3 shows the respective rates of occurrences of the two transitional types. It is clear from the table that the $+ \rightarrow -$ type generally predominates over the $- \rightarrow +$ type, and particularly in the vicinity of lightning discharges, almost all of the transitional type field changes are of the $+ \rightarrow -$ type. Thus the cloud discharge generally must be represented by a discharge process developed by a positive streamer descending from the upper positive charged portion to the lower negative portion of a thundercloud. This is somewhat contrary to the result obtained by Smith(6), who reported that a considerable part of positive dipole discharges in thunderclouds were produced by the ascending movement of a negative charge. Concerning this point, the occurrence rate of the $- \rightarrow +$ type, however, increases with the increase in the distances, although the reliability of the rate values in the ranges of distances $0 \sim 5$ and $15 \sim 25$ km is of course not high enough because of the shortage in the number of data in these ranges. If we may neglect these defects resulting from the shortage of the data, it will be somewhat questionable to conclude simply from the measured values of total occurrence rate of transitional type fields that about 3/4 of cloud discharges are produced by the downward development of a positive streamer, and that the rest 1/4 by the upward movement of a negative streamer.

One of the possible interpretations of the statistical character of the transitional type of field changes with the distances will be given as follows: a cloud discharge generally does not always take place between two opposing charge centers forming a dipole, but often between three or four opposing charge centers successively, in other words, two dipoles discharging succesively.

For example, if a cloud discharge is initiated with the breakdown of a positive dipole and followed by that of a negative dipole, then the $+\rightarrow-$ type will be observed in the short range of distances, while the $-\rightarrow+$ type will be observed in the long range of distances. If the greater part of actual cloud discharges have the structure of this kind of dual dipole, the statistical character shown in Table 3 will sufficiently be interpreted. In this interpretation, however, the subsequent negative dipole discharge must be considered being comparatively small in its scale and perhaps of a secondary meaning in contrast to the first positive dipole discharge, for the simple type of field changes clearly predominates over the transitional type in the near as well as distant ranges.

Another more probable interpretation of the statistical character given in Table 3 will be to consider the movements of the two opposite sign point charges simultaneously occurring in the reversed directions to each other. In this case the predominance of the $+\rightarrow-$ type in the short distances will be interpreted by the assumption that a considerable difference in the altitudes exists between the two streamer processes developed in the reversed directions, i.e., the assumption that the altitude of the moving positive point charge is considerably lower than that of the moving negative point charge. The field change due to a cloud discharge in the shorter distance will principally be influenced by the movement of a positive point charge representing the positive downward streamer located at a lower altitude, while in the longer distance, it will become to be influenced by the movement of a negative point charge representing the negative upward streamer located at a higher altitude as well as by the former. Therefore the field changes of this kind will be interpreted also from a discharge process composed of a mid-gap streamer as observed in the laboratory experiment of a spark discharge.(10) Generally a cloud discharge will be initiated at first in the neighbourhood of the boundary layer where the electric field is the strongest in the space between the two opposite poles of a discharge dipole. And the streamer thus initiated will probably advance to the upward as well as downward direction simultaneously, where the upward negative streamer will neutralize the positive electricity distributed in the upper portion of a thundercloud, and the downward positive streamer will neutralize the negative electricity in the lower portion of it. The process of a mid-gap streamer can be approximated by a positive and a negative point charge to start simultaneously in the reversed directions from a point s_3 located on the straight line connecting the two charge centers s_1 and s_2. The field change due to this mid-gap streamer model will be given in the following paragraph.

C) Discharge produced by the simultaneous movements of a positive point charge descending from s_3 to s_2 and a negative point charge ascending from s_3 to s_1.

i) $s_1 > s_3 > s_2 > s_0$: F_P and F_N are both the + type, so the resultant F falls into the + type.

ii) $s_1 > s_3 > s_0 > s_2$: F_P is the $+ \rightarrow -$ type and F_N is the + type, so the resultant F falls into one of the +, $+ \rightarrow -$, and $+ \rightarrow - \rightarrow +$ types.

iii) $s_1 > s_0 > s_3 > s_2$: F_P is the - type and F_N is the $- \rightarrow +$ type, so the resultant F falls into one of the -, $- \rightarrow +$, and $- \rightarrow + \rightarrow -$ types.

iv) $s_0 > s_1 > s_3 > s_2$: F_P and F_N are both the - type, so the resultant F falls into the - type.

The transition from i) toward iv) is seen to correspond to the increase of the distance between the discharge and the observation point, for if the distance increases, generally the value s_0 will increase at the same time. The cases i) and iv) actually correspond to the regions I and IV given in Fig. 4 respectively, and give the same result that we have already obtained through the discussion of the paragraphs A) and B). However, in the transitional cases ii) and iii), it is in any way not easy to see which type could interpret the actual field change, for the field change types in these cases vary their characters in a considerably complicated manner in accordance with the duration, velocity and direction of the movement of each point charge representing a streamer. Nevertheless, Table 1 shows that the $-\rightarrow+$ type, the minor group of the transitional types, accompanies a small number of the $-\rightarrow+\rightarrow-$ type field changes which may be interpreted as to represent the influence of F_P included in the case iii), while the $+\rightarrow-$ type, the major group, does not accompany even a small number of the $+\rightarrow-\rightarrow+$ type field changes which represent the influence of F_N included in the case ii). Thus it may be concluded that the negative slow process generally has only a secondary importance in the actual contribution to the neutralization of the thundercloud electricity.

Values of h_1, θ and h_2, θ can be estimated respectively with respect to the outer and the inner critical circles by employing the similar procedure through which values of h, θ have been estimated with respect to the reversal circle. In the cases A) and B) the inner critical circle separates the region corresponding to the + type from those of the other types, and likewise the outer critical circle separates the region representing the - type from those of the other types. In the case of the paragraph C) the relative positions of the two boundaries to distinguish the field change types may more or less approach nearer to each other, despite this we shall limit here our considerations to the cases A) and B) tentatively. If we consider a cloud discharge appearing at the distance r from the observation station, the probability p_2 that the station is included inside the inner critical circle, or in the other expression, the probability that the field change due to the discharge is of the + type will be represented as follows:

$$p_2 = 1, \qquad k_2 \geqq 1$$
$$p_2 = 1 - \cos^{-1}k_2/\pi , \quad -1 < k_2 < 1 \qquad (18)$$
$$p_2 = 0, \qquad k_2 \leqq -1$$

where $k_2 = (2h_2^2 - r^2)/3rh_2\tan\theta$.* The curves in solid lines shown in Fig. 5 represent the conditions imposed upon h_2 and θ to satisfy the following values estimated from Table 1.

$p_2 = 0.53 \sim 0.77$ at $r = 5$ km,
$p_2 = 0.18 \sim 0.53$ at $r = 10$ km and
$p_2 = 0$** at $r = 15$ km.

The probability p_1 that the observation station is included in the outer critical circle, or in the other expression, that the field change is of the types other than the - type will be represented as follows:

$$p_1 = 1, \qquad k_1 \geqq 1$$
$$p_1 = 1 - \cos^{-1}k_1/\pi , \quad -1 < k_1 < 1 \qquad (19)$$

---

* The quantity k_2 corresponds to the case where the observation point takes any location on the earth's surface with equal probability around the horizontal projection of the negative charge center N, and does not represent the case where the observation point takes any position on the same plane with equal probability around the horizontal projection of the center of the dipole PN. In the latter case k_2 will be represented as follows:

$$k_2 = \{2h_2^2 - r^2 - (h_1 - h_2)\ (h_1 + 5h_2)\ \tan^2\theta/4\}/r\ (h_1 + 2h_2)\tan\theta .$$

But the difference between these two is generally a trivial one.

** Table 1 indicates that if $r = 15$ km the observation point will always excluded from the inner critical circle irrespective of the position of the observation point relative to individual cloud discharges. So the p_2 value in this case should not be equal to $0 \sim 0.18$ but equal to 0.

$p_1 = 0, \qquad k_1 \leq -1$

where $k_1 = (2h_1^2 - r^2)/3rh_1\tan\theta$. Values of p_1 estimated from Table 1 are as follows in this case:

$p_1 = 1$ at $r = 5$ km, $p_1 = 0.68 \sim 0.97$ at $r = 10$ km and $p_1 = 0.16 \sim 0.68$ at $r = 15$ km.

The domain which satisfies these conditions is indicated with the curves in broken lines given in Fig. 5. We can estimate from the figure the altitudes h_1, h_2 respectively of the positive and the negative point charge centers P and N, which give the values no less than 8 km for h_1 and $3.5 \sim 6$ km for h_2. For a more accurate estimation of these altitudes, especially for h_1 value, it is needed to improve the measuring accuracy of discharge distances especially in the long range of distances. In the case C), the positions of both charge centers may be more separate from each other than the cases A) and B). Especially it seems probable for the value h_1 to increase in this case, for the influence of F_N on the resultant field change F is actually only a small one. But we have found that the cloud discharges producing the transitional type fields statistically have about 30 % longer durations than the discharges producing the simple type fields represented in the median values,(11) and this may reversely reduce the average separation between the two opposite point charge centers. As a conclusion the effective altitudes of the two charge centers may be estimated at about $7 \sim 11$ km and $3 \sim 6$ km respectively and the separation of them at about $3 \sim 6$ km. It is important to measure the distances of individual lightning discharges from the station more accurately to improve our knowledges about the vertical separations of the two opposite charge centers in a thundercloud.

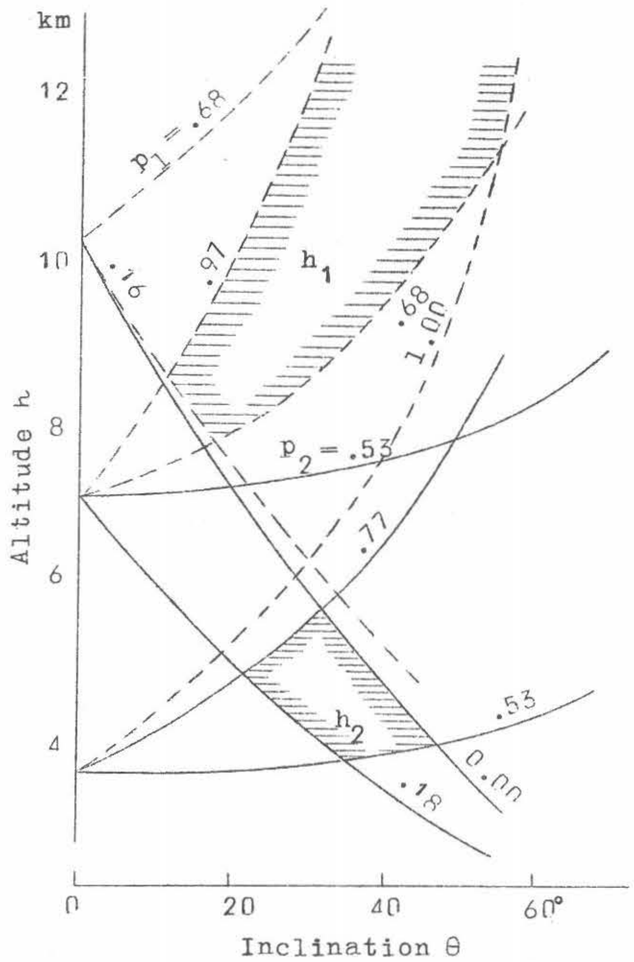

Fig. 5. The altitudes of both charges and the axial inclination of a dipole. Two hatched areas satisfy the conditions assigned from the observed occurrence rates of respective types in the electrostatic field changes due to cloud discharges.

6. Waveform of rapid field change

With the aid of a recording technique to eliminate the slow component of the field changes due to a cloud discharge and to emphasize the rapid component of them, we have found many small rapid field changes generally to repeat themselves in the course of the slow electrostatic field change due to a cloud discharge. (11)(12) The waveform of a rapid field change produced by a cloud discharge appearing in the near distance from the station is generally constructed of round pulses with the duration of several hundred microseconds. Although the form of such an individual pulse may be subjected to an appreciable deformation due to the short time constant 1 msec of the apparatus, it must generally correspond to an electrostatic field change due to a rapid movement of a considerably small amount of electricity. The round pulse will be designated as a static pulse hereafter following this standpoint. In maximum as much as 70 static pulses have been measured to appear on a slow field change due to a cloud discharge. The median value of the number of static pulses is 14 and half of the measured values of them lie between 7 and 25. Let us assume that a static pulse will be produced by 'a local discharge'. The amount of electricity and the transfer distance of it, which relate to a local discharge, must of course be much smaller than those of a slow process of cloud discharge. The electrostatic field change due to a local discharge, however, should be classified into anyone of the four types shown in Fig. 6(A) in accordance with the polarity of a local dipole, the polarity of a streamer that develops a local discharge, and the direction and the position of occurrence of it. The four types will be designated as the +, -, $\pm$ and $\mp$ types of static pulses respectively. Of course they will probably be subjected to a considerable deformation as illustrated in Fig. 6(B) under the influence of the too short value of the time constant of the apparatus.

In the intermediate distance, the rapider oscillatory pulses are seen to superpose themselves on a static pulse, and if the distance is increased further the high frequency oscillatory pulses become the only existence which occupies the whole duration of the field change due to a cloud discharge. Such a qualitative change in the waveform characteristics must be attributed to the propagation characters of the three terms composing an electromagnetic field change due to a cloud discharge. It is well known that these terms can be represented by the following equations, if the propagation distance of the field change is sufficiently larger than the altitude and the charge separation length of a signal source dipole.

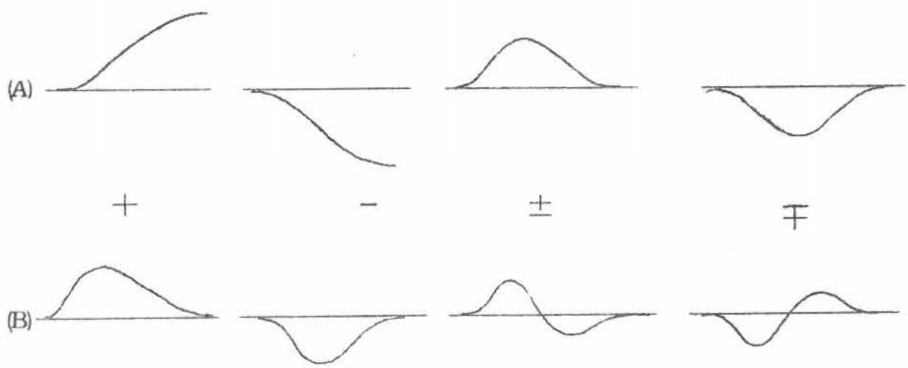

Fig. 6. Four types of static pulses.
(A) The actual waveform of electrostatic field change produced by a local rapid process.
(B) The observed waveform of static pulse, which is deformed by the influence of the short time constant of the recorder.

$$E_s = M/r^3, \quad E_I = (dM/dt)/cr^2,$$
$$E_R = (d^2M/dt^2)/c^2r, \quad E = E_S + E_I + E_R \tag{20}$$

where c is the velocity of light, M is twice of the vertical component of the discharge dipole moment, and the earth is assumed to have the perfect conductivity. The distance where E_R becomes larger than E_S depends upon the time dependent nature of the dipole moment M, and it becomes the smaller if the discharge process becomes the rapider, which point can clearly be seen in equation (20). If we take the relation represented by equation (20) into account, it will be reasonable to consider that a static pulse appearing on near distance waveforms does not come from the same origin as that of an individual radiation pulse actually observable in a longer distance, but it has a close relation to a group of radiation pulses so far as their origins are concerned. The radiation pulses will, therefore, give us the more detailed knowledge about the fine structure of a local discharge producing a static pulse. In this sense the relation between a static pulse and a group of radiation pulses may be compared with the relation between a gradual electrostatic field change and the repeated static pulses.

7. Relation between the slow electrostatic field change and the rapid static pulses

The slow electrostatic field change due to a cloud discharge is influenced for the most part by the slow movement of electricity contributing to the main part of a cloud discharge, while the static pulse, which can be recorded by employing an emphasizing technique of the rapid component of the field change, is mainly attributed to a rapid stream process of comparatively small amount of electricity. So that there should be some correlation to exist between the two. Following these ideas let us assume that a static pulse will be produced by a rapid small local discharge which occurs when the slow process of a cloud discharge

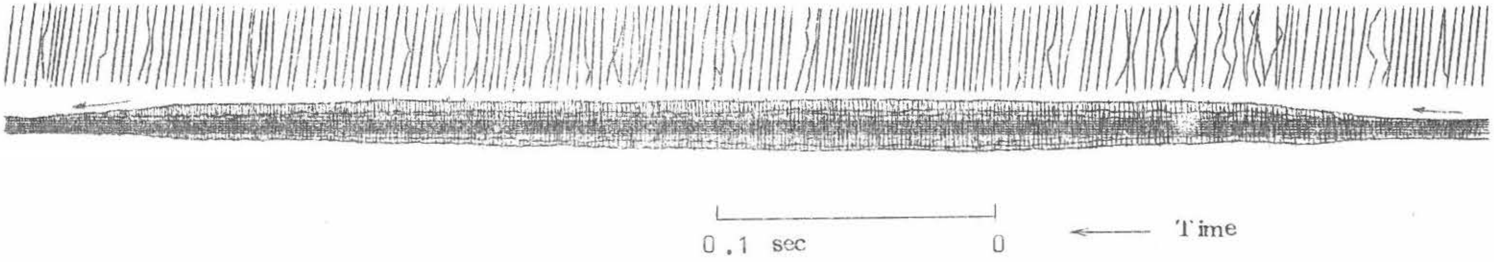

Fig. 7. An example of the simultaneous records of the electrostatic field and the rapidly changing field produced by a cloud discharge.

reaches a locally accumulated portion of electricity. If the slow process is mainly influenced by the movement of either of the two main point charges composing a cloud discharge, and if the rapid local process occurs in the neighbourhood of the effective moving head of the main point charge, and moreover if the difference between the directions of the two processes is trivial, the polarity of a static pulse will be the same as that of the slope of the slow field change with respect to the time. Table 4 shows the relation of both the polarities, which have been obtained from the measurement on the record of waveforms displayed on a dual beam oscillograph. An example of the record is shown in Fig. 7. In the table the electrostatic field changes are classified into respective 7 types. The percentage values in the table all represent the occurrence rates of the positive polarity of the static pulse, i.e., the + type, appearing in the periods respectively corresponding to the decreasing (-), the increasing (+), and the flat (0) portions of the slow electrostatic field change due to a cloud discharge. The occurrence rate of the negative polarity of the static pulse will be given by each residual value of the percentages given in the table. * The symbols +, -, and 0, each indicating the inclination of the slow electrostatic field change due to a cloud discharge, are arranged in the first column of the table in accordance with the variation in the inclination of the appearing slow field change.

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* The mixed polarities of the static pulses, i.e., the ± and ∓ types, have been neglected in the estimation of the table, but the occurrence rates of these two are considerably smaller than those of the positive and the negative polarities of pulses.

So that the upper half of the table represents the case where the decrease, flat, and increase appear in succession, or a decrease is followed by a flat, or a flat is followed by an increase. Likewise the lower half of the table represents the case where the increase, flat, and decrease appear in succession, or an increase is followed by a flat, or a flat is followed by a decrease.

Table 4. Occurrence percentage of the positive polarity of the static pulse in the respective portion of the slow electrostatic field change.

Polarity of dF/dt	Type of field changes							Total
	+	+→− (+)	+→− (−)	−→+→−	−→+ (+)	−→+ (−)	−	
−				13	10	10	8 %	9%
0	(9)	(40)		52	41	(21)	33	35
+	↓	↓		82	92	(67)		88
+	93	94	91	↓	↓			93
0	87	94	88	88	84			89
−		66	23	29				35

( ) : The number of data is less than 30.

Table 4 roughly satisfies the expectation given in the above discussion, and the polarity of the differential coefficient of the slow electrostatic field change roughly coincides with that of the corresponding static pulses. For example in the initial portion of a slow electrostatic field change, i.e., the - and the + portions respcectively of -, 0, + and +, 0, - inclination variations given in the first column of the table, no less than 90 % of the appearing static pulses have the same polarity as that of the inclination of the electrostatic field change. In contrast to this, it is also evident from the table that a flat portion preceded by a decreasing section generally produces more negative pulses than positive.

And inversely a flat portion preceded by an increasing section generally produces more positive static pulses than negative. These observational facts seem to indicate the point that the transition in the polarities of static pulses generally appears somewhat later than the variation in the polarities of the inclinations of the slow electrostatic field change. This point is particularly clear in the transition from positive to negative. In the $+\rightarrow-$ (+) type field, the decreasing section accompanies a considerably larger number of positive static pulses than negative pulses. This is rather contrary to the general agreement of both the polarities of the slow and the rapid field changes. In the case of the $+\rightarrow-$ (-) type field, the time duration of the decreasing section is to be statistically longer than that of the $+\rightarrow-$ (+) type field, so the decreasing section becomes to accompany a larger number of negative pulses than positive pulses. The time interval between the respective transitions of polarities of the slow and the rapid electrostatic field changes can be determined by measuring the time interval between the occurrence of a maximum or a minimum of a slow field change and that of the equal occurrence rates of positive and negative static pulses. It is generally rather difficult to obtain the exact values of the time intervals. However, the rough estimation we have made gives the values about 0.02 to 0.10 sec in the transition from positive to negative, and about 0.01 to 0.05 sec in the reversed transition.

These observational facts just described seem to lead us to the following inferrences as to the character of the rapid discharge process producing a static pulse, i.e., the local discharge. The effective position of occurrence of a local discharge must be located statistically somewhat behind the effective position of the main point charge which moves at a slow speed to produce the continuous and gradual field change due to a cloud discharge. * Therefore it seems necessary to infer that a local charge, which is forced to move by the arrival of the positive electricity moving slowly downward, will ascend rapidly over a

considerable length of the channel previously prepared by the slow process. The position of the rapid movement of a local charge inferred from the electric field change due to it of course represents nothing other than a rough sense, so the position may be thought to indicate the central portion of this movement. If the assumption is correct, a rapid movement of local electricity -- probably a rapid streamer process --, excited by the slow downward movement of positive electricity, should trace the distance from 0.4 to 2 km, which is twice as much as the distance traversed by the slow movement of positive electricity in 0.02 to 0.1 sec. In contrast to this, a rapid movement of a local charge excited by the slow movement of negative electricity seems to trace the distance shorter than the above estimated values, because the first, a negative streamer develops itself at a slower speed than a positive streamer under the same condition of spark development, (13) and the second, the time length of the transitional period in the case of the slow movement of negative electricity is only about half of that of positive electricity. However, it is rather an infrequent event to observe a negative slow process of electricity movement separated from a positive slow process, so the estimation of the length of the rapid movement of local electricity in association with the former will be a difficult problem.
For the purpose to interpret the superposed effect of the two slow processes of electricity movement, it is extremely desirable to locate the origin of each static pulse in the three dimensions.

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* In a rough approximation to replace an electrical process of an actual cloud discharge with a simple destruction of a dipole, the effective position of a moving main point charge at any instant during the discharge process will not generally coincide with the tip of an actual slow streamer developing the process. However, the difference existing between the two seems to be a trivial one as compared with the separation length of a local dipole because of the slow speed of cloud discharge development.

8. Discharge inside a thundercloud accompanied by ground strokes

It is well known that a slow discharge process generally takes place in a thundercloud during the period of a ground discharge. Concerning this point our records of electrostatic field changes also have indicated the variation similar to that of J and F processes reported by Malan and Schonland.(14)(15) The electrostatic field change called J field change appearing between each of multiple ground strokes is generally of a negative inclination in a vicinity of the discharge, but the polarity is reversed in a distant place from the discharge. In an intermediate distance, it is of the positive polarity between the strokes in the earlier half period of a ground discharge, but it turns to the negative in the later half period of it. Such a property of J field change is seen being similarly observable in F field change which appears after the last ground stroke. If we take the stepwise field changes due to the return strokes out of our consideration, the slow variation of an electrostatic field, which can be obtained by connecting the field changes appearing between successive strokes and after the last stroke, is classifiable in every case into one of the several types similar to the case of cloud discharges. The occurrence percentage of each type is shown in Table 5. On a record of the rapidly changing field due to a ground discharge, we can also find many static pulses to occur between, as well as after, the large pulses which correspond to ground strokes. The large ground stroke pulse has almost always a positive and very steep pulse front, so there is no difficulty to discriminate the static pulse from the ground stroke pulse. In this case, we can also recognize the same polarity principle between the polarity of the time differential of the slow electrostatic field and that of the static pulse included in the respective portion. The relation is shown in Table 6 in the same manner that we have used in Table 4.

Table 5. Occurrence percentage of each type of slow electrostatic field changes due to ground discharges.

Distance (km)	Type +	−	+→−	−→+	Number of data
0 − 5	5	75	20	%	16
5 − 10	22	22	56		23
10 − 15	53	6	38	3	32
15 − 25	83		17		6

Table 6. Occurrence percentage of positive polarity of static pulses in ground discharges.

Polarity of dF/dt	Type of slow change +	+→−	−	Total
+	93	89	%	91%
0	(87)	72	43	61
−		24	11	17

( ) : The case where the number of pulses is less than 30.

The general difference of the slow process of a ground discharge from that of a cloud discharge is as follows. The polarity of the dipole contributing to the slow process of a ground discharge is negative and has a reversed relation to that of a cloud discharge, because the net field change is negative in a near distance and becomes positive in a long distance. The slow process accompanied by a ground discharge neutralizes the upper negative and the lower positive charges, in other words, the main distribution of negative charge in the lower part of a cloud and the positive charge raised from the ground through the process of ground strokes. Therefore, the fact that almost all of the transitional field changes due to the slow processes of ground discharges fall into the +→- type tells us that the slow process is not advanced by a negative streamer but by a positive streamer ascending inside a thundercloud. It must be noticed that the main part of a slow process within a thundercloud is always developed by a slow streamer growing from the positively charged portion of a thundercloud independent of the polarity of a dipole contributing to a lightning discharge. The property of a streamer apt to develop from an anode rather than from a cathode has already been recognized in the laboratory experiments(13) and also in the theory of sparks.(16)

The altitudes of the positive electricity and the negative electricity distributions estimated from Table 5 are respectively 2 ~ 5 and 6 ~ 9 km on the average and are lower than those of a cloud discharge, though the negative charge center itself is represented in a somewhat higher altitude than the case of a cloud discharge. The data in Table 5 are too rough to give the estimate of the inclination of the dipole axis, but there seems to be no expectation of proving the point that the axis of slow process of a ground discharge should have a quite different inclination from that of a cloud discharge on the average and come nearer to the vertical direction.

9. Signs of static pulses

The sign of a static pulse is related to that of the differential coefficient with respect to the time of the portion of electrostatic field change, which involves the concerning static pulses, so that the signs of successive static pulses are apt to be kept the same over a considerable period of a cloud discharge. It is not rare that the successive static pulses have their signs unchanged over more than 10 times during the slow process of a cloud discharge. The variation of static pulse signs with the progress of a cloud discharge generally indicates rather a systematic character and can be classified into the following five categories: +, −, + → −, − → +, and complex types. These of course should correspond respectively to the electrostatic field types of the same denominations in their characters of origins. For example, the +→- type begins with a train of the + type static pulses and changes the sign on the way of the same cloud discharge process and ends with a train of the - type static pulses. Table 7 shows the occurrence rates of respective types on the signs of static pulse trains. In this case the number of data is much larger than that of the electrostatic field, because the records have been obtained at higher sensitivities than the case of electrostatic field recorder. As to the static pulses produced by a ground discharge we can see the similar property to the case of a cloud discharge. The comparison of Table 7 with Tables 1 and 5, which relate to the slow electrostatic field change, clearly shows the similar statistical character of the types with respect to the change in the distances. However, the degrees of variation in the former table are generally more insensitive compared with the latter two. This may be attributed to the broader distribution in the discharge altitudes or in the directions of axes of local discharges which produce static pulses. One of the reason of the above differences will consist in the direction of each local discharge, as a static pulse origin, to deviate from that of the slow process of a cloud discharge, but this factor would not influence appreciably the statistical characteristics of the local discharge directions, if we take account of what will be described in the following. Another fundamental reason will perhaps come from the accuracy of the estimation in distances of individual lightning discharges. In Table 7, the assumption has been made that all the discharges recorded on a cine film coiled up in one reel have the distances involved in a distance range represented in the table, for they have been recorded in the short period not exceeding five minutes. However, it is quite possible that an appreciable number of the data may frequently be classified into wrong distance ranges in the table. Further it was reported by Hatakeyama(17) that the succeeding lightning discharges changed their locations horizontally over the area of the magnitude 1 ~ 6 km in diameter from a discharge to another. The increase in the sensitivity of the recorder, in other words, to consider not only the larger amplitude records but also the smaller amplitude records at the same time, will result in giving a rougher estimation of the discharge distances.

Table 7. Occurrence percentage of each polarity variation type of static pulse trains.

Sort of discharge	Distance (km)	Type +	Type −	Type +→−	Type −→+	Type Compl.	Number of data
Cloud discharge	0 − 5	63	3	28	3	3%	341
	5 − 10	47	15	20	9	9	556
	10 − 15	34	34	12	14	6	406
	15 − 25	7	69	6	13	5	283
Ground discharge	0 − 5	27	35	30	2	6	77
	5 − 10	31	26	23	2	8	88
	10 − 15	44	29	24	0	3	59
	15 − 25	61	18	14	4	3	67

It is very well known that the photographic image of a lightning flash largely indicates bendings and branchings along its channel, and this seems to indicate the existence of space charge accumulations at these points. It is very probable that the condition to produce many space charge concentrations is fulfilled inside a thundercloud much better than outside of it, so that the slow discharge process in a thundercloud is expected to be subjected to much more bendings and branchings than what the flash photographs actually indicate. Some smaller electrostatic field changes neglected in the classification into the typical types may be responsible for such irregularities in the development of a slow discharge process. A static pulse generally has the sign similar to that of the time differential of the corresponding slow electrostatic field change. Nevertheless the direction of progress of a local discharge as the origin of a static pulse may deviate more or less from that of the main axis of the slow process, because the succeeding occurrence of static pulses will largely be influenced by a somewhat scattered nature of local charge accumulations. If the distribution of local charge accumulations were regular and the positions of succeeding local discharges were displaced in a regular manner on the main axis, the period of the + type static pulses and that of the - type static pulses would perfectly be discriminated on either side of the value s_0 in equation (14), and the period, where the + and the - types of static pulses were mixed with each other, would not be recorded. On the actual record, however, we can generally see a mixed period appearing on the way of the transition in the polarity of a static pulse train from + to - or from - to +. The length of a mixed period will be increased, if the degree of deviation of a local discharge direction from the main direction of a cloud discharge is increased, in other words, if the degree of irregularities in the distribution of local charge accumulations is considerable. The duration of a mixed period is, for instance, defined on the record of the $+\rightarrow-$ type rapid field change waveform as the time interval between the first - static pulse and the last + static pulse. However, so to speak exceptional pulses, which sometimes appear isolatedly during an opposite sign period of a static pulse train, are of course neglected in this measurement. The durations of mixed polarity periods are all of similar magnitude irrespective of the type of the rapid field change waveform, i.e., the $+\rightarrow-$ type or the $-\rightarrow+$ type, or of the discharges being related to the earth or not. The actual measurement gives the median value 0.06 sec and half of the measured values are distributed from 0.04 to 0.11 sec. The distance traversed by the slow process in these mixed periods will be $0.4\sim1.1$ km, provided the velocity of it is 10^6 cm/sec. Therefore, the difference in the altitudes of respective tips of branches of a slow process will not attain the value larger than 1 km, or the deviation of directions of local discharges from the main axis will usually be only several degrees.

Because, on the boundary of the mixed period, the following equation should be satisfied, if we follow the discussion described in section 4.

$$k(h_0 + \Delta h/2) = 1, \qquad (21)$$

where $k(h) = (2h^2 - r^2)/3rh \cdot \tan\theta$, $h_0 = r/\sqrt{2}$, and θ in this case is the angle of deviation from the main axis, which is assumed to take the vertical direction in this approximation. Hence

$$\tan\theta = 2\Delta h/3r. \qquad (22)$$

As the transition of the sign of the static pulses from + to - or from - to + generally is most frequently observed in the range of distances $6 \sim 10$ km, let us put these values into equation(22), then the result will be $\theta = 2 \sim 7°$. The estimated vlaues of θ would be too small to represent an appreciable deviation of the local direction from the main axis at any branching or bending point. Concerning this, it will be also reasonable to infer that the distance traversed by a local discharge is not very short in any way, but generally covers a considerable portion of a lightning channel previously prepared by the slow process of a intracloud discharge.

10. Static pulses of transitional type

If the transition point s_0 is traversed by a streamer to develop a rapid local discharge, the static pulse produced by it will fall into the $\pm$ or the $\mp$ type in accordance with the polarity of the local streamer as described in section 6. We shall designate these two types of static pulses as a transitional type hereafter. Generally speaking, the transitional type static pulse is expected to appear most frequently in a mixed period of both the + and the - type static pulses with each other. This period will be designated simply as a mixed period. Table 8 shows how many rates of the $\pm$ or the $\mp$ type static pulses are included in the respective four periods, i.e., the two mixed periods on the way of the transition from + to - or from - to + and the two simple periods where the occurring static pulses almost belong to the same simple type + or -. It is very clear that the table satisfies our expectation. As it has been described in section 9, the mixed period on a transitional type rapid field change waveform generally has a time length ranging from 0.04 to 0.11 sec and statistically occupies only from 10 to 30 % of the whole duration of a slow process due to a cloud discharge or a ground discharge producing a transitional type field. Moreover many simple type field data which do not represent the transition of the polarity of their pulse trains are actually included in Table 8 for the sake of convenience. Therefore we may infer that the occurrence rate of the transitional type static pulses per unit time must represent much higher value in the mixed period than in the simple period of a field change.

Table 8. Occurrence percentage of the transitional type static pulses in each period of rapid field change waveforms.

Sort of discharge	Type of pulse	Mixed period $+\rightarrow-$	Mixed period $-\rightarrow+$	Simple period $+$	Simple period $-$	Number of pulses
Cloud discharge	±	56	8	8	28 %	25
	∓	85	1	9	5	140
Ground discharge	±	33	0	66	0	9
	∓	68	0	8	24	38

Table 9. Occurrence percentages of two transitional type static pulses in respective periods.

Type of period		Cloud discharge: Type of pulse ±	Cloud discharge: Type of pulse ∓	Cloud discharge: Number of pulses	Ground discharge: Type of pulse ±	Ground discharge: Type of pulse ∓	Ground discharge: Number of pulses
Mixed period	$+\rightarrow-$	17	89 %	133	10	90 %	29
	$-\rightarrow+$	67	33	3			
Simple period	$+$	13	87	17	67	33	9
	$-$	50	50	14	0	100	9
Total		15	85	165	19	81	47

Table 9 is the rearrangement of Table 8, and indicates the occurrence percentages of ± and ∓ type static pulses in the respective periods indicated in Table 8. In the mixed period on the way of the transition from + to -, the ∓ type static pulses have been observed to appear about ten times more frequent than the ± type. This fact clearly tells that a rapid local discharge occurring in the course of a slow positive process of a cloud or a ground discharge is generally developed by a rapid negative streamer process. In the case of a slow negative process of a cloud discharge, rapid local discharges seem to be developed frequently by rapid positive streamer processes, although this conclusion is not so reliable as it is in the former case because of the shortage in the reliable data.
The similar tendency of a rapid local process has also been investigated in the case of transitional type static pulses which appear in the simple period of a rapid field change waveform. However, it is evident that the latter is rather an abnormal case, since we can not record frequently the transitional type static pulses in the simple period.
According to Table 9, the + type simple period of a field change due to a cloud discharge includes a larger number of the ∓ type static pulses than the ± type. This may be explained if the transition point located on the concerning discharge channel would be assumed to take a position close to the negative charge center. In this case the ∓ type static pulses accompanied by a slow positive process will predominate over the ± type pulses assumed to be associated with a slow negative process.
In contrast to this, the - type simple period due to a cloud discharge indicates a relative increase in the ± type static pulse occurrence as compared with the former case, because the transition point in this case would be located near to the positive charge center. In the case of a ground discharge, where no record of electrostatic field changes has been obtained to indicate the existence of a negative slow process associated, the predominace of the ± type static pulses in the + type simple period seems to indicate the following point that a kind

of secondary process growing into a local discharge would be produced rather frequently in the space between the upper positive and the lower negative electric charge centers composing the main dipole existing in a thundercloud.

Following these ideas the statistical results given in Table 9 will lead us to the following inferences concerning the mechanism of an intracloud discharge. A rapid local discharge will be initiated when a slow process composing the main part of an intracloud discharge will arrive at a point close to any one of the local portions which include each a considerable accumulation of electricity with the opposite polarity to that of the main slow process. At this instance, a streamer process developing a local discharge will progress at a high velocity toward the tip of the slow process and penetrate as far as a considerable distance into the channel previously prepared by the slow process. Fig. 8 illustrates the discharge mechanism model developed inside a thundercloud, from which the statistical results indicated in Table 9 may be obtained. Following this, it is usually unnecessary to consider a discharge process other than the following three to interpret the mechanism of a cloud discharge; the descending slow positive streamer process, the ascending slow negative streamer process, and the mid-gap streamer process which is the combination of the former two. In contrast to this, to interpret the discharge mechanism taking place inside a thundercloud in association with a ground discharge, it is not necessary to consider a discharge mechanism other than what is composed of an ascending positive slow streamer process. The relation between the main slow and the local rapid streamers seems to have a resemblance to that of a leader process to the following return stroke involved in a ground discharge, except for the differences existing in their scales, polarities and directions of their progressions. Concerning this point, it is well known from the rotating photographic records of lightning flashes that the 'recoil' sometimes occurs at the tip of a leader branch terminated in a clear air,(18) and this may be interpreted from the assumtion of the existence of a strong space charge concentration of the opposite polarity at the terminal point of the developed streamer.

i. Descending positive slow streamer process

ii. Ascending negative slow streamer process

iii. Mid gap slow streamer process

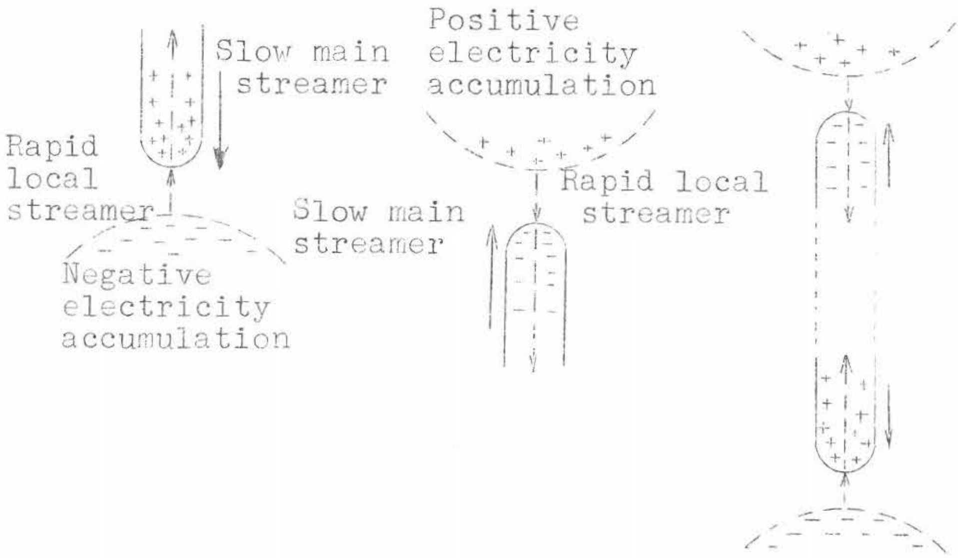

Fig. 8. A. Model of a cloud discharge

Ascending positive slow streamer process

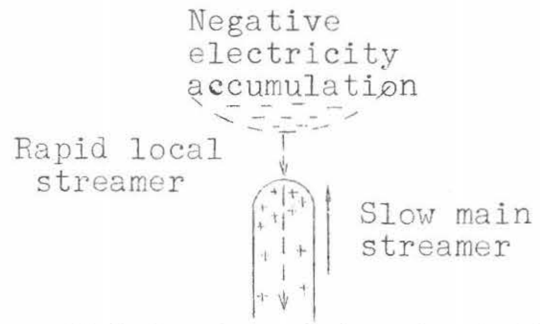

Fig. 8. B. Model of an intracloud discharge in association with a ground discharge.

If a rapid streamer travels a comparatively long distance, it will frequently pass through the concerning transition point and produce a transitional type static pulse falling into either of the $\pm$ or the $\mp$ type. For instance, if the distance developed by a rapid local streamer is of the order of 1 km, and if the occurrence number of rapid local discharges per one slow process which contributes to the main part of a cloud discharge is 14, and moreover if the total length of a slow process is 4 km, then the number of successive rapid local discharges passing through the transition point will not exceed 4 on the average in the case of a cloud discharge producing the transitional type field change. Generally speaking, the transitional type static pulses must be considered to have very small intensities in the case where the local discharges composing their origins have each an ordinary magnitude. For instance, if a vertical rapid local discharge with a given magnitude extends as long as 1 km, the center point of which is assumed to have the altitude indicated in the abscissa of Fig. 9, then the field change which will be recorded at the horizontal distance $6\sqrt{2}$ km from the local discharge will have the amplitude indicated in the ordinate. It is very clear from the figure that the amplitude of a transitional type static pulse* must usually be only about one tenth of that of the simple type static pulse. Therefore the transitional type static pulses which can be measured on the waveform records generally

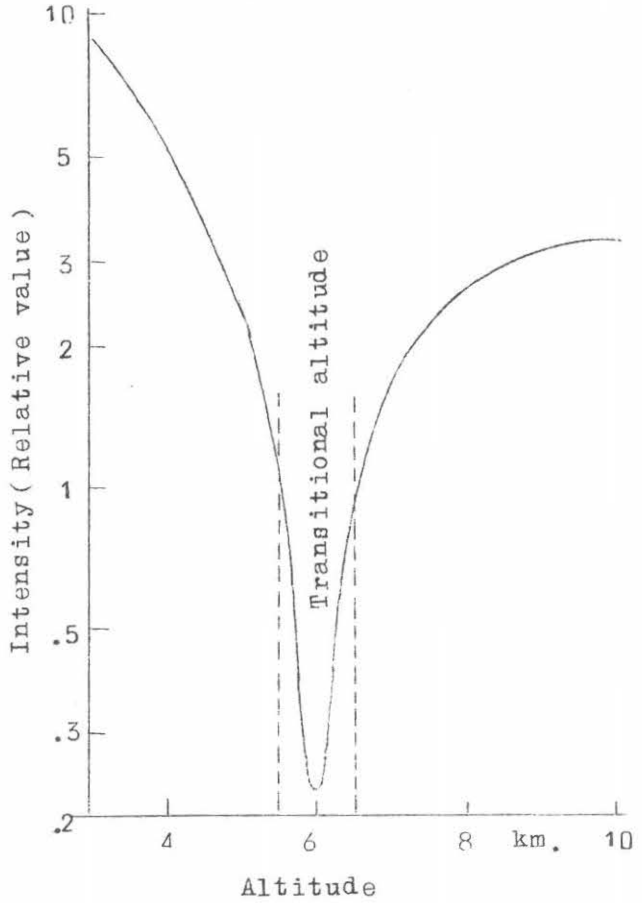

Fig. 9. The intensity of a static pulse due to a rapid process appearing at the distance $6\sqrt{2}$ km. The rapid process is assumed to extend to a vertical length 1 km. The abscissa indicates the altitude of the center position of the rapid process.

must correspond to local discharges having the larger scales, so that it will be quite possible that a waveform record of the $+\rightarrow-$ type does not always indicate any transitional type static pulse. Table 10 represents the occurrence percentage of field change waveforms due to lightning discharges which produce either of the $\pm$ type or the $\mp$ type transitional static pulses. The waveforms with static pulses less than 10 are excepted from the data giving the result of the table, because the sensitivity of the recorder in these cases may be too low to register the transitional type static pulses sufficiently. In the transitional electric field records, about half of them have the transitional type static pulses, while in the simple type field records the transitional type pulses are found in only 10 % of the data.

Table 10. Occurrence percentage of the rapid field change waveforms having or not having the transitional type static pulses.

Sort of discharge	Type of field	having tr. pulse	having no tr. pulse	Number of data
Cloud discharge	+	14	86 %	218
	−	9	91	57
	$+\rightarrow-$	43	57	119
	$-\rightarrow+$	8	92	13
	compl.	25	75	16
Ground discharge	+	33	67	6
	−	8	92	40
	$+\rightarrow-$	46	54	24
	$-\rightarrow+$	67	33	3
	compl.	50	50	6

* A local discharge located at the altitudes 5.5~6.5 km will produce a transitonal type static pulse, if it is recorded at a point on the earth's surface with the horizontal distance just described. The amplitude shown in Fig. 9 does not represent the net field change in these altitudes, but the maximal difference executed in the course of the process, i.e., the difference between the maximum value and the beginning or the end point of it.

The distance traversed by a rapid local discharge will closely be related with the amount of electricity accumulated in a local space which is the energy source of the local discharge development and the diversity of the electrical amount will be responsible for that of the forms of static pulses. If the scale of a local discharge will be the larger, the distance traversed by it will become the longer, and sometimes it will be possible that the streamer of a local discharge extends toward the outside of a thundercloud, if an appropriate ionized pass has been prepared for the streamer extension. This may result in an intercloud stroke that has the character of a dart leader in one case, or a dart leader progressing toward the ground in another case. Following this principle the intercloud stroke and the dart leader of a ground stroke must have the similar origin. The streamer process of a dart leader type requires always the existence of a pre-ionized channel to lead it, because a streamer of such a high velocity can not be maintained in a virgin air unless an extremely high electric field of the order of 10^6 v/cm is existing around the tip of the streamer, which will, however, be very improbable in the actual streamer process. If we follow these considerations, it will be very reasonable to conclude that a process similar to that of the slow discharge inside a thundercloud must always precede an intercloud stroke of a dart leader character in spite of the difficulty to photograph it with a rotating camera and to recognize its existence.

11. Numerical properties of the slow process and the rapid process in a thundercloud

In order to estimate the electrical quantity consumed by a lightning discharge, it is necessary to measure the absolute value of the electrostatic field change produced by it and to locate the position of discharge with a considerable accuracy. The sensitivity of our apparatus was not completely calibrated during our thunderstorm observation.

However as the first approximation, the intensities of the observed field changes due to lightning discharges generally have the values shown in Table 11. It is clear that the values of the slow electrostatic field changes given in the table are comparable with the value estimated from the assumption of a lightning discharge dipole moment of the order of 100 coul-km, i.e., the dipole moment usually adopted as the value to represent a cloud discharge.(7) The estimated ratio of the intensity of the slow process to that of the rapid process is of the order of 100. From the values of respective moments, the streamer lengths and the durations of their traversing (see II-Sections 4 and 6), we can estimate some other properties of the respective discharge processes, whose results are shown in Table 12.

It is very clear from the table that the greater part of the total electric charge 25 coul relating to a lightning discharge is dissipated actually by the slow process that occupies the main part of it. However, it is also to be noticed that the total amount of all locally accumulated electricities to cause every rapid streamer is not negligibly smaller than 25 coul. The extent of a locally acumulated portion of electricity which produces each rapid discharge process is the order of 100 m in diameter, which will be determined from the condition that the electrostatic field surrounding the surface of an assumed sphere to hold the locally accumulated electricity 1 coul must attain a value close to the threshould value 3×10^4 v/cm necessary to initiate an electrical breakdown.

Table 11. The observed and the estimated field intensities of the electrostatic field changes due to cloud discharges

Distance	Observed		Estimated
	Rapid process	Slow process	absolute value *
(km)	(v/m)	(kv/m)	(kv/m)
0 – 5	50 – 300	1 – 30	2.6 – 21
5 – 10	10 – 100	.1 – 5	0 – 2.6
10 – 15	2 – 20	.1 – 1	.25 – .31
15 – 25	..5 – 10	.05 – .5	.09 – .25

* It is assumed that +25 and -25 coul of electricity are located at the altitudes 8 and 4 km respectively on a vertical line.

Table 12. Average properties of the slow and the rapid discharge processes.

		Slow process	Rapid process
Moment	(c - km)	100	1
Length	(km)	4	1
Charge	(coul)	25	1
Duration	(sec)	0.3	0.0003
Velocity	(cm/s)	1.3×10^6	3×10^8
Current	(amp)	80	3000
Number		1	14
Total moment		100	14

12. Conclusions

We have inferred in the above discussions the structure of a lightning discharge occurring in a thundercloud by using statistically the records of the slow component as well as the rapid component of electrostatic field changes due to intracloud discharges. The conclusions of these investigations will be given as follows.

(1) Cloud discharges take place between the upper positve and the lower negative electric charge centers located in a thundercloud. The estimated effective altitudes of the two charge centers are distributed roughly 7~11 and 3~6 km respectively. The axis connecting them is inclined statistically from the vertical direction at an angle roughly less than 30°.

(2) The main process to neutralize the electricity of a dipole contributing to an intracloud discharge is developed at a considerably lower velocity of the order of 10^6 cm/sec. It is very probable that a lightning discharge will be initiated from the neighbourhood of the

boudary layer where the field intensity is the highest through the space between the positive and the negative charge distributions in a thundercloud. The discharge thus produced will mainly be developed by a positive streamer process descending at a slow speed. However, sometimes a slow upward negative streamer must be considered to appear coincidently with a positive slow process, and so a cloud discharge process is formed by a so-called mid-gap streamer process.

(3) The slow positive downward streamer will probably be subjected to many branchings and bendings. If one of the tips of many branches arrives at a portion which includes locally accumulated negative electricity, the local accumulation will produce a rapid negative streamer which ascends the channel previously ionized by the descending slow streamer. The rapid streamer thus produced seems to have the character of a dart leader streamer with progressing velocity of the order of 10^8 cm/sec or more, and the progressing distance of the streamer seems to have a close relation with the magnitude of the accumulated electricity, and it is estimated roughly at about 1 km on the average.

(4) The slow negative upward streamer also accompanies many rapid local discharge processes, which may be produced when the slow upward streamer will arrive at any one of the local accumulations of the positive electricity scattered in the upper portion of a thundercloud. At this moment a rapid positive streamer will be produced from the positive charge accumulation and will progress downward through the ionized channel prepared by the slow negative upward streamer.

(5) The estimated extent of each local electricity concentration is roughly of the order of 100 m in diameter, which is comparable with the extent of a subcell in a thundercloud,(19) and the estimated quantity of electric charge which it contains is roughly 1 coul. The considerable part of the cloud electricity is perhaps maintained in many local accumulations. However, the total electric moment consumed by the succeeding rapid local discharges must be considered to have a

negligible value as compared with that of the slow process.

(6) The intracloud discharge which is accompanied by the successive ground strokes forming a ground disbharge is composed of the successive development of an upward slow positive streamer occurring through the stroke intervals and further after the last stroke. In this case also rapid negative streamers will each be developed whenever one of the branched tips of the slow process reaches any one of the negative local electricity accumulations. It becomes evident that this kind of discharge process accompanied by multiple ground strokes has a very similar construction to that of a cloud discharge, except for the direction of the streamer progression being reversed between these two cases. It is very probable that a rapid negative streamer developed from a local negative electricity accumulation to have a sufficient magnitude will be able to progress toward the ground and become a dart leader leading the following return stroke.

(7) The main slow streamer in a thundercloud generally proceeds from the positive side independent of the sort of discharge being a cloud discharge or a ground discharge. This is just the point which will be expected from the result of the laboratory experiment as well as from that of the theory of spark breakdown. The fact that the first leader of a ground stroke actually starts from the lower negative portion of a thundercloud, however, will be interpreted as follows. The ground usually may be assumed to be very conductive, so that the electricity induced on the earth's surface must be spread out over a wide area and therefore it becomes difficult to build up a strong field which will be needed to initiate a streamer from the ground surface, except for the case of a very tall structure such as the Empire State Building.(20)

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THE MECHANISM OF DISCHARGES IN A THUNDERCLOUD

II. Flash Luminosities Accompanied by Cloud Discharges and the Correlation between the Flashes and the Electric Field Changes

Abstract —— The time variation of luminosity of a lightning flash has been recorded with a photoelectric method. The duration of a cloud discharge generally ranges from 0.2 to 0.5 sec. A weak luminosity continues with considerable fluctuations through the whole period of a cloud discharge process. It has reference to a slow main process in a cloud. Many strong pulsive luminosities are also emitted by rapid streamers associated with the slow process. The rising time of a pulsive luminosity, which perhaps represents the duration of a rapid streamer advancing in a cloud, is about 0.2 to 0.5 msec. The falling time of it is the duration of a so-called afterglow, whose distribution coincides with that of the longest afterglow on a visible lightning stroke channel measured with a rotating camera. Those indicate the rapid streamers being of the dart leader character.

The investigation of the amplitude relation between the pulsive luminosity and the rapid electric field change, both produced by the same rapid process, indicates a systematic displacement of effective positions of local rapid processes in a slow process. It gives the same result that we have presumed from the properties of electric field changes. A pulsive luminosity precedes the correspondent rapid field change in a vicinity of the origin, but the situations of them become contrary in a distant place. This is due to the variation in the form of a field change from the electrostatic type to the radiation type with the increase in the propagation distances.

1. Introduction

The mechanism of a cloud discharge has generally been investigated from the observation of the earth's electric field change produced by the discharge. It will be doubtless, however, that the use of a rotating camera has played the most directive role in the analysis of the lightning discharges. An essentially superior performance of a rotating camera is to make it possible to analyze simultaneously the spatial structure of a lightning channel and the process of growth of it. The high time resolving power of this sort of camera is attained by the photographic image distortion due to the rotatory motion of the optical system.
We also have carried out the observation with cameras of a low speed rotating lens type and of a high speed rotating mirror type,(1) and have obtained some new informations about lightning discharges.(2)
However, most of lightning discharges occur only in thunderclouds, so their stroke channels are excessively obscured by cloud droplets. Thus cameras are almost inefficient for recording the cloud discharge processes. This is the first reason why the mechanism of lightning discharges occurring in a thundercloud is not actually so definite as that of ground strokes, although it cannot be also overlooked that the meteorological and electrical conditions to affect the streamer development will be more complicated in a thundercloud than in a clear air. Nevertheless, the record of the fine structure of flash luminosities will correctly show the actual variation of the discharge activity despite the light absorption or the scattering by cloud droplets, though it may not give directly any knowledge about the spatial structure of the discharge process. In this respect we have executed the photoelectric measurement of lightning flashes together with the observation of the earth's electric field changes. In the present paper, the nature of flash luminosities and the relation of the flashes to the corresponding electric field changes will be described.
Those observations of flash luminosities or electric

field changes on the earth's surface, however, will indicate only indirectly the constitution of a discharge, and so there will still remain the questions insoluble without some methods to give the direct estimation of it, such as the use of an airplane, a radio-zonde or a radar.

2. Observation method

The time variation of flash luminosity was recorded in four summers from 1957 to 1960 with a photoelectric method(3) which involves the use of a photomultiplier tube MS9S. The general construction of the apparatus used in the last summer is shown in Fig. 1. The following three recording systems were adopted according to the respective purposes.

A) Recording on magnetic tape.

The luminosity of flashes is always recorded on a magnetic tape to investigate the comparatively slow variation of a flash luminosity. The recording is automatically performed except for the selection of an appropriate gain of the apparatus and the exchange of tapes in every hour. That is important in executing the thunderstorm observations of various kinds by a few hands. The output voltage proportional to the luminosity received with a photomultiplier tube is amplitude-modurated with about 2 kc to reproduce faithfully the slow variation components of it from the tape, but the time resolving power of the rapid components only reaches 1 msec. In analyzing the record, it is necessary to play back the portion of the tape having recorded a needed flash and to take again the photographic record of it with a cathode ray oscilloscope and a continuously running cine film. The magnetic tape recorder used is of two tracks, the other of which has been used to obtain the record of electrostatic field changes.

B) Recording continuously on 16 mm cine film.

To know the detailed relation between the flash luminosity and the electric field change produced by a lightning discharge, we have used a dual beam C.R.T., whose two bright spots draw side by side the rapidly changing waveform of the flash luminosity and that of the electric field respectively. The amplifier for the flash luminosity has the same time constant 1 msec as that of the recorder of electric field change, and thus the comparison of both the waveforms will become more simply. The time axis of the record is constructed from the sweep of the C.R.T. spot generated by a saw-tooth wave voltage repeated with 3 msec and the uniform movement of the 16 mm cine film. The time resolving power is nearly 30 μsec.

C) Recording in every frame on 16 mm cine film.

The amplifier used in this case has a long time constant 10 sec enough to reproduce the precise form of a flash luminosity. A waveform of flash luminosity swept on the C.R.T. screen with a triggered single time base, which is chosen according to demands out of 2, 20, and 200 msec, is recorded in a frame of 16 mm cine film. The waveform shows only a part of a complete discharge process which often covers several tenths of a second, but the consumed amount of film becomes extremely little. The cine film 100 feet in length mounted on a reel can cover well all the periods under the several storm activities in a summer season. The trigger action of a single time sweep is generated by the radio noise simultaneously radiated from a lightning flash. The time sweep is not always triggered at the beginning of a discharge process, but it frequently starts on the way of a process according to the trigger level or the tuning frequency of the radio noise receiver. We have assumed from those behaviors of triggering some relations between the mode of discharges and the high frequency character of them.(4) The exchange to the next frame of film is made automatically with relays which are

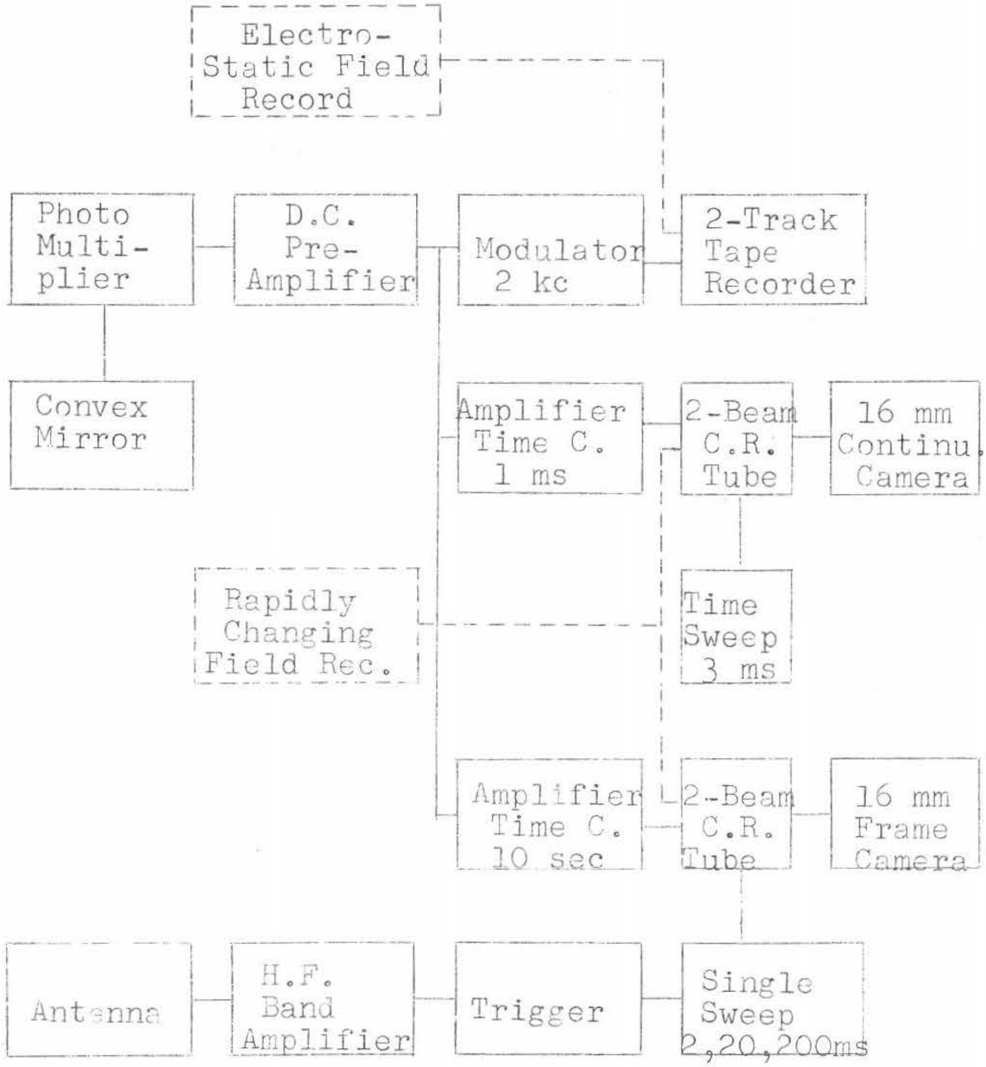

Fig. 1. The construction of the lightning flash luminosity recorder.

designed to operate immediately after the disapperance of the last waveform from the C.R.T. screen. An attached safety circuit works to suppress the next trigger action before the new frame is perfectly set. In the latest two seasons, a dual beam C.R.T. was also utilized in this case, and the slow electrostatic field or the rapidly changing electric field was recorded simultaneously with the flash luminosity in the same frame.

The correspondence between the above three recording systems is required to be precisely known. For this demand, in the A) system, a reference signal 200 c/sec with the duration 1 sec is recorded on the same magnetic tape. It starts 2 sec late from the trigger action to avoid the disturbance caused by itself. In the B) system, a neon lamp is lightened for a second from the moment of a trigger action and photographed in one side of the continuously running film simultaneously with the waveform.

The sensitivity of the apparatus can be varied in 10 db step by supplying an appropriate voltage to the anode of the photomultiplier tube, since a photomultiplier varies its sensitivity in proportion to about the seventh power of the anode voltage. The extent of the sensitivity to be altered to record flashes in a satisfactory condition ranges over 60 db or 1000 times in usual thunderstorm observations, and such a wide range needed in the recording sensitivity will be never attained by means of a usual photography. When the apparatus is set at the highest sensitivity, it will be able to record suitably all flashes visible with naked eyes, if the positions of flashes are not located in the neighbourhood of the horizon.

The amplitude response of the output voltage from the photomultiplier tube to the incident luminosity is not linear, but the former is roughly proportional to 0.7th power of the latter in the actual measurement. The range between the input intensity level to generate the maximum undistorted output and the noise level is about 35 db in the case of the standard gain, but in the A) system described first the dynamic range in the output reproduced from the magnetic tape is only about 20 db. Therefore, it will generally be difficult to record precisely the intensity of a variable flash luminosity on a magnetic tape, even though the sensitivity of the apparatus can carefully be altered according as the thunderstorm is located near or distant from the observation station. We must take notice of this respect in analyzing the observed data.

The field of vision of the apparatus can cover easily the whole sky by the use of a convex mirror. But we designed to take away from the field of vision the sky under the angle of elevation 10° to avoid the city lights entering. The radius of curvature of the adopted convex mirror is 260 mm, and the aperture of it is 300 mm. The mirror is horizontally placed, and the photomultiplier tube, whose sensitive screen faces the mirror, is installed at the height 1 m just above the center of the mirror. A diffuser for the incident light is inserted in front of the sensitive screen of the photomultiplier tube, and then the equivalent sensitive aperture of it becomes about 40 mm. The use of the convex mirror will cause the difference in the sensitivity with respect to an incident angle of light, but it has been ascertained through the calculation that the error due to the sensitivity difference will not exceed 10 % at all angles of elevation.

3. General composition of a cloud flash

A cloud flash recorded with a photoelectric method is composed of many pulsive luminosities with various intensities and durations. This bears a resemblance to the observational fact that a visible intercloud discharge or a ground discharge is often resolved into multiple strokes on a rotating photograph. The occurrence frequency of the pulsive luminosities in a cloud flash, however, sometimes reaches as much as several tens times, which is much more than the multiplicity of visible strokes less than 4 on the average.(5) Moreover the pulsive luminosities composing a cloud flash are usually of quite various forms one another. Those lead us to consider that all of them will not always be radiated from the multiple streamers repeatedly passing through the same channel. The pulsive luminosity is more suitably observed on records with the C.R. oscilloscope. The form of it is like to that of a static pulse found on the electric field change record. It will be often called as a photo-pulse hereafter from its form comparable with a static pulse.

The other important character of a flash is to indicate the existence of some weak and long luminosities, which sometimes continue over several tens milliseconds in the flash records obtained in a vicinity of the origins. Fig. 2 is an example of the simultaneous records of a flash having a long continuing luminosity and of the correspondent electrostatic field. There are usually found no pulsive luminosities in the period of a continuous luminosity recorded on a magnetic tape. This is probably due to the narrowness of the dynamic range in the tape recording and to the large difference between the intensities of the two types of luminosities. Many strong pulsive luminosities actually will occur repeatedly without any long pause through the whole period of a discharge.

It is evident from the properties of the two types of luminosities that both will be based upon the different modes of discharges from each other. In other words, it cannot be thought that a continuous luminosity may be produced as the result of only pulsive luminosities incessantly repeated for a long period. A continuous luminosity should be referenced to a slow process in a cloud, while a pulsive luminosity to a rapid process.

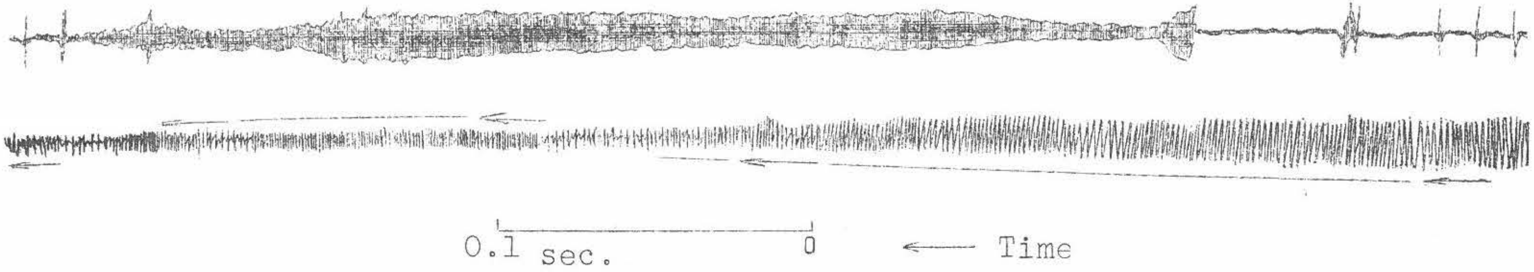

Fig. 2. An example of the simultaneous records of the electrostatic field and the flash luminosity reproduced from the dual track magnetic tape.

4. Duration of a complete discharge

The cumulative distribution of the whole duration of a complete lightning flash* is shown in Fig. 3, curve A. It is closely similar to a logarithmic normal distribution except for a portion of its shorter values. The median value of it is 0.30 sec and half of the data are included in the range from 0.18 to 0.46 sec.

A flash containing a long continuing luminosity generally has a relatively long duration as it will be shown later. That may be attributed to the assumption that a continuous luminosity will often be observed in the case of a discharge of large scale, for the larger discharge naturally will have the longer duration. But there seems to be another reason as follows. A continuous luminosity is thought to be recorded with a relatively high sensitivity, which may make it possible to catch up weak luminosities appearing in the beginning or the finishing part of a discharge. From the similar meaning to this, flashes with much shorter durations perhaps have been recorded with a relatively low sensitivity. Therefore, it is quite probable that the greater part of cloud discharges may actually have the durations 0.1 sec or more at least.

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* A complete flash here expressed signifies a group of successive luminosities clearly distinguishable with another group. It is essentially a group of constituent discharge processes which will closely be related one another in their occurrences and developments.

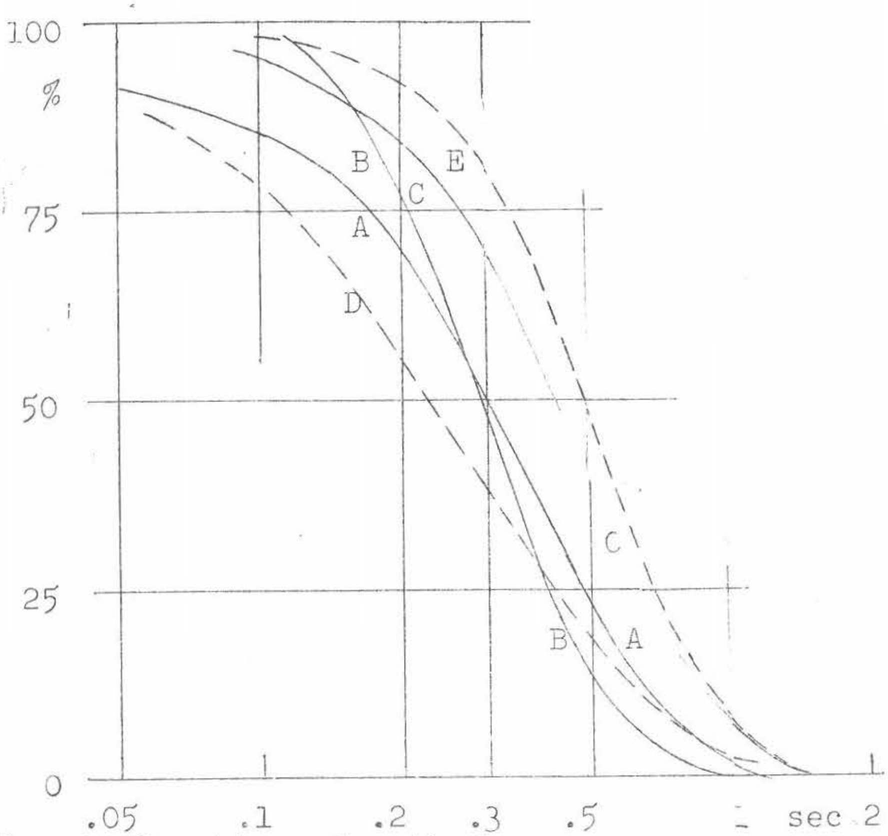

Fig. 3. Duration of a discharge.
Solid lines: Duration of a cloud discharge. Distribution curves are given by the following observation methods respectively.
(A) the photoelectric record of flash luminosity
(B) the electrostatic field change record.
(C) the rapidly changing electric field record.
Broken lines: Duration of a ground discharge. Curves are given by the rapidly changing field records. The two curves indicate respectively
(D) the net duration from the first ground stroke to the last one.
(E) the whole duration which involves the intracloud processes dependent on the main process between the cloud and the ground.

When the occurrence frequency of lightning flashes is appreciably high, we shall be unable to discriminate successive two or more flashes,* which will be treated as one flash. In some cases, a flash with an especially long duration may be thought to be rather composed of two separate flashes from the point of view about its detailed composition.

The duration of a complete discharge can also be measured from the record of the electrostatic field or the rapidly changing field. The distributions given by them are likewise shown in Fig. 3, curves B and C. Electrostatic fields changing gradually are usually recognizable in the case of discharges of comparatively large scales, which will produce a distribution that lacks the data of especially short duration values. While, the low sensitivity for recording electrostatic field changes and the geometrical conditions between the origins of them and the observation station to affect the forms of observed electrostatic field changes will result in the shortage of the data of longer durations. Thus the distribution obtained from the electrostatic field records comes to have a form of relatively smaller dispersion than that of the flash luminosity records. On the other hand, as it is shown in Fig. 3, the duration given by the pulse trains on a rapidly changing field record is statistically about 40 % longer than

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* Actually, two or more lightnings have often been found at the same time in different portions of a thundercloud. But it has not yet been examined whether such simultaneous occurrences of lightnings will be quite accidental or there will be some reciprocity between them, though their occurrence positions seem to be apparently quite isolated one another.

that of a flash measured with a photoelectric method. But the record obtained with such a high sensitivity as used in the rapidly changing field record may include small field change pulses not to be directly related to the main process development. Then it seems to be reasonable that the magnitude of the duration of a flash is taken up as the whole period of the main process of a cloud discharge.

It is difficult to distinguish whether a flash luminosity recorded on a magnetic tape was emitted from a ground discharge or from a cloud discharge. Regarding an electrostatic field record, however, it will easily be known that a field with extremely rapid stepwise changes is always produced by a ground discharge. Regarding a rapidly changing field record, the distinction of sort of the origin will be easier than the above case, for the waveform due to a ground discharge is characterized by a few positive large pulses with steep fronts, before which noticeable leader waveforms are often found. Fig. 3 also shows the distribution of the duration of a ground discharge thus determined on the record of rapidly changing field. The curve D shows the net duration from the first ground stroke to the last one, which corresponds to the duration to be measured on rotating photographs. It is evidently shorter than the duration of a cloud discharge. But some process of discharge should be maintained inside a thundercloud for a considerable period before as well as after the ground strokes,(6)(7) and the whole duration of a complete ground discharge, the curve E, is equivalent to that of a longer cloud discharge as shown in Fig. 3. This may suggest the point that the extent concerned with a complete discharge process in a cloud will not be particularly different between a ground discharge and a larger cloud discharge.

5. Continuous luminosity

Continuous luminosities have often been observed on magnetic tape records. They also have been found in some single sweep C.R.O. records, in which the bright spot is deflected continuously from the base line over a considerable period of a time sweep 20 or 200 msec. As described in the former section, the decision of kind of a flash origin is almost impossible on the tape record. But we shall be able to estimate whether a flash actually recorded was accompanied by a ground discharge or by a cloud discharge, if the record of the electrostatic field or the rapidly changing field has been obtained simultaneously with that of the flash luminosity. Then we have ascertained that continuous luminosities are found on photo-electric records of both kinds of discharges and that no difference between the properties of them is detected.

Continuous luminosities are not always found in every flash recorded, but the occurrence rate of them is considerably altered according to conditions such as the distance from the origin or the recording sensitivity. Fig. 4 shows the cumulative distribution curves of the duration of the longest luminosity found in each of complete flashes obtained in seven thunderstorms in 1957 and 1958, and the three curves in the figure represent the respective group divided in accordance with the recording sensitivity. The distances from the origins related to each curve are roughly estimated and shown by the sides of respective curves in the figure. From a condition of bending in the distribution curves, we can conclude that a luminosity with the duration longer than 10 msec should have the nature of the continuous luminosity. The longest luminosity nearly reaches 1 sec. Some flashes are covered even the whole periods of their lives by continuous luminosities. However, the occurrence rate of flashes with luminosities continuing longer than 10 msec occupies only 20 to 40 % of all flashes so far as our observation is concerned.

The sensitivity for recording flashes has of course been altered with the change of the distance from the flash origins to the station, and thus we have tried not to change the nature of flashes observed in different distances. In spite of our expectation that the effect would be considerably attained, flashes actually recorded with a low sensitivity, which would naturally have occurred in a near place, usually have much longer luminosities than distant flashes recorded with a comparatively high sensitivity.

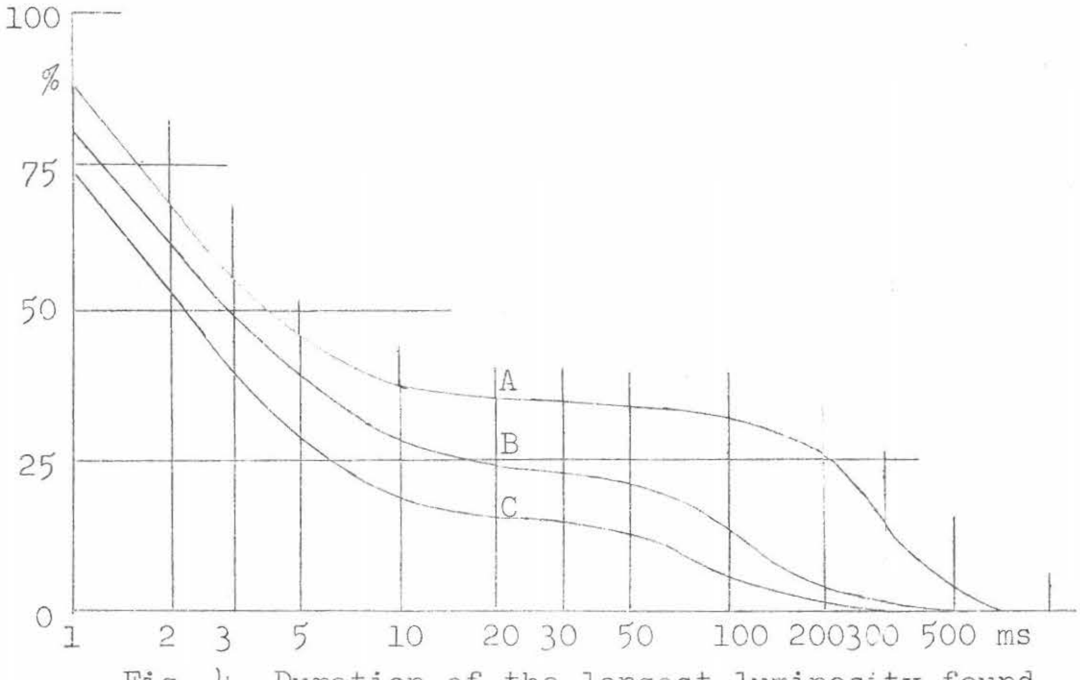

Fig. 4. Duration of the longest luminosity found in each of complete discharge processes. The distribution of duration is divided in accordance with the recording sensitivity. The sensitivity and the rough estimation of distances from the flash origins are as follows.

(A) 20 ~ 30 db, 0 ~ 10 km.
(B) 40 ~ 50 db, 5 ~ 15 km.
(C) 60 ~ 70 db, 10 ~ 25 km.

The fact shows that the selection of the sensitivity would not yet fully have served to the attenuation of the luminous intensity as the distance increased. Such an insufficient sensitivity as used in a distant place also should affect the recording of pulsive luminosities. Table 1 shows the median vlaues of the number of pulsive luminosities contained in a complete flash and those of the whole duration of it. These values clearly increase on the average with the increase of the duration of the longest luminosity included in respective flashes.

Table 1. Medians of the number of pulsive luminosities and the whole duration of a complete flash, which is divided into ranges in accordance with the longest luminosity duration.

Longest lum. duration (ms)	No. of pulsive luminos.	Whole duration (ms)	No. of data
1 - 3	7	210	395
3 - 10	12	330	180
10 - 30	17	410	43
30 - 100	19	540	62
100 - 300	19	570	57
300 - 1000	14	580	14
Total	11	300	751

Though it is difficult to estimate the degrees of insufficiency in the sensitivity used for a distant storm, it is evident that the light from a cloud discharge will suffer a much severer attenuation than in the free space. Therefore, if flashes occurring in the vicinity of the observation station are recorded with such a high sensitivity as used for distant flashes, they will become to be covered by continuous luminosities their respective whole lives. Then the rise and fall of the activity of a slow main process should be represented by the alteration of the intensity of the continuous luminosity. The occurrence position of the

observed longest luminosity through the whole life of a complete discharge activity perhaps indicates the time when the continuous luminosity supposed to cover the whole life of it will become the brightest, in other words, the slow discharge process will be the most intensified in its course. Table 2 shows which quarter of the process of each flash contains the occurrence of the longest luminosity.* But the case in which the duration of the longest luminosity is no more than 10 msec is here excluded. Actually the continuous luminosity is often found in the appearance divided into several fragments of it in a complete flash. Table 3 shows the number of luminosity fragments with the durations exceeding over 10 msec in a flash. The table is given in every quarter including the longest luminosity. From Table 2, we know that a continuous luminosity supposed to cover a complete process is usually the brightest in the second quarter and the darkst in the last quarter, especially in the case of the longest luminosity duration exceeding 30 msec.
Table 3 indicates that the continuous luminosity is generally observed divided into two or more portions in about 40 % of flashes with the luminosity continuing longer than 10 msec. Moreover flashes which have the longest luminosity recorded in their respective second quartersalso have the greatest number of luminosity fragments.

Thus we get at the conclusion that the activity of the slow main process of a cloud discharge usually reaches its maximum at the time of about one third from the initiation of it and afterwards decays rather slowly, though it must be noted that the activity in a main process is

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* In Table 2, when a long luminosity covers two or three successive quarters, every quarter whose larger half is included in the period of the luminosity is tabulated irrespective of the rate of the period occupied by the luminosity.

subjected to considerable slow fluctuations, which are probably attributed to somewhat partial processes associated with the main process.

Table 2. Occurrence percentage of the quarter containing the longest luminosity in a complete flash.

Longest lum. duration(ms)	Quarter 1/4	2/4	3/4	4/4		Number of data
10 - 30	35	28	23	14	%	43
30 - 100	14	48	26	12		62
100 - 300	16	40	37	7		57
300 - 1000	24	44	30	2		14
Total	20	40	30	10	%	176

Table 3. Occurrence percentage of the number of luminosities continuing longer than 10 msec in a complete flash.

Quarter of longest lum.	Number of cont. lum. 1.	2	3	4	5	6	7		Number of data
1/4	73	12	6	3	6			%	36
2/4	51	33	10	3	2		1		70
3/4	57	27	8	6		2			52
4/4	80	10	5	5					18
Total	60	24	8	4	2	1	1	%	176

6. Correlation between the continuous luminosity and the slow electrostatic field change

Some discharge process should maintain its development in a thundercloud through the whole period of a continuous luminosity. It perhaps produces a gradual electrostatic field change on the earth's surface. The equivalent velocity of this process, 1.3×10^6 cm/sec, which is estimated from the discharge duration 0.3 sec and the main dipole separation 4 km, is much smaller than the effective velocity of the first leader of a ground discharge, 3×10^7 cm/sec. The latter has been considered to correspond to the lower limit of the velocity of a negative streamer which can bridge across an unionized long gap.(8) However, slow streamers extending with the velocity of the order of 2×10^6 cm/sec have actually been found on our rotating photographs of intercloud strokes, though the obvious occurrences of them are quite rare.(2) Sourdillon(9) reported the usual existence of the type III discharge, which was characterized by a lightning stroke without any clear channel on his rotating photographs, and this character of the stroke is perhaps due to the slow development of the streamer and the weak luminosity continuing for a long time. Consequently, it seems no doubt that such slow streamers actually will occur, which will be related to weak continuous luminosities found in photoelectric records and slowly changing electrostatic fields. Now, a usual intercloud stroke of dart leader type should require some previously ionized channel before its development. The required ionization is perhaps formed by a slow streamer, which always precedes a clear dart type intercloud streamer but is generally not photographed with a rotating camera because of the weakness of its luminosity. But the slow discharge process will rather play an important role to neutralize the cloud electricity.

The comparison between a continuous luminosity and the correspondent electrostatic field change

has been made in the simultaneous records of them obtained with a double track tape recorder.
A relatively short luminosity is not always found in the period of noticeable inclination of the field change, but there apparently seems to be little obvious relation between both the occurrences. However, an especially long luminosity generally has the better correlation with the electrostatic field change. The number of luminosity data having no correspondence to any discernible field variation is only 2 among 34 very long luminosities continuing more than 100 msec. Table 4 indicates the relation between both simultaneous records in the 32 data. T_S shows here the time interval from the starting time of the long luminosity to that of the electrostatic field variation, while T_E shows the time interval between both ends.
In data shown in the column $T_S = 0$ or in the line $T_E = 0$, the starting times or the ending times of both the processes are respectively coincident within the period about 30 msec. It is noted that there is a relatively good agreement in both the starting times. Considering the point that the magnitude of field variation depends not only on the quantity of charge transferred through the process but also on the position and the direction of the development, the correlation indicated in Table 4 is very excellent. Fig. 2 is an example of the simultaneous records of the two.

Table 4. Correlation of the luminosity continuing longer than 100 msec to the slow electric field variation.

	$T_S > 0$	$T_S = 0$	$T_S < 0$	Total
$T_E > 0$	3	5	1	9
$T_E = 0$	1	8	2	11
$T_E < 0$	1	7	4	12
Total	5	20	7	32

On the other hand, the record of a high frequency radio noise in the MF band has been obtained in some daytime thunderstorms. It is likewise composed of many rapid pulsive noises and several comparatively long continuing noises, though the envelope of the latter is not so smooth as that of the continuous luminosity. These two types of noises are thought to be referenced to the pulsive and the continuous luminosities respectively, but in this respect we have not fully examined.

7. Photo-pulse

We have observed that a pulsive luminosity termed a photo-pulse is generally much stronger in the instantaneous intensity than a continuous luminosity. Unfortunately for the narrowness of the dynamic range in the tape recording system, it will not usually be expected that both are found at the same time, i.e., when a continuous luminosity is recorded with a sufficient sensitivity, photo-pulses will be unable to be distinguished from the record nearly saturated, while weak continuous luminosities may not be found with a sensitivity suitable for recording photo-pulses. However, the rough estimate of the discrepancy between both the intensities may be obtained from the average recording sensitivities. In 1957 and 1958, we observed mainly the continuous luminosities with magnetic tapes as mentioned in section 5, while in 1959 and 1960, the pulsive luminosities were taken up as the main object of the analysis, so the continuous luminosities were seldom found. The bounds and the mean values (in parentheses) of recording sensitivities in both the groups are shown in Table 5. The estimated discrepancy between the sensitivities of the two groups is about 20 db or 10 times, the value of which is perhaps not less than the actual discrepancy between the average intensities of continuous and pulsive luminosities, considering the point that even the high sensitivity used in the former group could not perfectly record long continuing luminosities. The extent of the origin of a continuous luminosity will be much larger than that of a photo-pulse, if we may assume many branchings to occur in a slow main process growing. Then the difference of both the radiations per unit volume in respective channels will become still greater. This means that there will be a great difference between the ion concentrations in the respective channels, or consequently between the velocities of their developments.

Table 5. Recording Sensitivities.

Distance (km)	1957, 58 (db)	1959, 60 (db)
0 - 5	20 - 48 (36)	-3 - 17 (9)
5 - 10	27 - 55 (40)	7 - 21 (18)
10 - 15	40 - 60 (51)	17 - 21 (19)
15 - 25	44 - 68 (56)	27 - 47 (36)

The precise waveform of pulsive luminosity is given with the observation method C), which involves a long time constant enough to reproduce the slower components of it and a high resolving power of time needed to indicate the rapider components of it. The idealized form of a photo-pulse, which is given from the median value of about 1000 pulse forms actually observed, rapidly rises in 0.3 msec and then relatively slowly decays in 1.2 msec. The time width of the section exceeding over half of the peak value is 0.6 msec. The idealized form is represented approximately by the following expression:

$$P=(\alpha t)^2 \exp(-\alpha t), \qquad (1)$$

where α is about $6\times10^3\ \mathrm{sec}^{-1}$. The form is illustrated in Fig. 5. But the actual waveforms of photo-pulses are subjected to such a considerable fluctuation as the distribution curves of the pulse durations in Fig. 6 indicate.

The fluctuation is not yet small, even though only successive pulses which belong to the same cloud discharge process are collected. In other words, the photo-pulses found on a discharge process have not a characteristic form concerning the discharge, but the pulse forms are always of similar magnitude dispersions in every discharge. This will be an indication of the character of origins of photo-pulses, which seem to be produced by small local discharges occurring in different portions one another even in the same complete discharge process. The diversity in their pulse forms will somewhat be based upon the electrical structure of a thundercloud.

The beginning time of a photo-pulse can be decided comparatively clearly as shown in the idealized form of Fig. 5. The cumulative distribution curve of the rising times of actual photo-pulses is shown in Fig. 6, curve A.

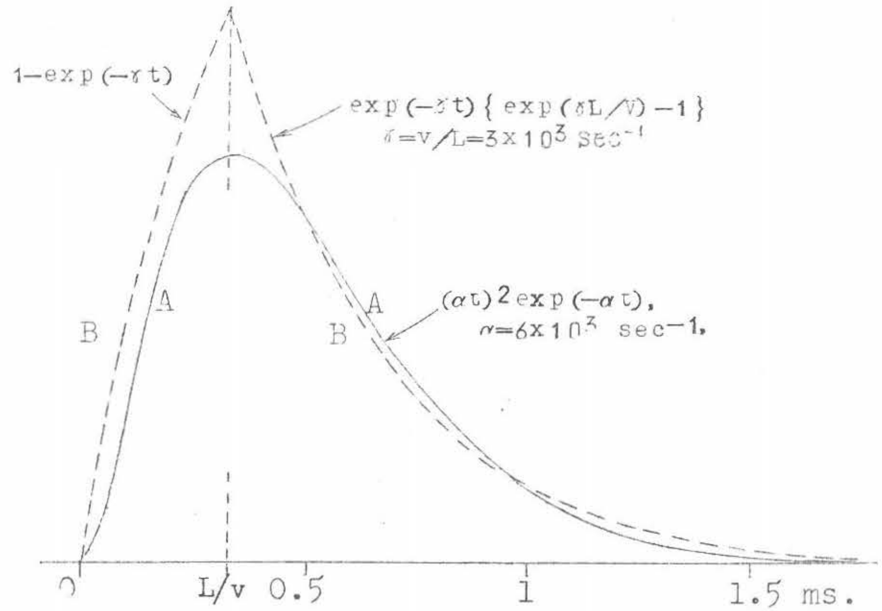

Fig. 5. The idealized form of a photo-pulse(A) and the estimated form of it from a simple model (B).

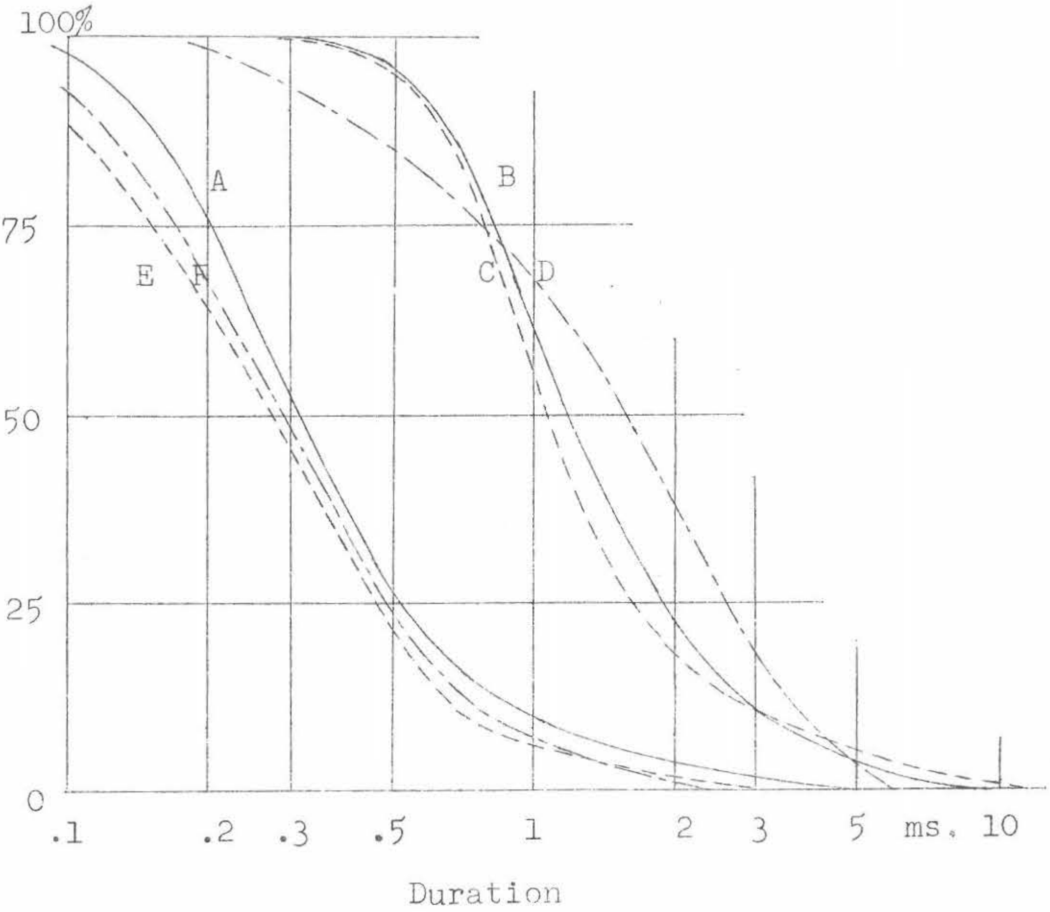

Fig. 6. The rising time (A) and the falling time (B) of a photo-pulse and the duration of afterglow measured on photographs with a rotating camea in the cases of inter-cloud strokes (C)(E) and ground strokes (D)(F).
(C)(D): the long streakwise afterglow.
(E)(F): the short usual afterglow.

The median value is about 0.3 msec, and half of the observed data are contained in the range from 0.2 to 0.5 msec.

From images on rotating photographs of lightning discharges, we can see the rapid decrease of the brightness in a stroke channel left after the passage of the streamer tip. This decrease occurs in the succession of the streamer development. The length of the brightest portion along a channel is roughly proportional to the velocity of the advancing streamer tip, so the remarkable brightness at a certain point on a channel has the similar duration about 5 μsec irrespective of the nature of stroke, such as a dart leader or a return stroke.(8) Since the time value 5 μsec is sufficiently small to be compared with the rising time of a photo-pulse, the following model will be considered here. For the sake of simplicity, let us take the assumption in which the brightness of any point on a stroke channel reaches the maximal value from zero in the moment of the passage of the streamer tip at that point and then decays exponentially. If the streamer velocity v is constant, the tip will advance the distance vt in the period t after the start of the streamer development. Then a portion of the channel located between the distances x and $x+\Delta x$ from the starting point of the streamer will produce the luminous intensity $p\Delta x$,

$$p\Delta x = A(x)\exp\{-\gamma(t-\frac{x}{v})\}\Delta x\,, \qquad vt > x > 0 \tag{2}$$

where γ is the decay constant of the brightness and $A(x)\Delta x$ represents the maximal radiation at this portion on the channel. But since the effect of the variation of A(x) with x may usually be assumed to be much smaller than that of the decaying at each portion, A(x) will be treated first as a constant in the following discussion. Now the total radiation from the whole streamer channel at the time t is given as follows respectively before and after the streamer tip stops the development.

$$P = \int_0^{vt} p\cdot dx = \{1-\exp(-\gamma t)\}Av/\gamma\,, \qquad 0 < t < L/v \tag{3}$$

$$P = \int_0^{L} p\cdot dx = \exp(-\gamma t)\{\exp(\gamma L/v)-1\}Av/\gamma\,, \quad t > L/v \tag{4}$$

where L is the final length passed by the streamer tip. Fig. 5 also illustrates in a broken line the total radiation P given by this model. The form of P rises as long as the streamer tip continues the progression and reaches the maximal value when the progression comes to the end. In the case of an actual lightning discharge in a thundercloud, however, we can not consider the existence like a definite electrode wall where the advancement of a streamer will instantly stop, because the electrode in a cloud discharge is constructed of a group of the space charge scattered in a thundercloud. Therefore, the effect of the gradual decrease of A(x) in the neighbourhood of the end of streamer development will become to be comparable to that of the luminosity variation due to the decaying at each point on the channel. Then the actual total radiation in the neighbourhood of the maximal point will not show such a rapid increase as we expect from the estimated pulse form shown in a broken line, and the form of it will be transformed into such a smooth one without any discontinuity as the idealized form shown in a solid line. The similar effect to this will also occur more or less on the occasion of the start of a streamer and it will make the actual photo-pulse to rise more gradually than the estimated case from the simple model. However, the position of the peak of the actual luminosity form is perhaps not so altered from the point of the calculated discontinuity L/v. Then the distribution of the rising time of a photo-pulse shown in Fig. 6, curve A will be able to be replaced, as it is, to that of the duration of the rapid discharge proceeding in a cloud. If either of the velocity or the length of a local rapid discharge is known, the other unknown will also be deduced statistically. Now, we have none of the direct evidence on the velocity estimation because of the inevitable lack of the photographic records of intracloud streamers. The luminosity emitted from a rapid process, however, is usually much stronger than the continuous luminosity from a slow process and it is of the magnitude near to the luminosities of the dart leader portions of ground strokes, when these are compared on the photoelectric record. Moreover the dart leader type is most frequently observed in intercloud strokes. If the average velocity of the dart leader 3×10^8 cm/sec may be adopted from the above reasons as the velocity of a rapid process in a cloud, the length traversed by a rapid process will range from 0.6 to 1.5 km, the value of which agrees fairly well with the one estimated from the properties of electric field changes. (see I-Section 7)

Following the model described above, the decay portion of a photo-pulse is the period of a so-called afterglow. It is a well known fact that several particular points on a lightning stroke channel sometimes have very long afterglows, which are recognized on rotating photographs of lightnings as long streaks exposed along the direction of rotating of the optical system. This effect has been explained by the geometrical relation between the observation point and the direction of stroke development, i.e., a portion of stroke channel, which advances in the direction along the line of vision of observer, concentrates the radiation of the portion into a point and so produces the very bright point and the long afterglow. A portion that had initially contained the dense space charge accumulation may produce the long afterglow, too. Since our photoelectric method accepts the radiation accumulated over the whole channel of stroke, the photo-pulse will naturally show a long afterglow comparable to the streakwise afterglows found on rotating photographs. The curve B in Fig. 6 shows the duration distribution of afterglows measured from the photoelectric records. The curves C and D show the duration distributions of the streakwise afterglows in particular points on stroke channels, which are measured from rotating photographs of intercloud and ground strokes respectively. The curves E and F show the respective usual short afterglows along the stroke channels. According to what Fig. 6 indicates, the expectation about the accordance between the durations of both the photoelectric and the photographic afterglows is well satisfied. Moreover it must be noticed that the accordance of the afterglow duration is realized between strokes of different kinds, which may be compared with the fact that the period of remarkable brightness of a stroke channel is always of about 5 μsec irrespective of the stroke properties. The value of the decay constant γ of the afterglow, about 3×10^3 sec^{-1}, is given from the comparison to the idealized form of photo-pulse. Such a long afterglow as to come up to nealy 1 msec is probably too long to be maintained by only the recombination process of ions left in the stroke channel after the streamer passage.(10) The fact indicates the point that the excited state of ions will still be preserved in the channel for a while, though the ion concentration itself will rapidly be decreasing. The considerable amount of electricity should still be transferred after the streamer tip has finished its progression. This means the duration of the field change does not always coincide with the period of the streamer advancement.

The usual short afterglow of a lightning channel shown by the curve E or F in Fig. 6, and the rising time of a photo-pulse shown by the curve A are closely alike in their durations. However, the likeness of the durations does not mean that the short afterglow will be maintained through the period of a streamer advancement. Because we can ascertain that for instance the form of luminosity produced by a ground return stroke actually has the steep front less than 100 μsec, the value of which is comparable with the period of a return streamer and is much smaller than the usual short afterglow of the return stroke channel.

The observational fact that both the intercloud stroke and the ground return stroke, which have different velocities and durations from each other, have the afterglows of the similar durations may somewhat be attributed to the recombination process common to general discharges despite of the supply of fresh ions kept still for a while.

8. Amplitude correlation between the photo-pulse and the static pulse

The simultaneous recording of the electric field and the flash luminosity were performed with a dual beam oscilloscope in two summers of 1959 and 1960. We have found the very precise correlation existing between the respective occurrences of both the pulsive changes. Fig. 7 shows two examples of records. In a shorter distance where the electric field usually does not involve any oscillatory radiation pulse, both records of the electric field and the flash luminosity are so alike to each other in shape that they are almost indistinguishable except the point that deflections on records are found on only one side of the base line in the record of flash luminosity while on both sides of it in the electric field record. But the amplitude correlation between the two kinds of pulses produced by the same local rapid process in a cloud is not always so good as it is expected from the impression of the simultaneous records of them. This may be rather reasonable, considering the following several reasons. The propagation conditions of both pulses are different from each other. The direction, as well as the position, of the development of rapid discharge process affects the static pulse intensity. The pulse with an especially slow front is not correctly reproduced since the short time constant adopted in the respective amplifiers deforms it. Moreover fundamentally, the intensity of a static pulse is proportional to the electric moment of the discharged local dipole, while that of a photo-pulse is related to the channel ion density and the ion temperature, which rather depend upon the discharge current. Kitagawa and Kobayashi(11) reported that the intensity of a photo-pulse had the better correlation with the occurrence frequency of radiation pulses superposing themselves on a static pulse than with the intensity of a static pulse itself. However, it is definite that a larger static pulse accompanies a larger photo-pulse statistically.
For example, many dots in Fig. 8 show the amplitude correlation between static pulses of the + type and

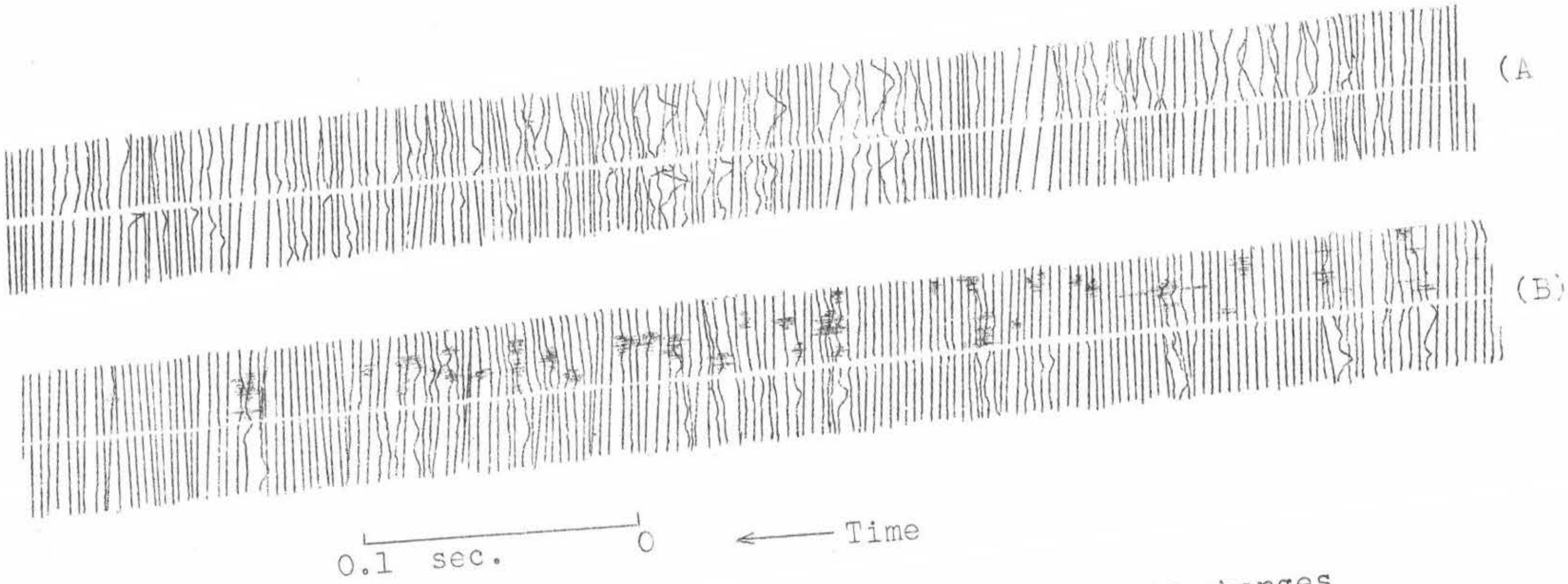

Fig. 7. Examples of simultaneous records of rapid changes of the electric field and the photo-emission. (A) r = 4 km. (B) r = 20 km.

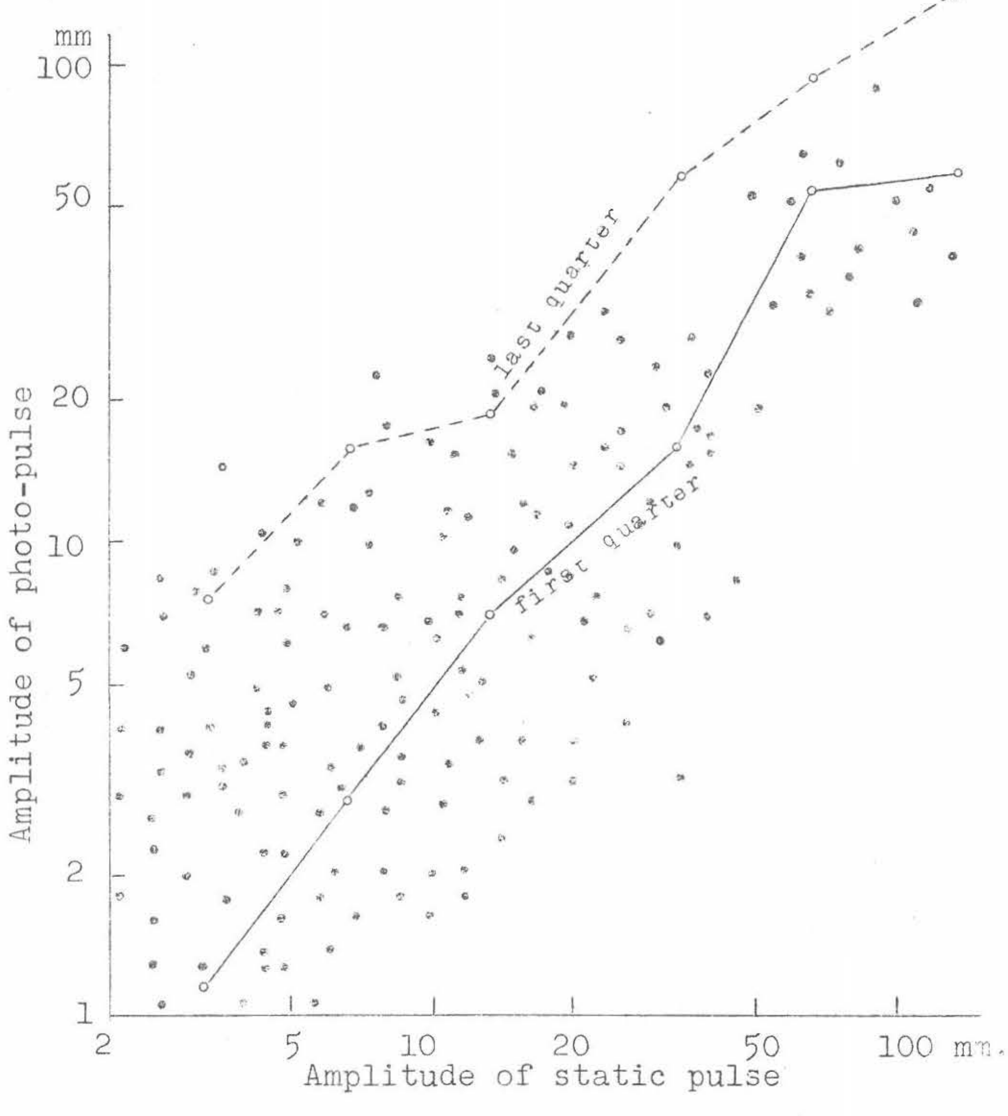

Fig. 8. The amplitude correlation between the photo-pulse and the static pulse found in the first quarter in each of complete processes appearing in the distance range 0 to 5 km. The open circles in the figure indicate the average photo-pulse amplitudes in the first or the fourth quarter of each complete process.

photo-pulses which are found in the first quarter of each discharge process appearing in the nearest distance range 0 to 5 km from the observation station. A curve shown in a solid line connects the mean intensities of the dotted photo-pulses. Each of the mean values is obtained in respective ranges of the static pulse intensities divided with logarithmic equal intervals. The other curve in a broken line likewise gives the mean intensities of photo-pulses found in the last quarter of each waveform recorded in the same nearest distance range. The intensity difference of photo-pulses indicated by the two curves will be interpreted by our estimation that the occurrence altitudes of the pulse origins are to be gradually changed in the course of a complete discharge. Therefore the mean intensity ratio of both pulses corresponding to each other found in a certain limited section of a complete discharge process will be fully significant to investigate the displacement of positions of local pulse origins. This mean ratio, which will be written as the P/S value hereafter, is thought to indicate the ratio to be measured about the local rapid discharge having an average property in that limited section.

To reduce somewhat the probable deviation resulting from the diversity of pulse forms, the P/S value is calculated here regarding the limited static pulses, whose peak deflections are included in the range from 2.5 to 10 mm on the fluorescent screen of the used oscilloscope.* This range of the deflection is comparatively abound in data,

* Of course such a range of deflection does not indicate the absolute intensity range. But if the sensitivity has carefully been altered according as the storm is located near or distant, the limitation in the amplitude received will statistically mean the one in the scale of local discharge as an origin of static pulse.

whose intensities can be measured correctly. The restriction in the intensity of static pulse is probably useful to except very long streamers which may bridge from a cloud to another. The recording sensitivity was appropriately altered in every storm as well as in every reel of film recording. However, the fluctuation of the mean P/S value estimated in every film, which is due to the relative gain difference coming up to 10 db in maximum between the records of the flash luminosity and the electric field change, is actually not more than 30 %, so it is not taken into account in the summation of Table 6.

The P/S value counted in every appropriate section of a discharge process will indicate a variation equivalent to the systematic displacement of the occurrence positions of local rapid processes in a complete slow process. Table 6 shows the P/S values averaged in every quarter of a complete process. The table shows the relative P/S values given when both the sensitivities would be converted into the respective standard gains.

Table 6. P/S values averaged in every quarter of a discharge process.

Sort of discharge	Field type	+ type pulse				- type pulse				Number of data
		1/4	2/4	3/4	4/4	1/4	2/4	3/4	4/4	
Cloud discharge	+	0.5	1.1	1.6	2.3					201
	+→−	0.8	1.7	2.5	2.7	2.2	2.0	1.9	1.1	118
	−→+	1.1	0.9	1.0	0.7	0.9	1.3	0.9	0.7	9
	−					1.5	1.5	1.4	0.7	36
Ground discharge	+	1.6	1.7	2.3	3.8					22
	+→−	2.5	3.0	4.2	3.6	3.9	4.6	3.3	2.5	27
	−					2.8	3.4	2.3	2.1	40

We have not any precise knowledge about the actual propagation condition of the light from a lightning flash. A received flash luminosity perhaps suffers a heavy attenuation through the scattering or the absorption by precipitations in a thundercloud, but the condition outside a cloud seems not to be particularly different from the condition in the free space. Let us try here to estimate roughly the effective propagation condition from the recording sensitivities used for different storms. As it has already been described, if the recording sensitivity is so well selected that the recorded intensity of flash luminosity is always not altered with the change of the distance on the whole, the relation between the recording sensitivity and the distance from the flash origin to the observation point will represent statistically the condition of the attenuation of the light with increasing distances. Now, the real distance from an origin to the observation point will be determined easily at every horizontal distance between them, if the origin of photo-radiation is located at a certain limited altitude. Fig. 9 indicates that the mean sensitivities in the respective distance ranges shown in Table 5 will be roughly proportional to the second or the third power of the real distance, provided that the origins are located in the altitudes from 4 to 8 km. But for the sake of simplicity, the case in which the intensity of light received is inversely proportional to the third power of the real distance will here be calculated, because the sensitivity for a distant thunderstorm in the figure is perhaps too low as previously mentioned. Then if the altitude of a local discharge as the origin of a photo-pulse is h and the horizontal distance from it to the observation point is r, the received intensity of the photo-pulse P will be given by the following expression:

$$P \propto 1/(r^2 + h^2)^{3/2} \,. \qquad (5)$$

On the other hand, the intensity of the static pulse S produced by the above local discharge will be given as follows, when the discharge depending on a vertical local dipole is treated as an averaged case.

$$S \propto (r^2 - 2h^2)/(r^2 + h^2)^{5/2} \,. \qquad (6)$$

From the expressions (5) and (6), the ratio P/S is shown as a function of h/r.

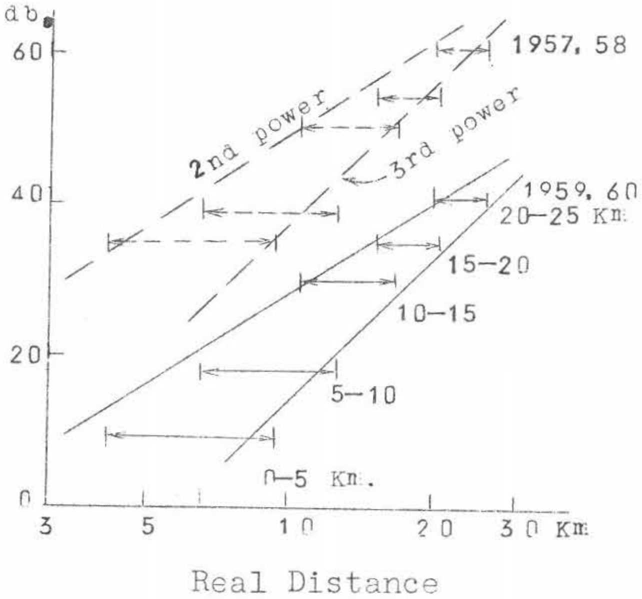

Fig. 9. The average sensitivity used to record flashes in each horizontal distance range shown in the figure. The abscissa indicates the real distance when the altitude of flash origin is supposed to be located between 4 and 8 km.

$$P/S \propto (1+x^2)/(1-2x^2)\ , \tag{7}$$

where $x = h/r$. The curve of P/S calculated is illustrated in Fig. 10. Actually, even in the case where P will be inversely proportional to the second or the fourth power of the real distance, the tendency of the P/S ratio is not particularly altered from the above case since the effect of S is much larger than that of P in the neighbourhood of the reversal distance. The curves of P/S in those cases are also shown in broken lines in Fig. 10. It is to be noted that static pulses produced by local rapid discharges of the same polarity have opposite signs in both sides of the reversal point $x = 1/\sqrt{2}$, i.e., the regions (A) and (B). The discontinuity of the curves at the reversal point results from S being nearly zero, but the actual P/S value will not have such a extremely high value as shown in the region (C), for static pulses should fall into the transitional type $\pm$ or $\mp$ in this region. The width of the region (C) on the logarithmic x axis depends on the length bridged by a rapid local discharge and the distance from the discharge to the station. The bounds of this region in such a case that the length traversed by a local discharge is 1 km are shown in Fig. 10, when the distance r is, for instance, 5 or 10 km.

Static pulses in a waveform obtained in a near distance from the origin usually should be included in the region (A), while static pulses found in a distant place should be in the region (B). And if the principal sign of pulse train on a waveform is reversed on the way of a complete process, then the pulses will be divided into the two regions (A) and (B) according to their signs. Since the static pulses which belong to the + type electrostatic field produced by a cloud discharge are usually found in a near distance, most of them will naturally be included in the region (A). Therefore, the tendency of the P/S ratio increasing in a process as shown in Table 6 will be able to be interpreted by the descending of the successive positions of local discharges as the origin of pulses. The static pulses which belong to the -

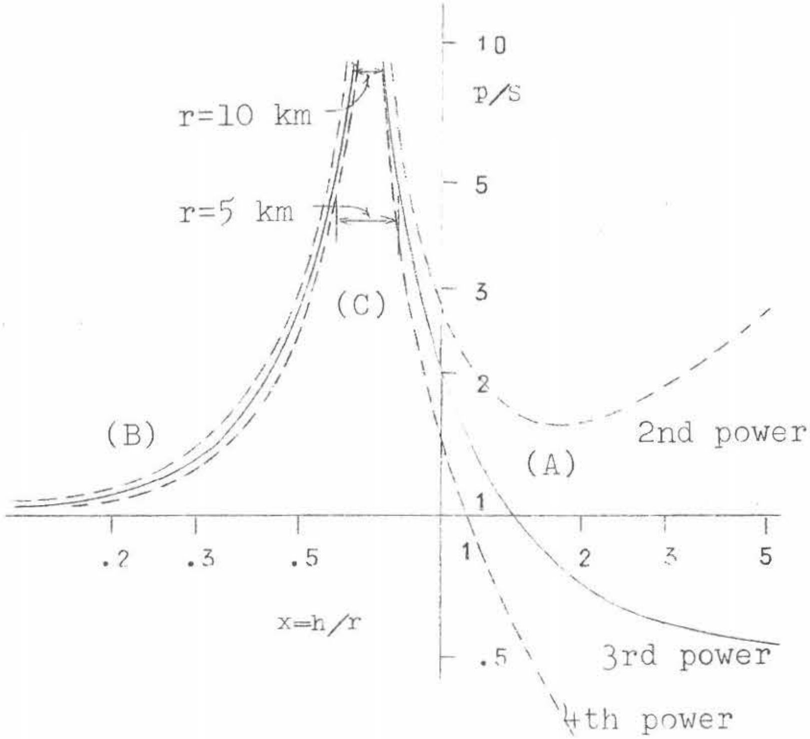

Fig. 10. P/S value calculated from the estimation that P is reversely proportional to the second, the third or the fourth power of the real distance from the origin to the observation station.

type field due to a ground discharge are also found in a near distance, so they should enter the region (A). In this case the decrease of the P/S value in a process will indicate the ascending of the successive pulse origins. On the other hand, the static pulses of the - type field due to a cloud discharge and those of the + type field due to a ground discharge are usually observed in a distant place and included in the region (B), so the tendencies of the respective decrease and increase of the P/S values indicate likewise the respective descending and ascending of the positions of local discharges. Concerning the + and - type static pulses which belong to an electrostatic field of the $+ \rightarrow -$ type, the P/S values vary similarly to the + and - type pulses included respectively in the + and - type electrostatic field changes. But the P/S value of the former are clearly higher than those of the latter, because the $+ \rightarrow -$ type field will include a larger number of static pulses observed in the neighbourhood of the discontinuous region (C). Thus the displacement of successive rapid local processes occurring in a slow complete process can be ascertained from the comparison between both the pulse intensities, and the comparison gives the same result that the properties of electric field changes have given.

The change of the P/S value in the $- \rightarrow +$ type field is not always definite, since the data in this case are very poor. But it seems that the P/S values of the + and - static pulses both decrease. This may indicate that the positions of pulse origins will ascend in the case of + pulses, i.e., the + pulse in this case will generally be produced by the rapid process associated with a negative streamer process moving slowly upward, and that the successive positions of origins will descend in the case of - pulses, i.e., most of the - pulses will rather be attributed to the rapid processes associated with a positive streamer process moving slowly downward. Then the conclusion is that an observed $- \rightarrow +$ type field variation will result from a process which involves the slow positive streamer process moving downdard as well as the slow negative streamer process moving upward. Therefore the latter perhaps does not occur alone without accompanying the simultaneous occurrence of the former. That should be connected directly with the concept of the mid-gap streamer process. In this respect, we consider that the origin of the $-\rightarrow+$ type field also will be nothing but the normal discharge process in a thundercloud. The small occurrence rate of this type field is probably only an indication of the secondary importance of the slow negative process in the neutralization of the cloud electricity.

9. Phase correlation between the photo-pulse and the static pulse.

By the use of a dual beam oscilloscope, we can easilly investigate the relation between both the occurrences of the photo-pulse and the static pulse corresponding to each other with a considerably high time accuacy. Although both the pulses have not always correctly been reproduced, the degrees of deformations in their respective pulse forms will be similar to each other, for the pulses have both been influenced through the same time constant 1 msec. Fig. 11 shows examples of several pairs of pulses. The upper waveform of each pair shows a static pulse and the lower shows a photo-pulse, and the time bases of both the pulse forms are adjusted with the accuracy within 100 μsec.

The time interval between both the peaks of the photo-pulse and the static pulse in a pair, so to speak, the phase difference of both the pulses is also systematically altered with respect to the distance from the origin of them. A photo-pulse generally precedes the corresponding static pulse in a near place, while the former appears somewhat later than the latter in a distant place. Particularly, in the record obtained in a more distant place, where an electric field is usually composed of only oscillatory radiation pulses, we often have found the fact that a group of several radiation pulses, which actually corresponds to a photo-pulse, finishes its activity before the

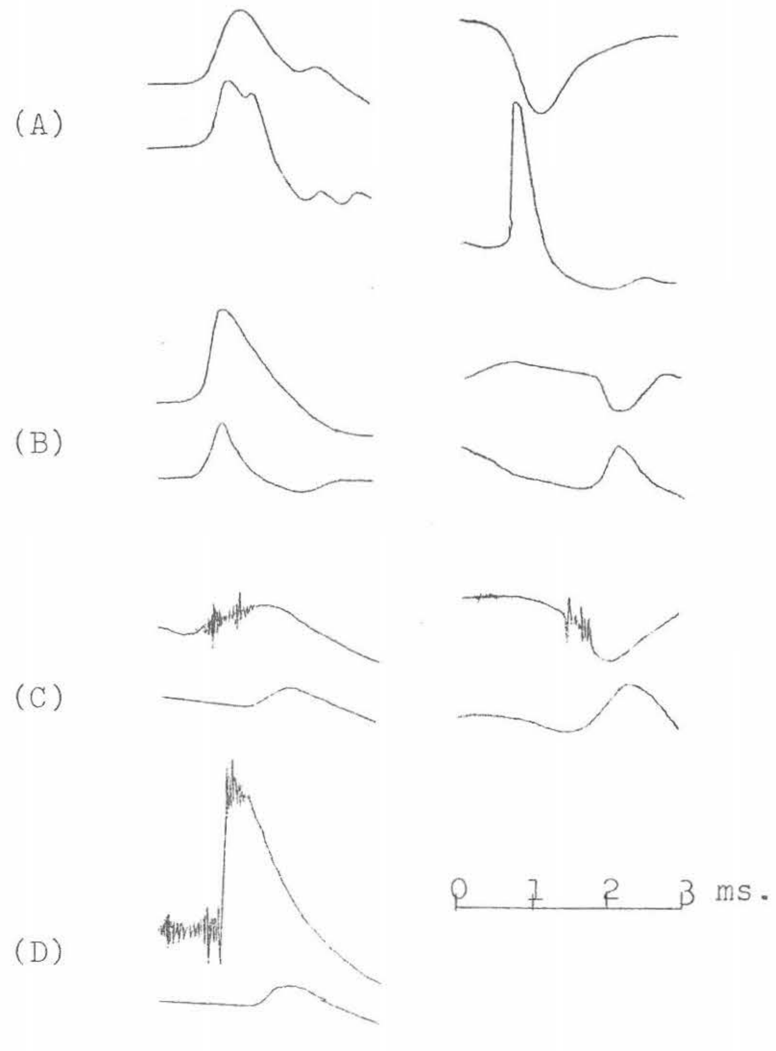

Fig. 11. Examples of pairs of pulses.
The upper waveform is of the electric field change and the lower is of the flash intensity. The distances from respective origins are as follows.
(A) 4 km. (B) 8 km. (C) 16 km.
(D) 20 km.

discernible rise of the photo-pulse. Table 7 shows the mean time interval between respective peaks of the two kinds of pulses. Data adopted in the calculation of the table have freely been selected out of records obtained in several storms, and the number of data is about 200 in every range of distances. The sign used in the table is positive when the photo-pulse precedes the static pulse.

Table 7. Time interval between both the peaks of the corresponding photo-pulse and static pulse. The positive sign is used when the photo-pulse precedes the static pulse.

Distance (km)	Time interval (μs)	
	Cloud discharge	Ground discharge
0 − 5	100	80
5 − 10	60	30
10 − 15	−20	−40
15 − 25	−180	−230

The above tendency on the phase difference between both the pulses may probably be interpreted as follows. The time necessary for a photo-pulse to reach its peak is favorably comparable with the duration of a rapid streamer advancing in a cloud. However, the electrostatic field will somewhat be changed successively for a while after the stop of the streamer advancement, for a considerable amount of electricity is perhaps still transferred through the period of afterglow. The emission of the light from a discharge channel rather will have reference to the discharge current. Therefore if we assume a photo-pulse having a similar form to that of the induction field due to a rapid process, the form of the electrostatic field given by integrating that of the induction field will arrive at its peak value subsequently to the peak in the photo-emission, even though both the recorded forms will be deformed through the short time constants of respective amplifiers. On the other hand, if the radiation field due to a rapid process itself, which is of course dissimilar in character of the origin to the group of oscillatory radiation pulses superposing themselves on a static pulse, influences the form of a static pulse observed in a distant place, the actual form of electric field change in this case will have a peak preceding the photo-emission peak. According to the above interpretation, an electric field change that have been called as a static pulse by this time may rather represent nearly an induction or a radiation field form due to a local rapid process in a distant place. The form of a photo-pulse is thought not to be changed with the distance, while the static pulse is altered in the form from the electrostatic type to the radiation type and its pulse front will become gradually steep with the increase in the propagation distance. The times of initiations of those corresponding two pulses decided on an actual record, however, do not always coincide and this time difference of initiations between the two also has the similar tendency with the distance to that of both the peaks. In other words, the discernible initiation of a pulse, static or photo-pulse, cannot perfectly indicate the actual initiation of a rapid process activity. Hence the degrees of the decrease of rising times of the pulses with the increase of the distances shown in Table 8 are in any way insufficient to produce the phase difference given in Table 7, and thus the above expectation about the static pulse form alteration with respect to the propagation distance is not fully satisfied. This may perhaps be attributed to the estimate that observed pulse forms will be influenced for the most part by the too short time constant of the amplifier. The slower components of those pulses, which seem to continue considerably long before as well as after the noticeable rapid component, will not be found with such a recording method as used in the present apparatus.

Table 8. Rising times of both pulses and difference between them.

Distance (km)	Cloud discharge Photo (μs)	Static (μs)	Diff. (μs)	Ground discharge Photo (μs)	Static (μs)	Diff. (μs)
0 – 5	290	420	130	350	440	90
5 – 10	310	370	60	320	350	30
10 – 15	290	330	40	270	340	70
15 – 25	320	310	– 10	350	310	– 40

However, we can find another cause which answers partially to the bahavior of the phase difference between both the pulses. In the case of a return stroke of ground discharge occurring in a longer distance, the photo-pulse also appears delayed about a few hundred milliseconds from the rapid stepwise

field change due to the return stroke itself, and moreover it has not such a steep front as it will be expected from the rapid progression of the return stroke. Fig. 11 (D) is an example of this sort of photo-pulse. The delay of the photo-pulse in this case is perhaps due to a quite different cause from the alteration of the static pulse form. It may somewhat be attributed to the observation technique. Because the field of vision in our photo-electric arrangements is limited by the angle of elevation 10° , so the photo-emission from the lightning stroke proceeding through a layer lower than h = r. tan 10° should not be found except for the slight reflected light from an upper part of the cloud. For instance, at the distance r = 20 km, a return streamer ascending from the ground will be barely found with our photoelectric apparatus after the tip of it arrives at the altitude h = 3.5 km. The time necessary for a return streamer to reach this altitude will usually become the order of a few hundred microseconds. A similar effect to this, for instance the effect due to some obstacle for the transit of light from the discharge channel to the observer may influence the delay of an observed distant intracloud flash luminosity described previously.

10. Time intervals of successive local rapid discharges

Static pulses or photo-pulses produced by successive local rapid discharges are of course found repeatedly many times. We can see that the value of each time interval between their occurrences is almost arbitary even in a complete process. Now let us consider the probability $p\,\Delta t$ that a discharge will occur in a period from t to $t+\Delta t$ after the appearance of the previous discharge. If successive discharges occur at random, in other words, if there is none of causes and effects between every discharge occurrence, the occurrence probability denoted here with p will be constant irrespective of the lapse of time t. Now the probability P that any discharge will not occur in the period from 0 to t after the occurrence of a certain discharge must be equal to the probability that the time interval from the occurrence of this discharge to that of the next discharge will fall between t and infinity. Hence,

$$P = \int_t^\infty Pp \cdot dt \qquad (8)$$

Solving this equation (8) with the condition of p being constant, we shall get at the following relation:

$$P = \exp(-pt)\,, \qquad \text{or} \qquad \log_e P = -pt\,. \qquad (9)$$

Hence if the discharge intervals are of the random distribution, the curve of their cumulative distribution, which should be equivalent to P, will become a straight line on a semi-logarithmic diagram. The inclination of the curve in this case indicates the occurrence probability p, the reciprocal of which is equal to the mean value of the distribution of time intervals.

The distribution curve of time intervals of actual photo-pulses is shown in Fig. 12. There is not found any significant difference between the pulse intervals of cloud discharges and those of ground discharges. The curve can roughly be divided

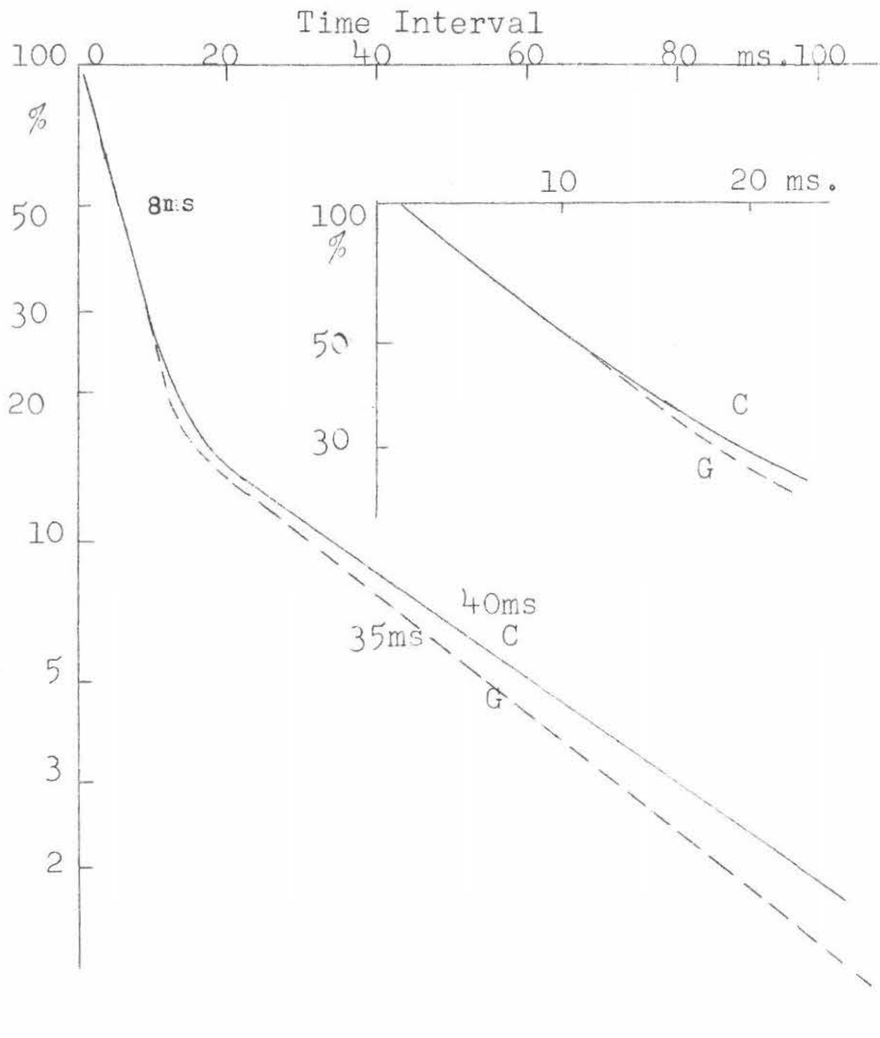

Fig. 12. Probability curves of the time intervals of photo-pulses. The curves (C) and (G) represent the cases of cloud discharges and ground discharges respectively.

into two straight portions which have different inclinations respectively. Such a concave bending of the probability distribution curve as shown in the figure will result from gathering two or more groups having different probabilities of occurrence. For example, if the ratio of numbers of data which belong to two random groups with respective different occurrence probabilities p_1 and p_2 is given by k_1/k_2, where $k_1 + k_2 = 1$, then the cumulative distribution of the whole composed of the two groups will be shown as follows:

$$P = k_1 \exp(-p_1 t) + k_2 \exp(-p_2 t) \quad (10)$$

Then the inclination of the cumulative distribution curve on a semi-logarithmic diagram will be given by the following equation:

$$p(t) = -d(\log P)/dt$$
$$= \frac{k_1 p_1 \exp(-p_1 t) + k_2 p_2 \exp(-p_2 t)}{k_1 \exp(-p_1 t) + k_2 \exp(-p_2 t)} \quad (11)$$

Now $p(0) = k_1 p_1 + k_2 p_2$, and $p(\infty) = p_2$, if $p_1 > p_2$. In a group of larger occurrence probability, the time interval generally will become shorter and naturally a larger number of data will be counted in the distribution. If $p_1 > p_2$, then the relation $k_1 > k_2$ is usually satisfied and $p(0)$ will become nearly equal to p_1.* Namely, the respective inclinations of the two straight portions on the cumulative distribution curve indicate the occurrence probabilities of the two groups. The two mean intervals given by the reciprocals of the inclination values of the two straight portions in Fig. 12 are respectively about 8 and 40 msec. The group of larger intervals perhaps corresponds

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* If both the groups are summed up throughout the same long period, the relation $k_1/k_2 = p_1/p_2$ will statistically be satisfied. Then $\bar{p}(0)$ always has a value between p_1 and $0.83p_1$.

to the case in which the recording sensitivity used in the observation would be relatively low, and it may be based upon the locally charged portions of comparatively large scales. The distribution of the time intervals between multiple strokes of a ground discharge just coincides with that of this larger interval group on the whole.(12) This confirms the interpretation in which the difference between the origins of the rapid streamers appearing in clouds and those of the dart leaders guiding the subsequent ground strokes is nothing but the difference of scales of the locally charged portions with reference to the above two processes. On the other hand, the group of the shorter time interval naturally should represent the local charge accumulation of relatively small scale. The space equivalent to the mean interval 8 msec is about 100 m, provided that the slow process is developed with the velocity 1.3 x 10^6 cm/sec. It is of the same magnitude as the average extent of a locally charged portion.

The curve also indicates the point that the time interval of pulses has a lower limit of about 1 msec, and there appear to be two possible standpoints to account for this. The one will be attributed to a measuring technique: i.e., the successive two pulses will not be separable unless the time interval between them is longer than the duration of the previous pulse, which is usually the order of 1 msec. From the assumption that the next pulse often will occur successively before the activity of the previous pulse has not yet perfectly finished, it is required that local rapid discharges as the origins of pulses do not only occur along one main trunk, but do along many branches to be supposed. The other standpoint is based upon the consideration that there must be some space of very low charge accumulation between the respective local highly charged portions which can develop the rapid discharges separated from one another. Then the lower limit of the time intervals of pulses will indicate the time necessary for a slow process to traverse the minimal space, if the greater part of pulses are produced along only one main trunk. However, the extent of the space estimated from the above minimal time interval is only about 10 m and this value seems to be too small as compared with the average extent of locally charged portion about 100 m in diameter. Here it will be more reasonable to take up the first interpretation.

11. Conclusions

We have investigated the flash luminosity in connection with the earth's electric field variation due to the lightning discharge. The results confirm the assumption derived from the properties of electric field changes concerning the composition of a discharge process occurring inside a thundercloud. Those will be summarized as follows.

(1) A complete discharge process which takes place in a thundercloud usually has the duration from 0.2 to 0.5 second. The median value of it is 0.3 second.

(2) A slow process continues through the above duration. It produces a gradual electrostatic field change on the earth's surface and simultaneously accompanies a weak continuous luminosity and a high frequency electromagnetic radiation. The intensity of a continuous luminosity is subjected to an appreciable fluctuation through the process, but on the whole it takes a form with a peak at the position of about one third from the initiation. This probably represents the variation of the main process activity in a cloud discharge.

(3) Many strong photo-pulses are found coincidently with individual static pulses appearing in a slow process. They show the occurrence of many rapid streamers which are attributed to the ununiform distribution of space charge in a thundercloud. The advancing period of a rapid streamer estimated from the form of a photo-pulse ranges from 200 to 500 μsec and the velocity of it should be of the order of 10^8 cm/sec or more. The form of a photo-pulse also indicates that a considerable amount of electricity will still be transferred for a while after the development of rapid streamer has finished.

(4) From the comparison between the rapid changes of the flash intensity and those of the electric field, we can estimate a systematic displacement in the occurrence positions of many rapid local discahrges in association with a slow principal discharge process. The estimate accords fairly well with the result deduced from the occurrence rates of the observed types of electric field changes: i.e., most of the successive positions of local discharges gradually descend in the case of a cloud discharge process, on the other hand they generally ascend in the case of a ground discharge.

(5) The electric field change denominated as a static pulse does not always represent only the electrostatic field change due to a rapid process, but becomes to be influenced by the induction or the radiation field due to it, in a longer distance exceeding over 20 km. For that reason, the phase difference arised between the photo-pulse and the static pulse, both produced by the same rapid process, is altered with the change of the propagation distance. The former usually precedes in a shorter distance, while the latter precedes in a longer distance. The alteration in the phase difference comes up to about 300 μsec while the distance from the origin increases from 0 to 30 km, when both pulses are recorded through the amplifiers with the same time constant 1 msec.

(6) Values of time intervals between successive rapid processes in a thundercloud are of a nearly random distribution, and this indicates that the upper positive or the lower negative electric charge of a thundercloud will respectively be composed of many local highly charged portions scattered at random in the thundercloud. It should be connected with the subcell construction of a thundercloud. The observational fact that there is no definite lower limit in the distribution of the time interval of pulses indicates that all rapid processes should occur along many branches to be involved in a main slow process.

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