Progressive Lightning
III—The Fine Structure of Return Lightning Strokes

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[Plates 5–10]

1—Introduction

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It has been established in two previous papers by Schonland, and the authors (Schonland and Collens 1934; Schonland, Malan and Collens 1935) that the lightning flash involves two consecutive processes, a downward moving leader and an upward moving main or return process. These two processes are repeated for each separate stroke of the series which may make up a complete flash.

In these papers it has been shown that the return stroke travels with a velocity of the order of 2×10^9 cm./sec., and that the velocity decreases as the stroke travels upwards. Variations in luminosity and in velocity have been found to occur after the stroke has passed points where the original leader channel has branched.

The present paper is concerned with a detailed study of these variations in luminosity and velocity, and with their relation to the branches of the channel. It will be shown that the luminosity-time curve at any point along the channel is not a simple one but has an important fine structure (Malan, Schonland and Collens 1935; Malan 1935). This fine structure indicates that at various times after the luminosity is first produced at a point by the upward-moving process, the luminosity rises and falls as the result of the development of additional energy in the channel.

Thus we are led to picture the channel as the seat of a number of "component" return strokes. It will be shown that the evidence indicates that most of these components are called into being by the branches on the channel.

The material available consists of Boys' and other camera photographs of 120 lightning flashes.

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2—The General Nature of the Return Stroke

In order to simplify the discussion of the evidence as to the fine structure, it is desirable to consider first a general picture of the luminosity-time relation in the return stroke channel. In the case of the first stroke of the series which constitutes a lightning flash, the channel is fairly heavily branched. Fig. 1 is a diagrammatic representation of such a stroke in an idealized vertical channel, as it would be recorded by a camera with one lens moving past a fixed film in the direction indicated by the arrow.

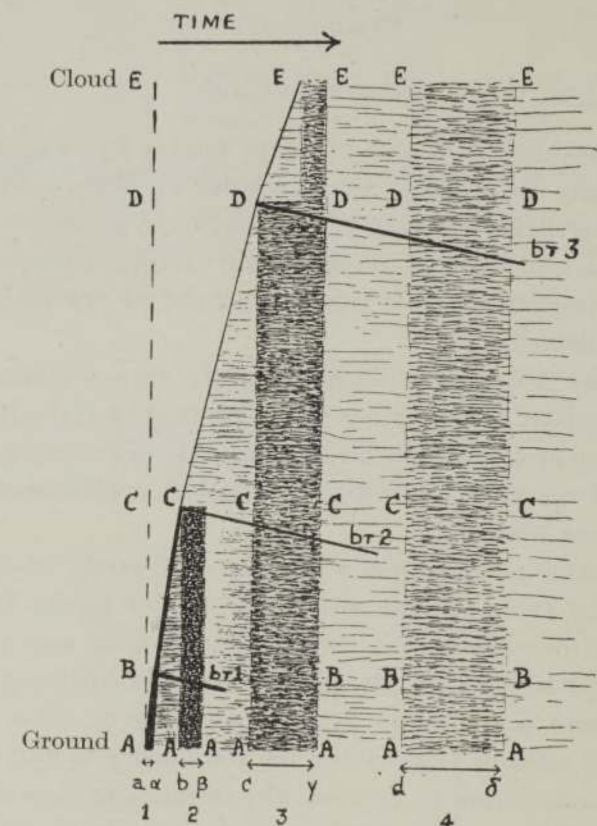

Fig. 1

For any point on the channel, a horizontal line gives the time in the direction of the arrow, and the intensity in terms of the density of the shading in the figure. Thus at the base of the flash the luminosity-time curve indicates the existence of four succeeding components in luminosity, while at the top of the flash these components are two in number, the first being itself double.

These components are distinguished by sharp initial boundaries, *a*, *b*,

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c, *d*, and less clear final boundaries at which their intensity substantially decreases, α, β, γ, δ. The time intervals $a\alpha$, $b\beta$, $c\gamma$, $d\delta$ give therefore values for the effective durations of components 1, 2, 3 and 4, while the time intervals *ab*, *bc*, *cd* give the time separations of the succeeding components. The letters *A*, *B*, *C*, *D*, *E* are used to mark definite points along the channel, while *br* 1, *br* 2, *br* 3 denote successive branches.

The slope of the line *ABCDE* for the leading edge *a* of the first component is due to the lens movement and gives a measure of the velocity of movement of the first appearance of luminosity in the upward-moving return stroke. Its curvature is an indication of the fact that the velocity of edge *a* decreases as component 1 moves upwards.*

Fig. 1 further indicates by the lack of curvature in the leading edges of succeeding components that the measurements to be discussed show that components other than the first travel with a velocity so high that it cannot in general be measured by us. Some of these components, as the diagram shows, are able to catch up with their predecessors, component 2 at branch 2, component 3 at branch 3. (It is probable that an unmarked component 1′ catches up at branch 1.)

The connexion between the components and the branches in the channel will be shown to be very close. Thus component 2 starts at the moment† when component 1 has reached branch 2, and component 3 when component 1 has reached branch 3. Each of these components travels so fast that it extends from the ground to the branch concerned a very short time after it has first been called into existence.

When component 1 reaches *B* (branch 1) it travels outwards along branch 1 and upwards towards *C*. Both the preceding channel length *AB* and branch 1 are observed to be very intensely illuminated, but a definite diminution in intensity is observed in the channel length from *B* to *C* (Schonland, Malan and Collens 1935, p. 618).

At the instant† when component 1 reaches the second branching point *C*, component 2 is observed to start at *A* and to cover the distance *AC* without appreciable delay. This component increases the luminosity along the whole length *AC*, and this increased luminosity is evident also along the branch 2. Again, we observe that the further development of the channel from *C* to *D* proceeds with decreased intensity, as if the channel

* Owing to the difficulty of making accurate measurements on short lengths of channel traversed at high velocities, this change in curvature after branching points has only been established for the uppermost portions of a lightning stroke where the velocity has been found to be much lower than that near the base of the stroke.

† "At the moment" or "instant" as used in this connexion in this paper signifies that the events occur within 10μsec. of one another.

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below C were chiefly interested in the development of branch 2. Indeed, if branch 2 is short and there is not a prominent branch which the upward moving fused effort of components 1 and 2 can reach before the completion of branch 2, component 2 ceases and its time of duration $b\beta$ is found to be the same as the time for the whole of branch 2 to be blazed. In case such a prominent branch does exist very near to and above C, the structure of component 2 becomes more complicated. Such cases are dealt with in detail in § 7.

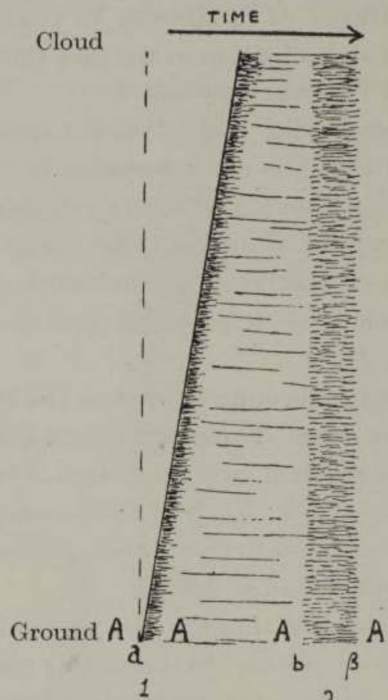

Fig. 2

Component 3 in many cases only lasts until branch 3 is completed. In other examples we find, as in fig. 1, that it continues upwards after branch 3 is completed. This occurs if branch 3 is not exceptionally long and is fairly near the base of the cloud, and suggests that after the completion of branch 3 component 3 is chiefly concerned with a branch or similar call upon its activity hidden in the cloud.

Component 4 starts after the first component has reached the cloud and all the branches have been completed. It is thus concerned with a process taking place in the cloud itself.

There may be also additional components after component 4 which are connected with processes of discharge inside the cloud.

Fig. 2 illustrates what is found in the case of subsequent strokes which

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carry no branches. In such cases components other than the first start after the first component has reached the cloud and are comparatively weak in intensity.

In cases where a subsequent stroke—generally the second stroke—does carry a branch, it is observed that a component which is connected with the illumination of this branch exists in the same manner as in fig. 1.

The evidence in support of this picture of the fine structure is given in succeeding sections. It must, however, be pointed out that the photographic method of analysing the fine structure is not ideal. The first leading edge *a* of component 1 is clearly marked, but the leading edges *b*, *c*, *d*, etc., of subsequent components are somewhat diffuse and do not lend themselves to measurement to the same degree of accuracy. Further complications arise owing to the tortuosity of the actual channel, which gives rise to difficulty in the observation of the components when the momentary direction of the channel is nearly the same as the direction of relative motion of the lens and the film. In many cases only a few reliable measurements on components other than the first are possible.

For similar reasons, while a great many cases permit of reasonably good investigation upon the original negatives, it is only rarely that an example can be found which will show the fine structure in satisfactory detail for reproduction.

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3—Method of Measurement

The procedure adopted for drawing up the time table for the leading edge *a* of the first component has already been described (Schonland and Collens 1934, p. 655). A contact print is used for these measurements, a fine line being drawn to join corresponding points on the two images of the same stroke formed by the two Boys lenses. The print is cut up and the two corresponding images are mounted side by side so that the two portions of the line are parallel, with the instantaneous direction of motion of the lenses outwardly directed. By measuring the difference in separation between pairs of corresponding points on these images, the time of formation of the leading edge *a* can be determined for any part of the stroke. This edge is considered to start at the base of the stroke (marked *A*) at the zero of time.

As the edges *b*, *c*, etc., of subsequent components are not sharply defined, prints have been found unsatisfactory and the original negatives have been used instead, measurements being made with a transparent glass scale graduated in tenths of a millimetre. The time separation of these edges from the leading edge a in the direction of instantaneous motion of the lens is measured at definite points on the stroke. These readings are then added to the times of formation of the corresponding points on the leading edge a. In this way a complete time table can be drawn up for all the components of a stroke.

The first leading edge of component 1 can be measured to an accuracy of about 3 μsec. In a few good cases the possible error of measurement for subsequent component edges b, c, d, etc., is 5μsec., but it may rise to 20 or even 50μsec. for weak components of high order whose edges are usually very indistinct.

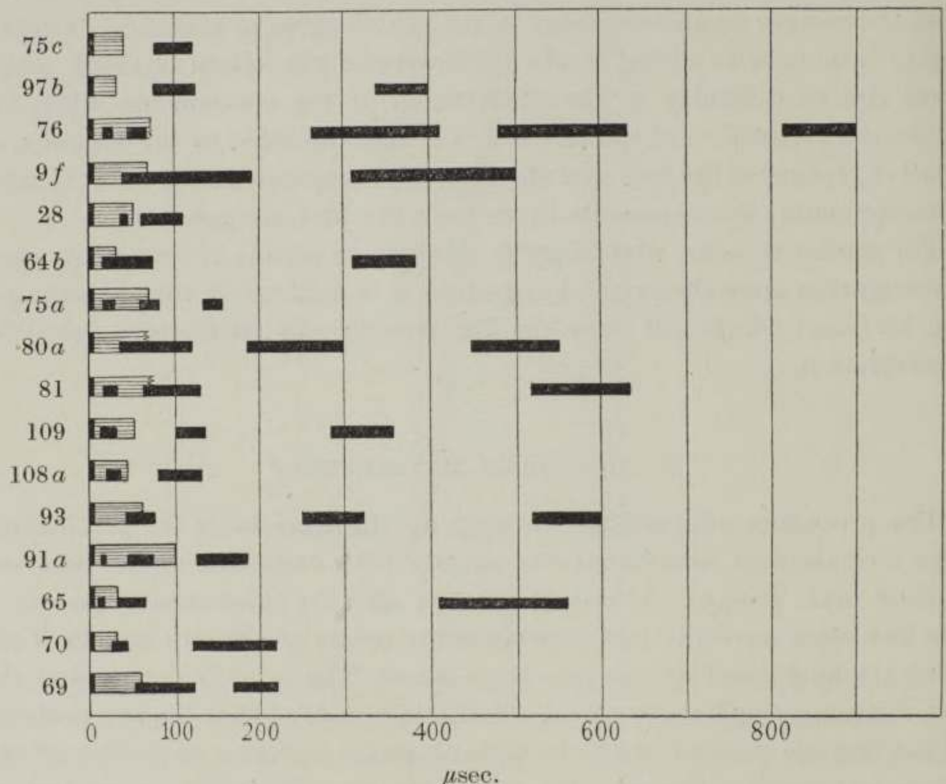

Fig. 3

4—Distribution of Components in Time and Duration

Fig. 3 shows the distribution in time and the duration of the components at the base of fourteen branched and two unbranched strokes, these last being numbers 97b and 75c. The vertical line at the extreme left indicates the zero of time, which is also the time at which the stroke first starts at

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the ground (i.e. edge *a* at point *A*, using the terminology of § 2). The figures at the left are the serial numbers allotted to the strokes on the records. The small rectangles shaded with thin horizontal lines indicate the times taken for the stroke to reach the cloud.

The black strips refer to the components making up the complete stroke, the length of the strips indicating their times of duration. The left-hand edges of the strips give the times of commencement and the right-hand edges the times of stopping of the components.

The duration of component 1 at the base of a stroke is very short, and owing to the intense blackening and consequent halation produced on the film at this point, an accurate estimate of the duration is usually impossible. It has been estimated, however, that the upper limit of the duration of component 1 is of the order of 10μsec. This limit is shown by the narrow black strips at the extreme left of the diagram.

Strokes 76, 80 and 81 were too near the camera to get full pictures of these strokes, and the time they took to reach the cloud has been estimated.

It can be seen that for the case of branched strokes the second and sometimes the third components start before the stroke has reached the cloud, whereas strokes 97*b* and 75*c* which are unbranched have their second components starting after the cloud has been reached.

Some of the second components which are apparently of long duration (strokes 69, 64*b*, 9*f*) may be composite (see § 8).

Fig. 4 is a distribution table showing the times at which the different components set out from the base of the discharge. The time of the initial appearance of component 2 is seen to vary from 10 to 50μsec. after the start of component 1, the most frequent value being 25μsec.

The time of appearance of component 3 varies from 30 to 300μsec., while that of component 4 varies from 100 to 500μsec. in extreme cases.

Fig. 5 shows the relation between the durations of components of the same branched stroke. The circles indicate as ordinates the times of duration in microseconds of successive components starting with component 2 at the left. Circles joined by lines indicate components belonging to the same stroke whose serial number is given by the number alongside.

The slope of the lines show that the duration of a component increases with its order, the third lasting longer than the second, the fourth longer than the third, etc. The only exceptions are stroke 69, where the second component lasts longer than the third, and stroke 76, where the fourth and fifth components are of the same duration and the sixth shorter than either of these. The reason for this increased duration is that the prominent

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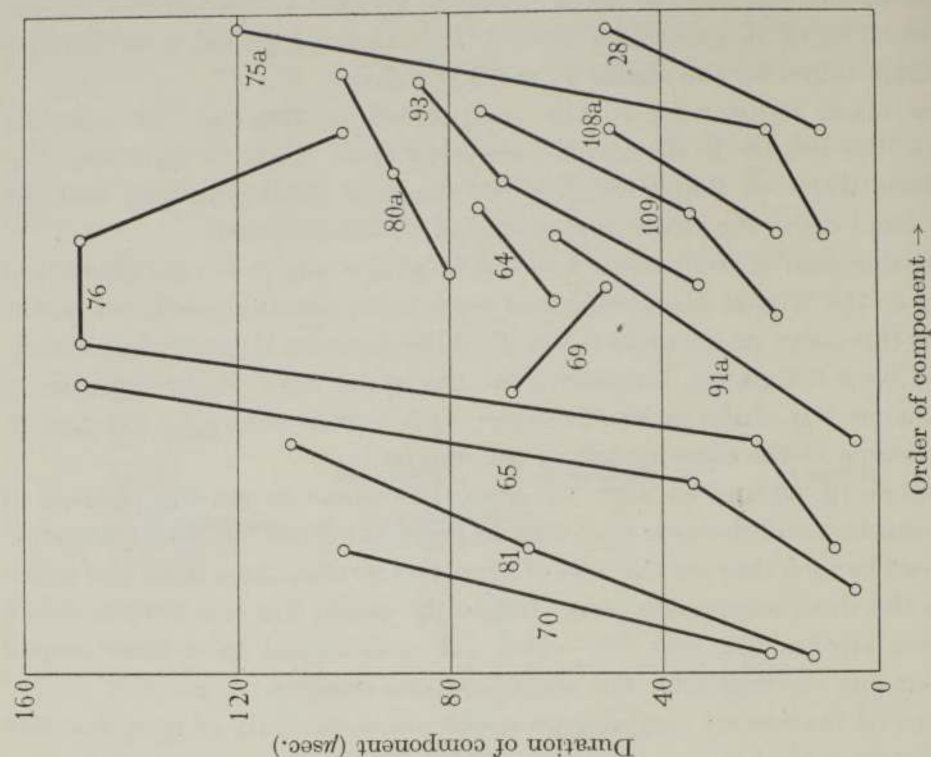

Fig. 5

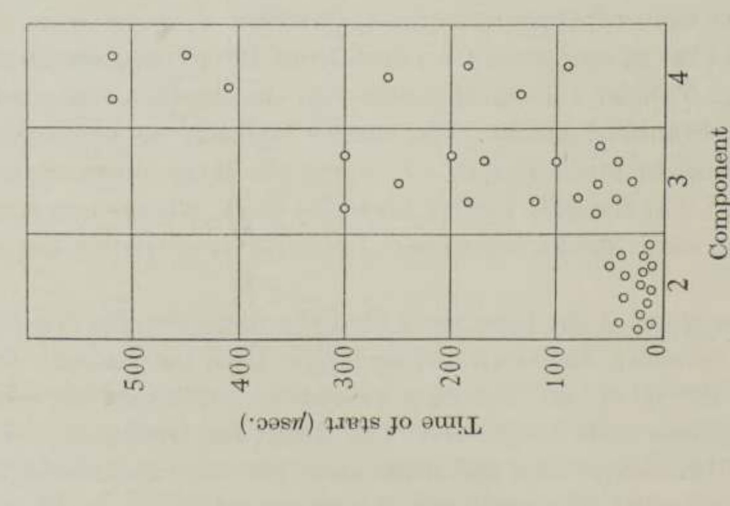

Fig. 4

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branches high up the track are usually longer and develop more slowly than those lower down.

The most frequent values of the durations and the times of starting of the components of branched strokes are shown in Table I.

TABLE I

Component	Duration μsec.	Time of start μsec.
1	<10	0
2	20	25
3	50	70
4	100	(150–500)

5—RELATION OF THE COMPONENTS TO THEIR CORRESPONDING BRANCHES

(*a*) *Time of Starting*

It has already been pointed out in the discussion of the general case (§ 2) that the time of starting of a component related to a branch is practically coincident with the time at which the first upward flow of luminosity reaches a branching point in the channel originally formed by the downward moving leader.

In fig. 6, which shows this connexion, the time of starting of a component at the base is plotted against the time of branching of its related branch. Cases of very profuse branching have been omitted, as it is possible that in such cases a component may be related to more than one branch (§ 7), making it impossible to determine which branch was chiefly responsible for the commencement of the component. If the points lay on the line drawn at 45° to the axes, the diagram would indicate that the starting at the base and the branching were simultaneous.

Actually the points tend to lie slightly above this line, so that the time of starting of a component must be considered to lag slightly behind the time of commencement of the branching process. The order of magnitude of this lag is 10^{-5} sec./km. of channel length from the ground to the branch. The possible error of measurement is slightly above 10^{-5} sec./km., so that the actual value of the lag may be less but is certainly not more than this figure.

(*b*) *Durations of Components and their Corresponding Branches*

From the general picture given in § 2 it would be expected that a component would definitely fall off in luminosity as soon as its corresponding

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branch was completed. This has been established in the case of a few good photographs. Generally, however, precise measurement is impossible on account of the bad definition of the edges β, γ, δ, etc., at which the luminosity decreases. This decrease is much more gradual than the increase in luminosity at the leading edges. In addition, by the time the branch is completed, the initial upward moving luminosity may have passed other subsequent branches which in turn also make a demand on the channel and produce fresh components [§ 7 (*b*)].

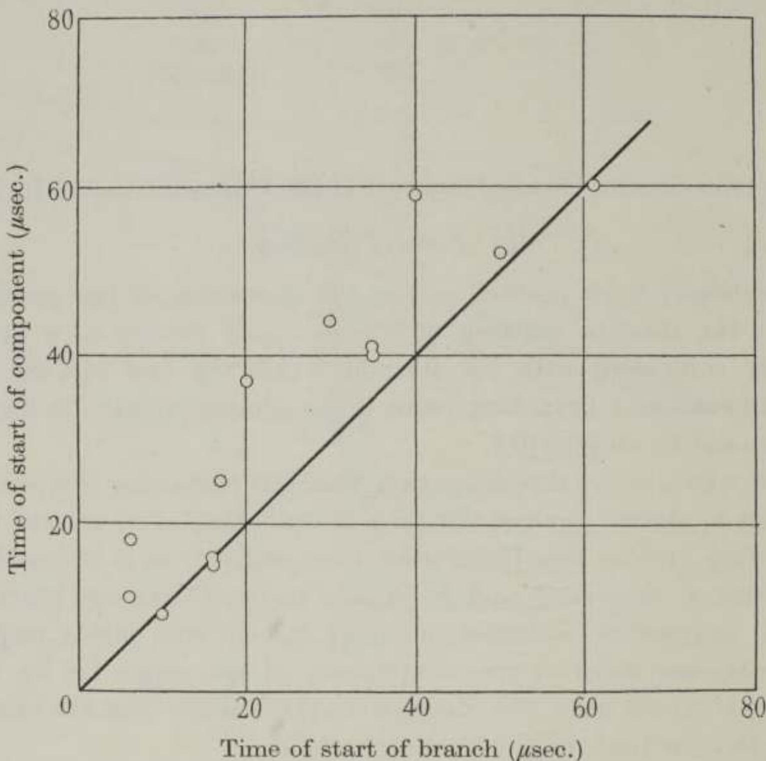

FIG. 6

6—VELOCITY AND DIRECTION OF COMPONENTS

(*a*) *Components Associated with Branches*

It has been mentioned in § 2 that components associated with branches have been found to take a very short time to cover the distance between the ground and the branching point. The magnitude of the time interval will of course depend on the height of the branch above the ground. When this height is relatively small the related component is usually intense and its leading edge is fairly sharp, but the time interval to be measured is

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extremely short. On the other hand, when the branch is high up the channel, the longer time interval should allow of greater accuracy of measurement, but unfortunately the leading edge in this case is found to be more diffuse than in the former. For these reasons it is in most cases extremely difficult to make an estimate of the velocity, or even to determine the direction of progression of a component. All that can be said as to the direct evidence on this important question is that the direction of movement is indeterminate with our present data, for the velocity in all measurable cases definitely exceeds 10^{10} cm./sec., a value which is the limit of measurement under these conditions.

For components not associated with branches the velocity, as is shown in the next section, is sometimes low enough to be determined.

(*b*) *Components not Associated with Branches*

These components always reach the whole way from the ground to the cloud and are associated both with branched and with unbranched strokes. They constitute the later components of branched strokes and the only subsequent components of unbranched strokes.

An analysis of nine cases where a definite conclusion can be drawn as to their direction shows that two progressed upwards from the ground and seven downwards from the cloud.

Many of these components have very high velocities either upwards or downwards exceeding 10^{10} cm./sec. Others again which have lower velocities are observed to progress downwards only. Four such "cloud" components which were definitely progressing downwards had velocities of $4 \cdot 10^9$, $2 \cdot 10^9$, $4 \cdot 7 . 10^9$ and $2 \cdot 7 . 10^9$ cm./sec. respectively.

7—Discussion of Specific Cases

Prints of some of the original photographs are given in figs. 7, 13, 15, 16, and 17 (Plates 5–9). They are explained by means of diagrams (figs. 8–12,14, 18 and 19) which illustrate the different components. The time separations of the components are not drawn to scale on the diagrams, as they would then be too near each other to depict clearly what can be seen on the corresponding photographs.

Definite points along the channel are again marked by the letters *A*, *B*, *C*, etc. A figure next to one of these letters at the first leading edge denotes the time in microseconds at which the return stroke first reaches that point. The zero of time is again the time of starting of the stroke at the ground. A figure at a point next to a branch indicates the time the

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luminosity first reaches that point. Thick arrows show the direction of instantaneous motion of the lens of the Boys camera.

Tables are also given of the time in microseconds when the edges b, β; c, γ; d, δ, etc., reach the points A, B, C, etc.

(a) *Strokes with Single Branches*

(i) *Stroke* 70.

TABLE II (figs. 7 and 8)

(Time in microseconds after start of first component at A)

Point on track	Comp. 1	Comp. 2		Comp. 3	
	a	b	β	c	γ
A	0	20	44	120	220
B	3	20	40	—	—
C	5	17	47	115	—
D	10	17	46	—	—
E	17	—	—	—	—
F	16	(P 28)	—	116	—
G	26	—	—	110	—
H	28	—	—	—	—

Table II shows that component 2 starts at A (fig. 8) shortly after component 1 reaches the branching point above E. Component 2 is interested in the branch until it is completed at a little over 23μsec. By this time the first component has reached the cloud and some hidden branching process is probably responsible for the fact that component 2 progresses upwards to the cloud as shown by the shaded strip at P (fig. 8) which starts at 28μsec.

Component 3 is interested in the cloud only and starts at about 90μsec. after component 1 has reached the cloud.

(ii) *Stroke* 64b.

TABLE III (figs. 7 and 9)

(Time in microseconds after start of first component at A)

Point on track	Comp. 1	Comp. 2		Comp. 3	
	a	b	β	c	γ
A	0	15	74	310	384
B	5	—	—	—	—
C	16	—	68	—	—
D	22	—	60	—	—
E	32	—	—	272	—

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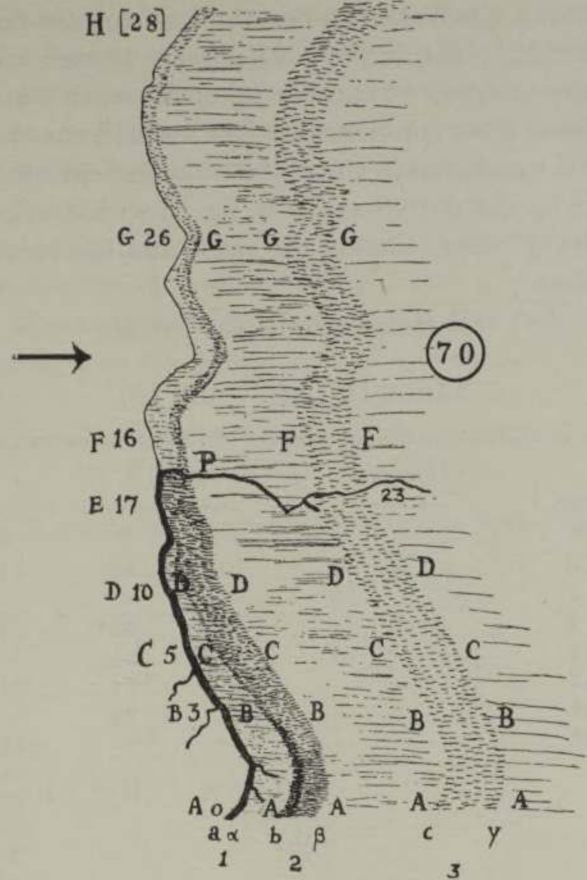

Fig. 8

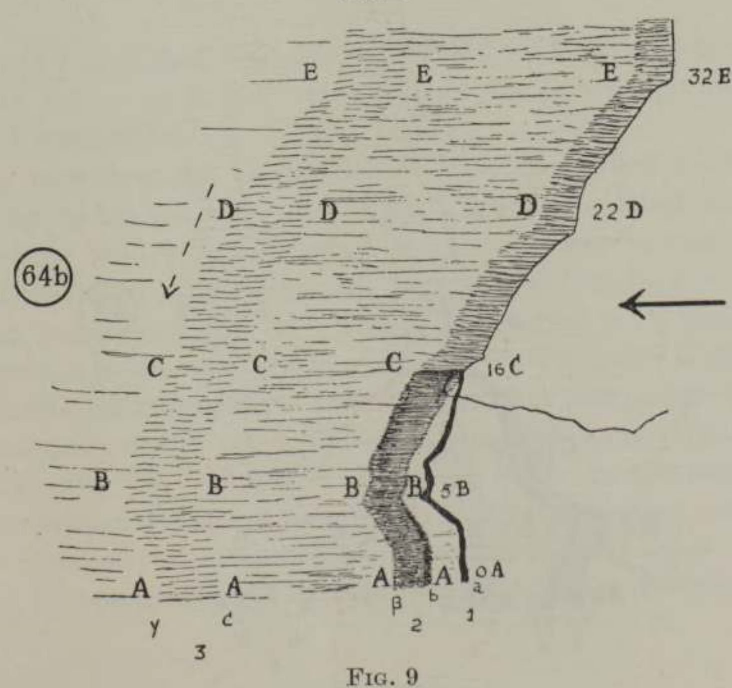

Fig. 9

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Here component 2 again starts when the first upward flow of luminosity reaches the branching point at C (fig. 9), namely 16μsec. after component 1 has started at the ground. It catches up component 1 at C and lasts till 74μsec., i.e. 30μsec. after component 1 has reached the cloud.

Component 3 is interested in the cloud only and definitely moves downwards (indicated by the dotted arrow in fig. 9) with a velocity of $4{\cdot}7 \times 10^9$ cm./sec. Branch C is very faint on the print and has been indicated by a series of white dots.

(b) *Heavily Branched Strokes*

(i) *Stroke* 65.

TABLE IV (figs. 7 and 10)

(Time in microseconds after start of first component at A)

Point on track	Comp. 1	Comp. 2		Comp. 3		Comp. 4	
	a	b	β	c	γ	d	δ
A	0	9	13	30	65	410	560
B	2	—	13	—	—	—	—
C	4	—	—	26	63	374	—
E	11	—	16	29	—	—	—
F	12	—	—	—	71	348	—
G	18	—	—	—	92	—	—
H	26	—	—	—	—	[326]	—

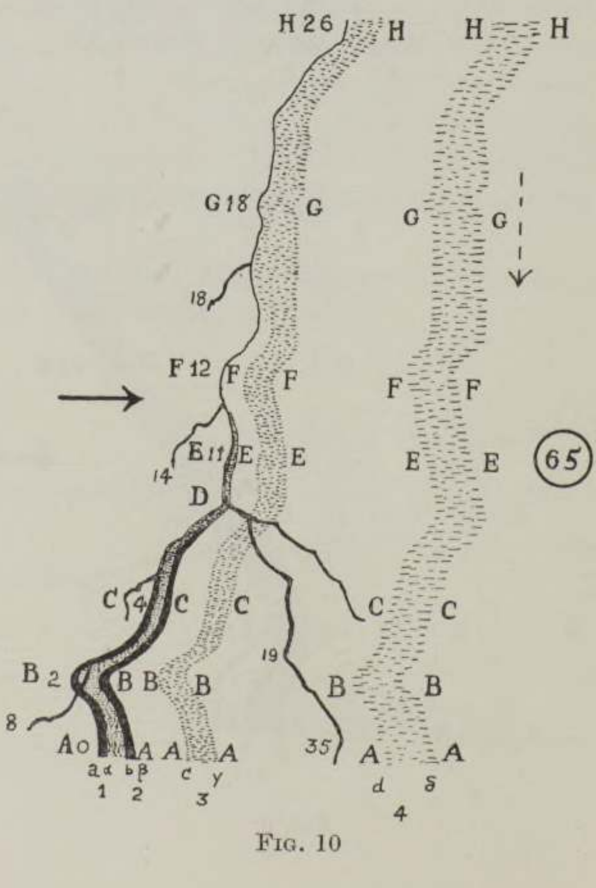

FIG. 10

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Flash 65 consists of a single heavily branched stroke. Component 2 starts at the ground when component 1 reaches the branching point at D, viz. at about 9μsec. after the stroke has started at the ground. Above D, component 2 is also interested in the branch above E as illustrated in the diagram. Component 3 starts at about 30μsec., i.e. when component 1 has reached the cloud.

In component 4 the luminosity travels downwards (indicated by the dotted arrow) with a velocity of 4×10^9 cm./sec.

The next few illustrations (figs. 11–14) show how more than one component can contribute to the completion of a branch.

(ii) *Stroke* 93.

TABLE V (figs. 7 and 11)

(Time in microseconds after start of first component at A)

Point on track	Comp. 1	Comp. 2		Comp. 3		Comp. 4	
	a	b	β	c	γ	d	δ
A	0	41	[74]	250	320	520	600
B	7	—	—	—	—	—	—
C	9	40	—	—	—	—	—
D	20	—	—	260	—	—	—
E	27	49	—	—	—	—	—
F	33	—	92	253	—	—	—
H	47	—	—	—	—	—	—
L	60	—	—	—	—	—	—

Component 1 is probably double, its second part being initiated by the branch at C, but owing to the intense blackening on the film its two parts cannot be distinguished.

It will be seen from fig. 11 that the component marked 2 is first called into being by the branch at G. Before the latter is completed, component 1 has reached the branches at H and at K which are not very far beyond G. These branches then start developing slowly as shown by the "drag" on the moving lens record (fig. 11). The main channel is in the first place chiefly occupied in the completion of branch G. When this is effected, the channel directs its attention to branch H so that component 2 does not lose its luminosity at this stage. The same process is again repeated for the branch at K after the completion of the one at H. In the meantime the stroke has reached the cloud, where a hidden branching or other process (at 80μsec.) makes yet another demand on the channel below and causes component 2 to progress right up into the cloud before the long branch K

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is fully completed. This is shown in fig. 11 by the shaded band above K immediately to the right of component 1.

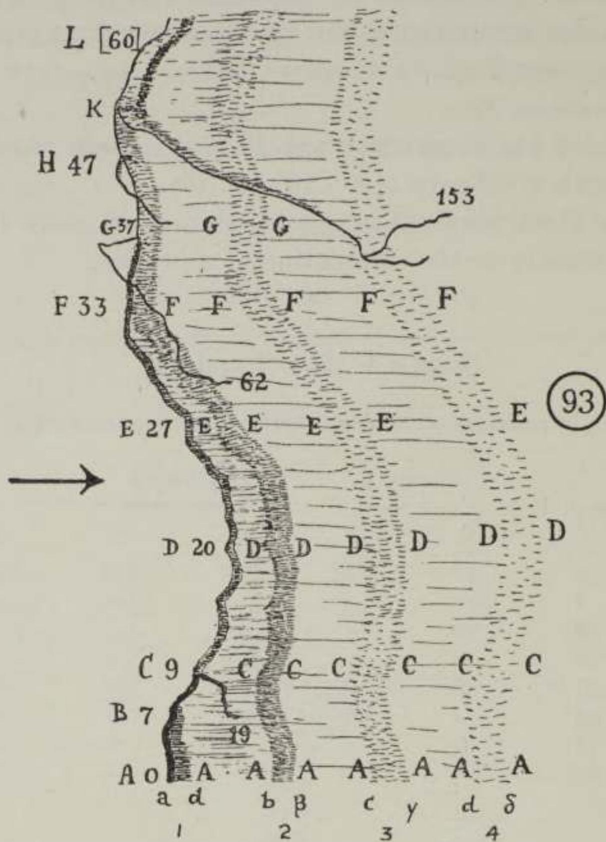

FIG. 11

The result is that component 2 lasts much longer than the 25μsec. required for the completion of the branch from G. It is in fact related to the three branches G, H, K, and to an additional branching process in the cloud and has a total duration of the order of 50μsec. Components 3 and 4 are interested in the cloud only.

(iii) *Stroke* 75*a*.

Stroke 75*a* is the first heavily branched stroke of a series of seven strokes. Component 2 starts when component 1 reaches the branching point at D at 15μsec. (fig. 12). Before branch D is completed, component 1 has reached the two branching points at F and the two branches, *br* 4 and *br* 5, start developing slowly. As soon as branch D is completed, the lower branch at F (*br* 4) receives the full attention of the channel to ground and

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TABLE VI (figs. 7 and 12)

(Time in microseconds after start of first component at *A*)

Point on track	Comp. 1	Comp. 2		Comp. 3		Comp. 4	
	a	*b*	*β*	*c*	*γ*	*d*	*δ*
A	0	16	[36]	60	80	135	157
B	2	—	—	—	—	—	—
C	7	—	—	—	—	—	—
C′	—	—	—	60	—	125	—
D	15	—	—	—	89	—	155
E	21	—	—	—	—	—	—
E′	—	—	—	68	—	140	—
F	32	—	—	—	—	—	152
F′	—	—	—	64	95	—	—
G	43	—	—	58	—	133	153
H	61	—	—	—	—	—	—
J	64	—	—	—	—	—	164

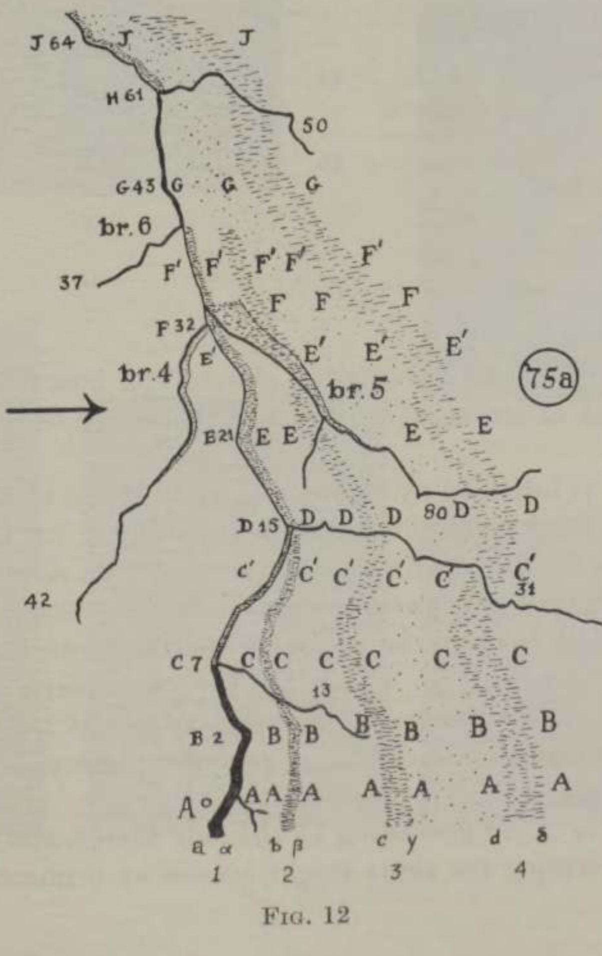

FIG. 12

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is completed to its tip. By this time (42μsec.) the next branch (*br* 5) has progressed an appreciable distance, the branch above F' (*br* 6) has been fully completed and the main channel luminosity has reached the point G. Branch 5 now being far advanced does not seem to be able to make a heavy demand on the channel and slowly advances (shown by the "drag") while component 2 decreases in intensity. In the meantime, however, the point H is reached where the last visible branch causes the initiation of component 3 which then also helps in the final completion of branch 5 as is clearly shown in fig. 12.

Component 4 is concerned with events taking place in the cloud.

(iv) *Stroke* 91*a*.

TABLE VII (figs. 13 and 14)

(Time in microseconds after start of first component at A)

Point on track	Comp. 1	Comp. 2		Comp. 3		Comp. 4		
	a	b	β	c	γ	d	δ	δ'
A	0	11	15	44	75	—	—	220
B	1	8	12	—	—	—	—	—
C	11	—	—	—	—	—	—	—
D	17	—	—	39	—	107	—	—
E	18	—	—	—	—	—	166	—
F	26	—	—	—	—	100	—	—
G	47	—	—	—	—	—	157	—
H	48	—	—	—	—	85	—	—
K	[98]	—	—	—	—	—	—	—

Fig. 13, Plate 6, shows the original photograph (inset) and an enlargement of the base of stroke 91*a*. (Flash 91 consisted of a single stroke to ground.)

Component 2 is initiated by the branch at C. While this branch is being completed, the luminosity progresses faintly higher up the channel and along the longer branch R immediately above C. As soon as the whole of the branch C is blazed, the branch R develops more energetically, increasing its luminosity and that of the main channel between C and R. This is shown by the shading in fig. 14 and on the photograph in fig. 13 where the leading edge of the channel of the first component between C and R is picked out with three white dots and that of the second component with three black dots.

Component 3 is called into being by the long branch above F and is also responsible for blazing the short bright branch at G immediately beyond it.

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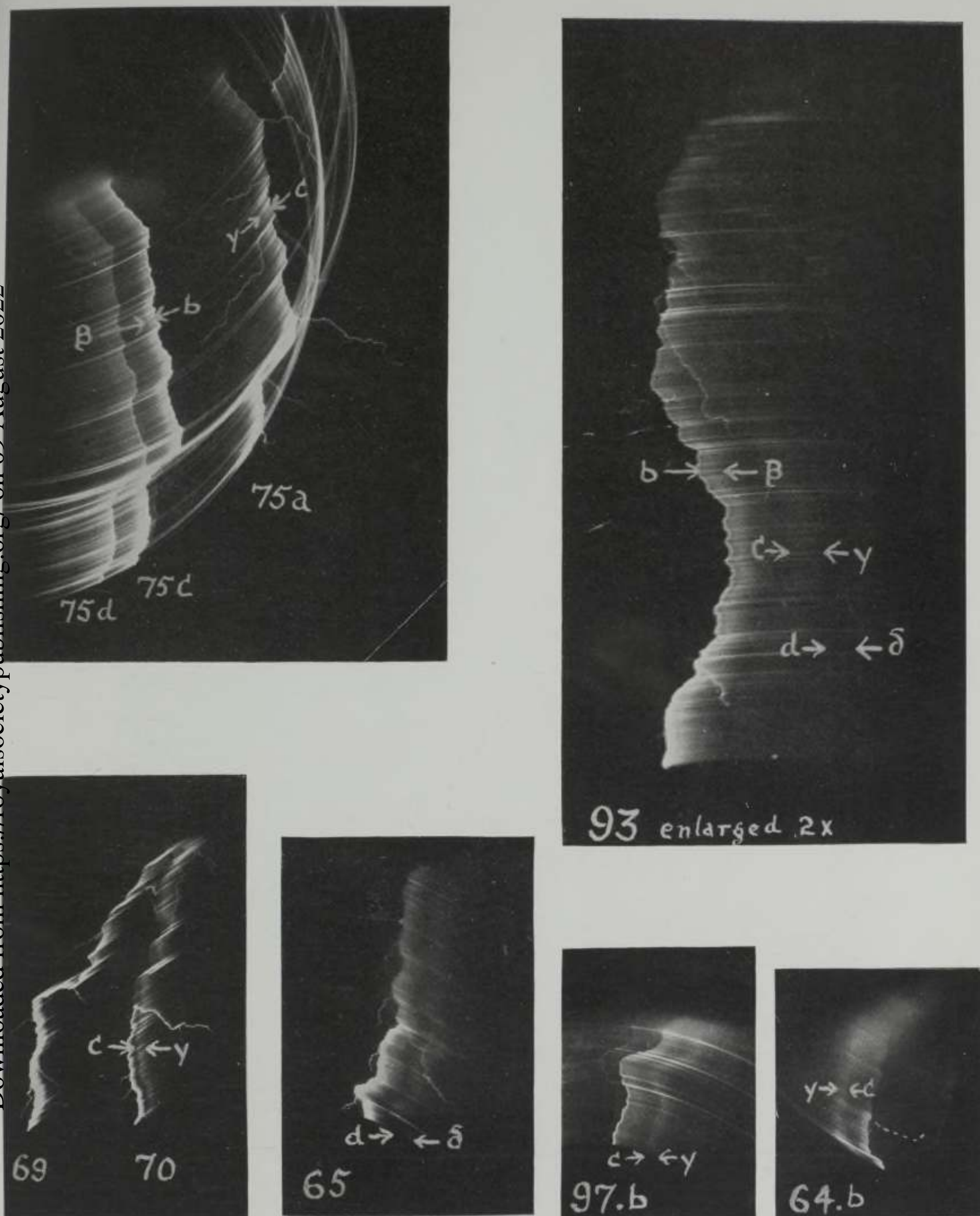

Fig. 7

(*Facing p.* 192)

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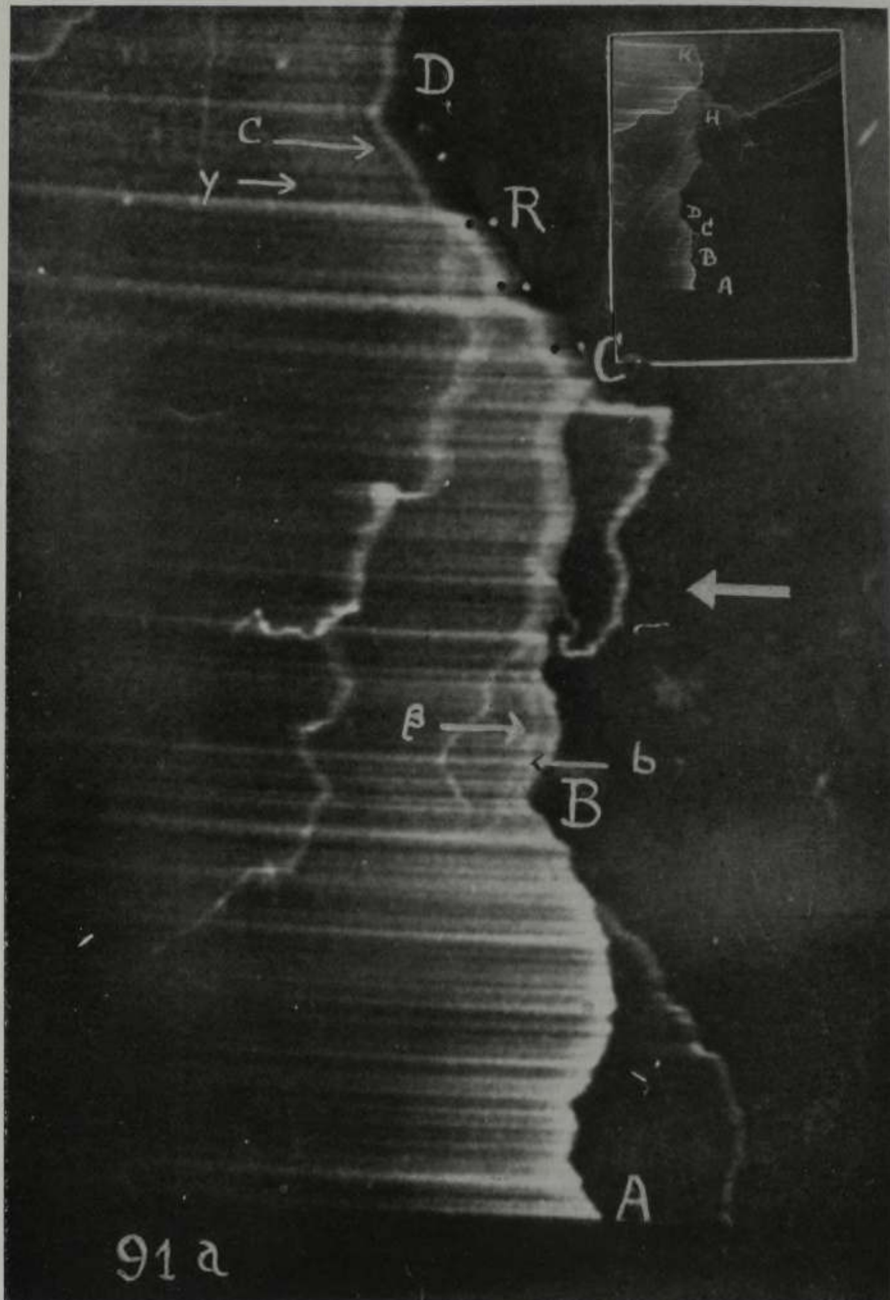

Fig. 13

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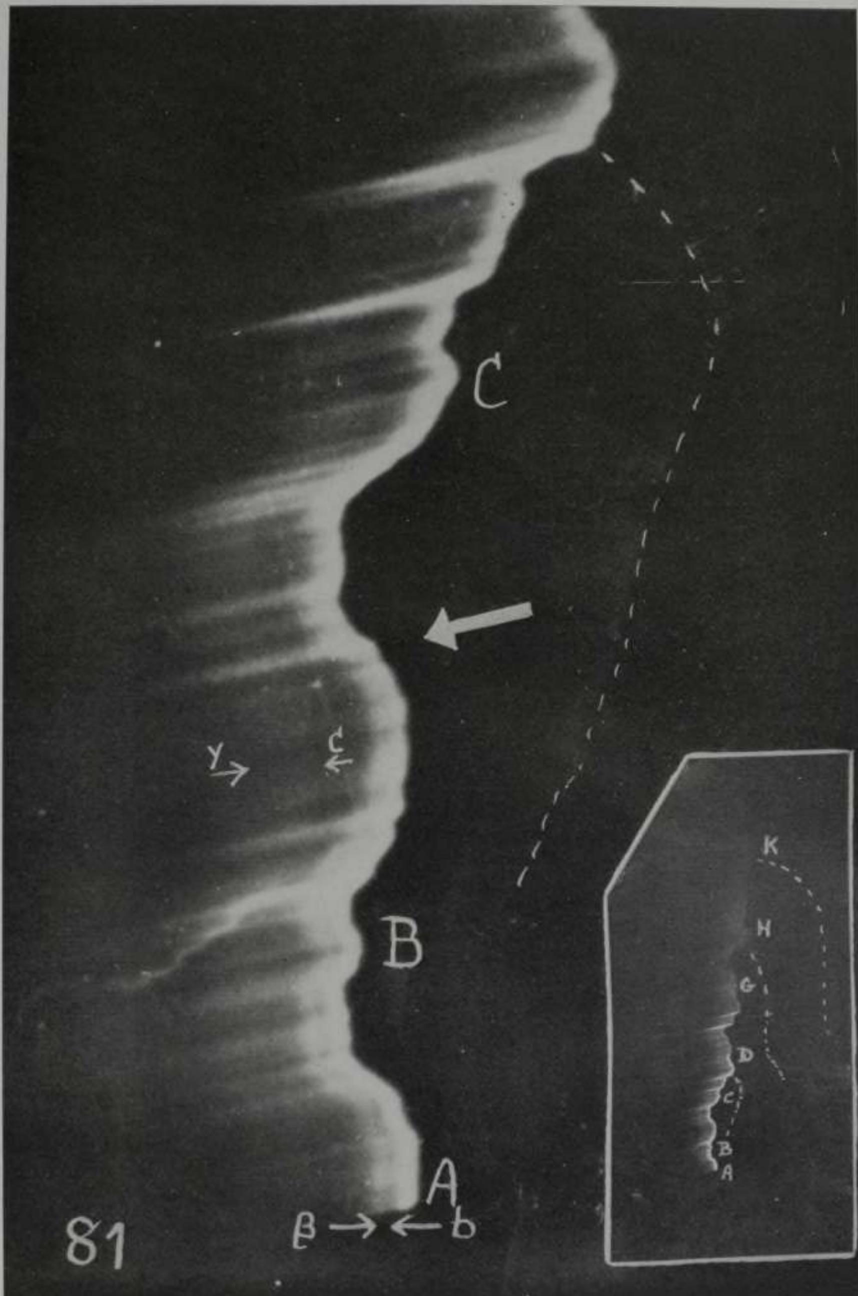

FIG. 15

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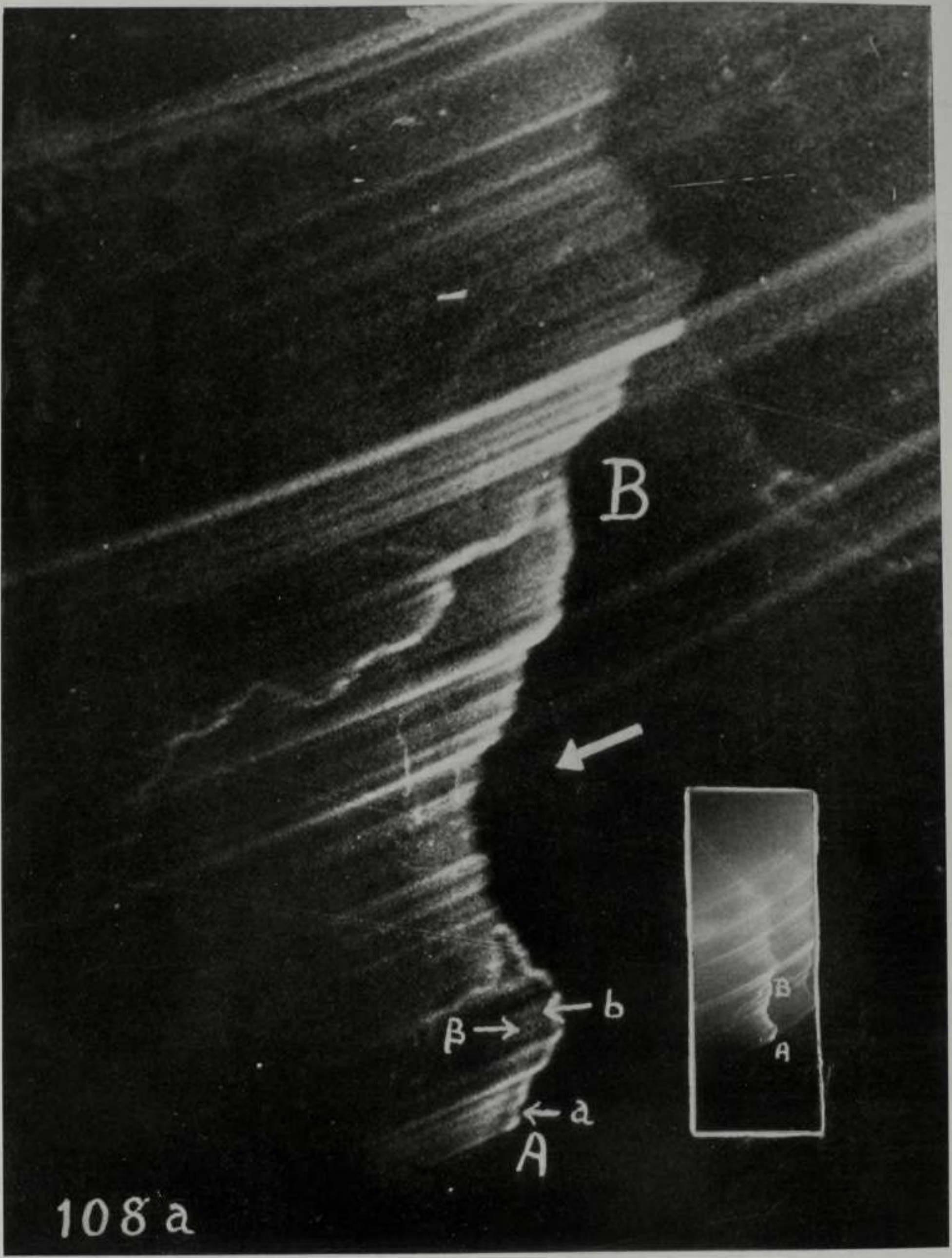

Fig. 16

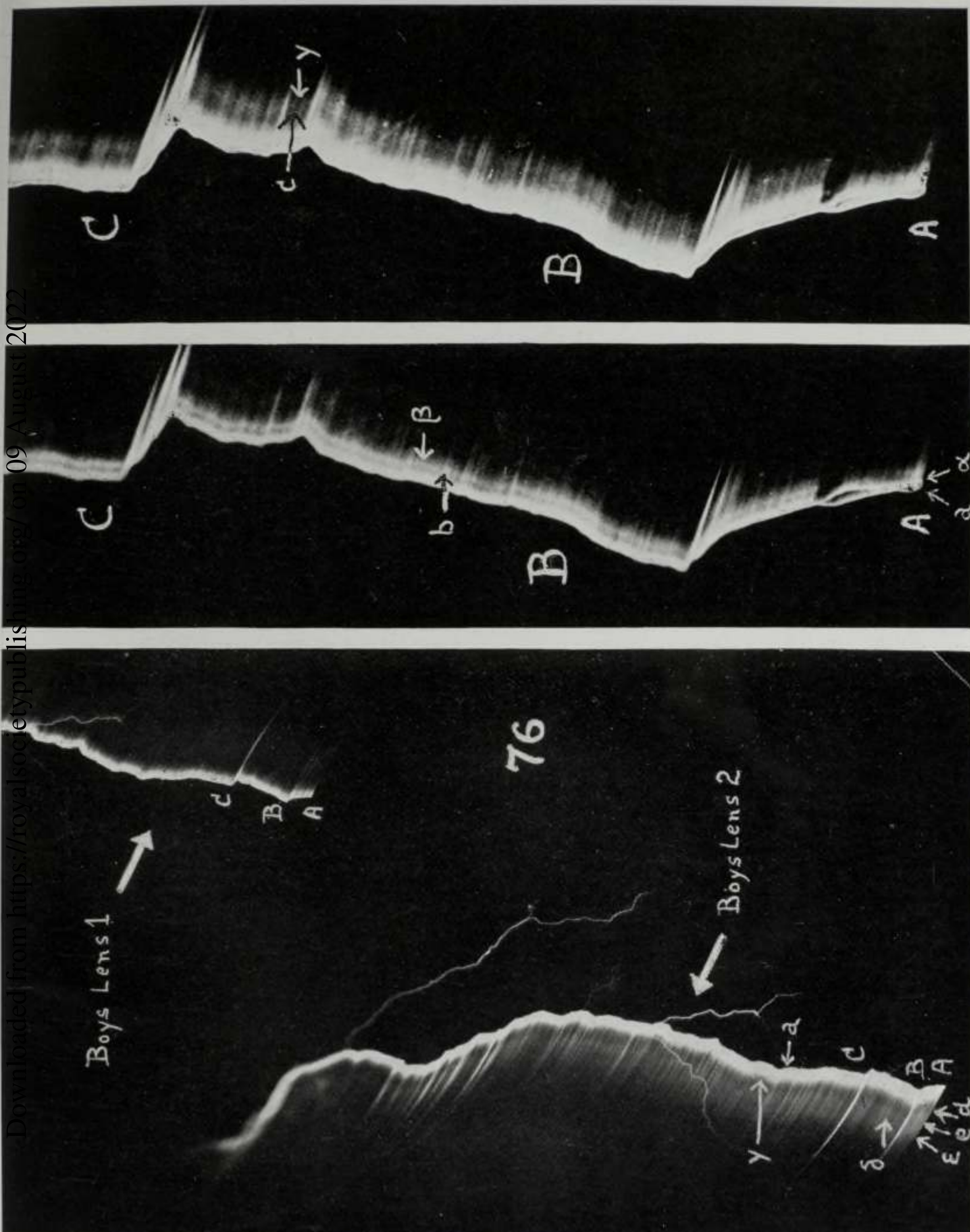

FIG. 17

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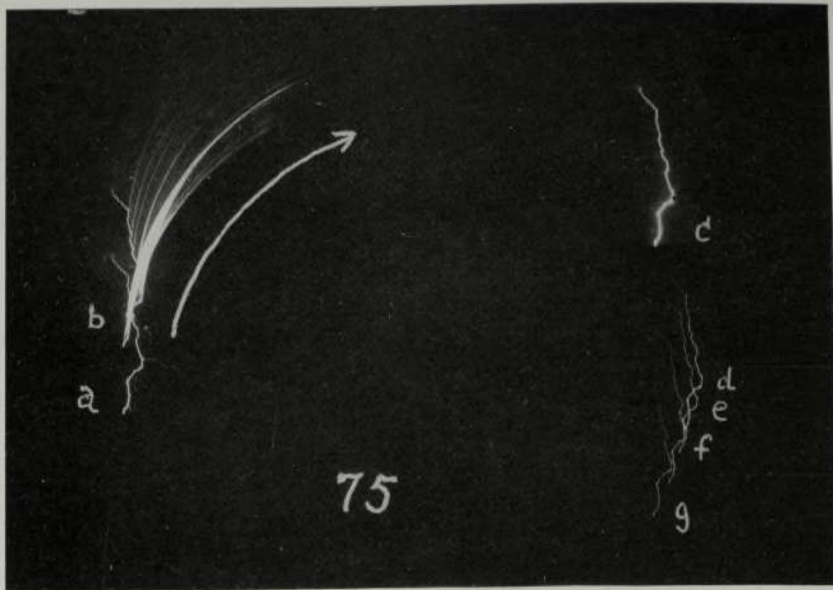

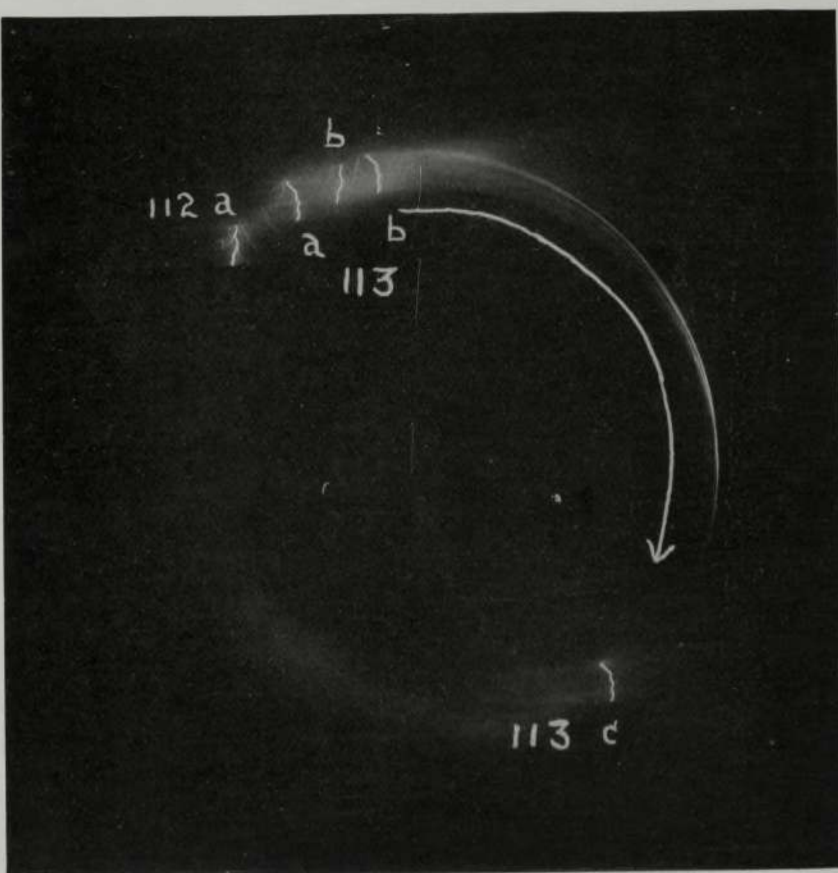

FIG. 20

Component 4 is double, its dual nature only being distinguishable above F. It aids in the final completion of the branch at S. It also has a faint continuation until the time marked by δ' (fig. 14).

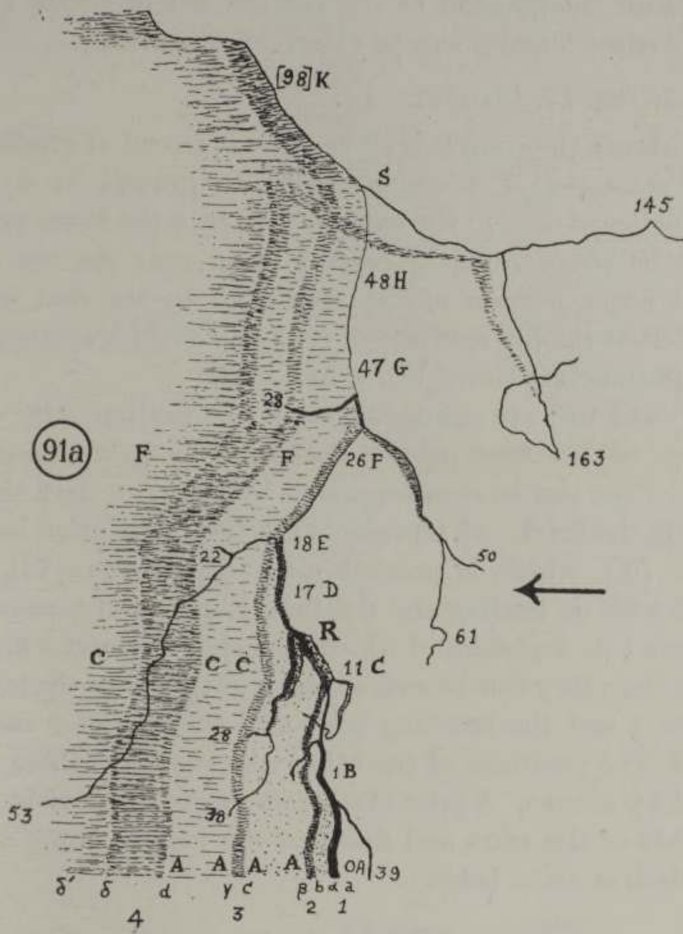

FIG. 14

The next two figures (15 and 16, Plates 7 and 8) are photographic enlargements showing component 2 more clearly than is usual. These strokes (81 and 108a) have components following the general behaviour described above, so that it would be superfluous to describe them in detail by means of diagrams.

(v) *Stroke* 81 (fig. 15, Plate 7).

This gives the original photograph of the whole track and an enlargement of the lower portion ABC of stroke 81 showing the edges b and β

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of component 2 exceptionally clearly. Component 3, edges c and γ, have also been marked.

(vi) *Stroke* 108a (fig. 16, Plate 8).

This shows an enlargement of the portion AB of stroke 108a (inset). Component 2 edges b and β can be clearly distinguished.

(vii) *Stroke* 76 (fig. 17, Plate 9).

Fig. 17 (i) shows the complete Boys camera record of stroke 76.

Flash 76 consisted of a single stroke to ground at a distance of $2 \pm 0{\cdot}5$ km., being so near to the camera that only the lower portion of the stroke could be photographed. Lens 1 being near the top of the film, recorded the lower portion of the stroke up to the first branch only. (Lens 2 was left at the full aperture of $f/6{\cdot}3$ and lens 1 was stopped down to $f/16$ for the purpose explained below in § 10b).

Fig. 17 (ii) and (iii) are enlargements of the portion ABC of the Boys lens 1 picture. (ii) has been printed dark to show up components 1 and 2 more clearly. They can be seen separated by a narrow dark line (of width αb) running up the track. αb represents the time separation between these components. (iii), which is printed more lightly than (ii), brings out component 3 with its leading and finishing edges c and γ respectively.

On the Boys lens 2 picture of (i), components 1, 2 and 3 are lost in the intense white line (they can be seen on the negative), but the leading edge d of component 4 and the finishing edge ϵ of component 5 can be clearly distinguished. The positions of the other edges (δ, e) of these components are indicated by arrows. A faint sixth component also exists.

A time table of the start and finish of the various components at the base of the flash is given below:

TABLE VIII (stroke 76, fig. 17)

(Time in microseconds after start of first component at A)

Point on track	Comp. 1		Comp. 2		Comp. 3		Comp. 4		Comp. 5		Comp. 6	
	a	α	b	β	c	γ	d	δ	e	ϵ	f	ϕ
A	0	11	18	26	46	67	260	410	480	630	815	900

(c) *Unbranched Strokes*

The results of an analysis of two typical examples of unbranched strokes (75c and 97b, fig. 7, Plate 5) are shown in figs. 18 and 19. Full time tables of all the components are given on the diagrams.

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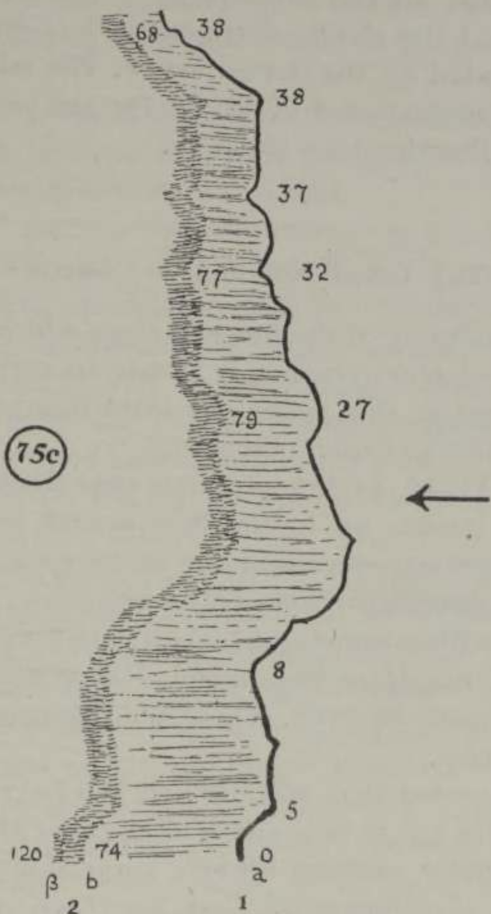

FIG. 18

FIG. 19

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It will be seen that all the subsequent components start after component 1 has reached the cloud. Component 3 of stroke 97*b* progresses downwards as indicated by the dotted arrow. The edges of component 2 of this stroke and component 2 of stroke 75*c* are too uncertain to state definitely in which direction they progress.

8—The Total Number of Components

Owing to the complexity of the fine structure which has been described and the difficulties of photography, it is safe to surmise that in several of the examples cited in this paper the total number of components is higher than that which has been observed.

Referring to figs. 11, 12, 14, it is probable that the very intense parts at the bases of these strokes up to the first branch really consist of two components. The over-exposure and the small time separation of these components would not allow them to be resolved. An examination of photographs taken with a camera of higher time resolution, having a film mounted on a revolving drum (Schonland, Malan and Collens 1935; Boys 1929), shows such cases to exist. These photographs are, however, too diffuse for reproduction.

It can thus be expected that each branch will have its own component unless, as described in § 7, it is so situated as to be able to make use of a component initiated by another branch lower down the channel. The maximum number of components that has been observed for a first branched stroke is 6, the most frequent number being 4. Unbranched strokes rarely have more than two and mostly have only a first component. In exceptional cases the number may even go up to 20 (§ 9, stroke 113*b*).

9—Total Duration of Channel Luminosity

The luminosity along the main channel may persist for a relatively long time (Schonland and Collens 1934; Walter 1935; McEachron and McMorris 1936), and a duration as long as 0·23 sec. has been mentioned in the literature (McEachron and McMorris 1936).

The total duration of channel luminosity as measured on the photographs taken with a Boys camera would of course depend on the conditions of photography. A specific instance is that of stroke 76, fig. 17 (Plate 9), where the apertures of the two lenses were $f/6{\cdot}3$ and $f/16$ respectively. The $f/16$ lens

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photograph shows a total duration of 2200 μsec., while the $f/6{\cdot}3$ photograph gives a duration of 4000 μsec. owing to the greater light-gathering power of the lens.

The most frequent value of the duration as measured on the photographs appears to be of the order of 1000 μsec., ranging in extreme cases from a few hundred microseconds to half a second.

The long "drag" (shown by the arrows) on the slow-moving camera pictures of strokes 75*b* and 113*b* (fig. 20, Plate 10) shows these strokes to be of exceptionally long duration, lasting for 0·25 and 0·50 sec. respectively. The property of long duration seems to have no relation either to the order of the stroke (McEachron and McMorris 1936) or to its relative intensity as compared to the other strokes composing the flash.

Stroke 75*b* shows three faint components in the "drag" following the first intense component, and stroke 113*b* actually shows at least twenty such components.

The suggestion of Walter (1935) that the long duration is due to a high ground resistance has already been refuted by McEachron and McMorris (1936), who pointed out that the different strokes of a flash to a steel structure showed different times of total duration, although the ground resistance was small and was the same for all the strokes.

It has been pointed out in this paper that the earlier components of branched strokes are related to the branches irrespective of the nature of the ground, and that a later component sometimes starts immediately after the stroke has reached the cloud, so that in all probability the latter is related to a branching or other process taking place in the cloud. From the general nature of these components it will be legitimate to assume that still later components, which are similar in appearance and behaviour to the former, are also related to processes in the cloud itself. The existence of several components in most strokes of long duration thus strengthens the view of McEachron and McMorris that long duration is entirely due to processes in the cloud and has no relation to ground resistance.

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10—Intensity Distribution

(*a*) *Variation Along the Channel*

It is known that there is a distinct diminution in intensity of component 1 after passing points of branching (Schonland, Malan and Collens 1935, p. 618). A discussion of two specific examples will serve to show the marked nature of these variations.

Referring to stroke 65, fig. 10, it will be seen that component 1 is very bright up to the branch at C. After reaching C it is chiefly concerned with this branch which is consequently very intense. Component 1, however, continues progressing upwards along the main channel with greatly diminished luminosity till it reaches the branching point of the long branch at D a short distance above C. Component 2 is now called into being as a result of the development of this branch. From C to D component 2 now actually becomes brighter than the original component has been along this part of the channel. From D to E components 1 and 2 have fused after a marked diminution in intensity of the latter at D. Component 3 catches up with the first leading edge just above F with the result that from here to the cloud the channel is illuminated at any point along its path by a glow of low intensity lasting for about 35 μsec. after it has first become visible.

Stroke 91a (figs. 13 and 14) shows a similar effect. From A to C component 1 is the brighter of the first two components but loses most of its intensity beyond this point. In the short distance from C to R, where the next branch is situated, component 2 becomes brighter than its predecessor, as is clearly shown both in figs. 13 and 14. From here to E they have merged and are of the same intensity. Beyond E they have again fused with component 3, giving a much fainter illumination lasting for about 30 μsec. at any point from E to F.

A frequent type of variation in channel luminosity illustrated by the foregoing is as follows:

We may suppose a short branch to be reached by the first component of the main stroke—which may or may not have fused with the second component. This short branch causes a fresh component to run along the channel, catching up the former and delivering energy to the branch. At the same time the first component is travelling upwards with a reduced luminosity, and if it reaches a long branch a short distance farther on, this branch will start developing faintly. It will not have progressed very far, however, before the former branch is completed, and since the channel will now be free to supply it with energy, it will make a demand on the last component, causing the illumination of the channel to increase till it may surpass its former intensity along its track between the two branches under discussion.

If the upward moving luminosity reaches a branch after all the previous branches have been totally or almost totally completed, this branch will call into being a component of its own.

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(b) *Variation with Time at any Point Along the Track*

A luminosity-time curve at the base of any stroke will have as many maxima as the total number of existing components of the stroke. This will be true for any point along the channel for *unbranched* strokes. If the stroke is branched, however, the number of components may become less after the passage of branching points according to the general principles discussed in § 10*a*. Thus the stroke illustrated by fig. 1 has four components from A to C, three from C to E and only two above E.

A detailed photometric study of stroke 76 (fig. 17), made in order to determine the relative intensities of these components, will now be discussed. In taking photographs with the lenses of the Boys camera at full aperture ($f/6{\cdot}3$) it is found that owing to the intensity of the luminosity of the first component it is often over-exposed on the film. To obtain a normally exposed image of this component it was found necessary to use a smaller aperture on one of the lenses ($f/16$, § 7 (*b*) (vii)). Some of the weaker components recorded by this lens will be under-exposed but may have a normal exposure in the full aperture picture.

Knowing the apertures of the lenses in the two cases, it is possible by the application of the principles of photographic photometry to find which parts of the images are normally exposed and also to compare the light-intensities of the different components.

A recording microphotometer (Lambert and Chalonge 1926), where the image of an illuminated slit is focused on the photographic film and the intensity of the transmitted light is measured by means of a photoelectric cell, has been used for this purpose. Since the lenses of the Boys camera move in circles, the film is mounted on a special table having a circular motion.

Fig. 21 shows a curve obtained in this manner at the point C on the negative of the Boys lens 1 image of stroke 76 (fig. 17, Plate 9).

The zero line AB represents the photoelectric current when no light falls on the photocell. The illuminated slit is made to move from right to left across the negative of the upper image of fig. 17 (i), the recording of fig. 21 being taken from left to right. The slit is first obscured so that a small portion of the zero line can be traced. When the obstruction is removed the light passes through the clear part of the film to the right of the photographic image and the curve moves upwards off the paper. As the slit image approaches the more intense part of the film the curve moves down towards the right till it gives the minimum for component 3 whose edges are indicated by γ and c. When it successively crosses components 2 and 1,

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two further minima are traced out but this time much lower down owing to the greater blackening produced by these components whose edges are marked by β, b and α, a respectively. After passing the edge a the light traverses the clear part of the film and the curve again moves upwards off

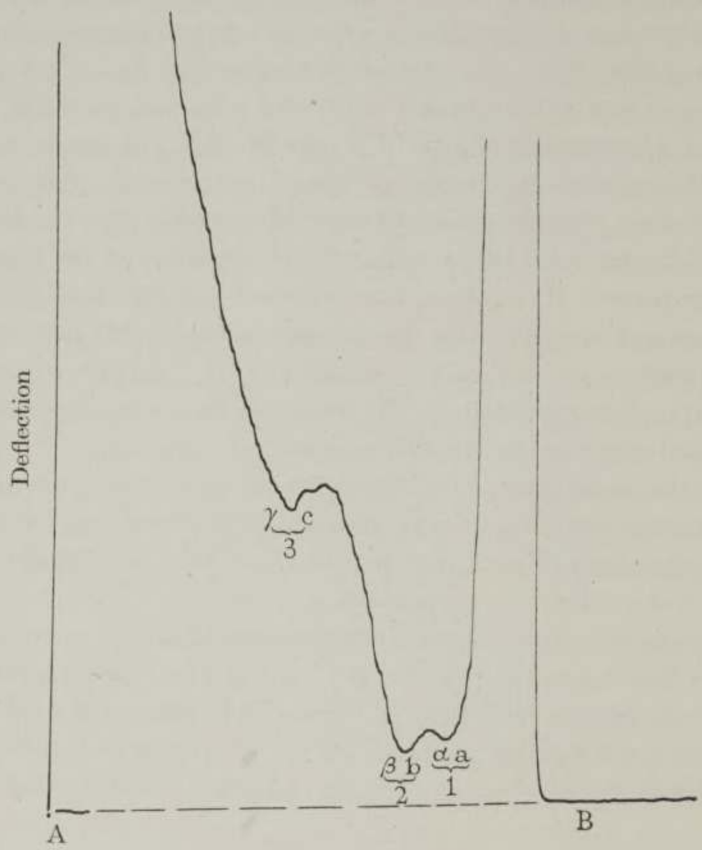

Fig. 21

the paper. To get the zero line the slit is again obscured. This is done because the axes are not rectangular.

The curve of fig. 21 has been used to determine the densities of the photographic images produced by the various components. The relative intensities can be calculated from the densities.

The derived intensity-time curve for the first four components at the point C of stroke 76 is shown in fig. 22, the intensity of the first component being arbitrarily taken as 100. It can be seen from this curve that the channel first has a luminous intensity of 100 and then fades to about 45

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and increases again to about 115 for component 2. There now comes a sharp decrease to about 2, followed by two maxima of 18 and 2 for components 3 and 4 respectively. Component 5 has an intensity of 2, and component 6 is too faint for measurement. Components 4, 5 and 6 are not included in fig. 21.

It is evident that in the case discussed components 1 and 2 are of the same order of intensity and are the most important of the series. This

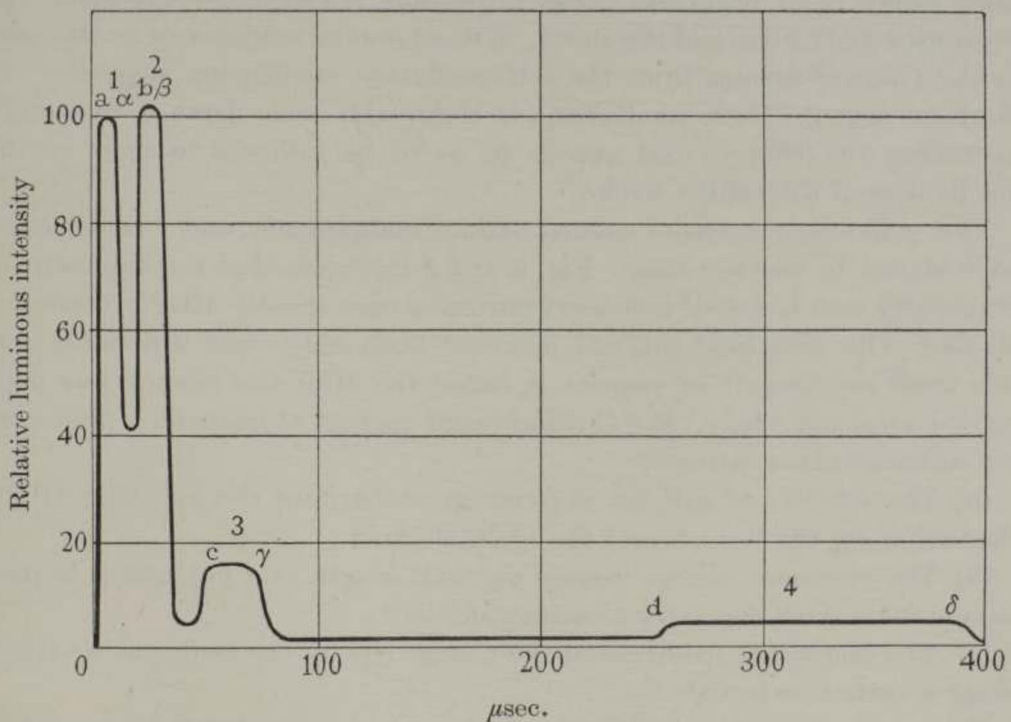

Fig. 22

conclusion appears to hold in general—the third and further components are much weaker than the first two.

This method involves the assumption that the spectrographic intensity distribution of the light remains constant till all the components are completed. It is also assumed that the channel width of the stroke remains constant, thus giving uniform exposure time for all the components at a fixed point on the stroke.

Special care has to be exercised that the photometric analysis is not made across bright streaks (Schonland and Collens 1934, p. 657) which are over-exposed.

A detailed study with improved spectrographic apparatus is in progress.

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General Discussion

This analysis of the luminosity-time relations in the return stroke shows clearly that within the limits of a resolving power of the order of 10 μsec., the only important variations in luminosity are those connected with the development of branches. Since it is natural to associate the luminosity in the channel with the current passing through it, we conclude that within the limits of our measurements important current variations in the channel arise solely from branches. Less important variations occur after the return stroke has reached the cloud. We can find no evidence of oscillations in the channel arising from the self-oscillation mechanism suggested by Simpson (1929). Such oscillations if they exist must have a frequency exceeding 100,000/sec. and appear to us to be unlikely in view of the mechanism of the return stroke.

The connexion between return stroke components and branches we have shown to be very close. Fig. 6 of § 5 indicates that a component of luminosity and hence of increased current arises shortly after a branch is reached. Our measurements are, however, such as to make it possible that this fresh component of current is called for after the branch has been carried some little way. For this increased current at branching points we can advance three causes:

(*a*) The additional call for current on account of the splitting of the channel along the branch and the main channel.

(*b*) The increased charge carried per unit length of a horizontal branch as compared with the vertical main channel.*

(*c*) The increasing freshness of the charge left by the leader as we move along a branch outwards.*

It is not proposed to discuss these causes in further detail here, as they are being dealt with in a more comprehensive survey of the discharge mechanism elsewhere.

We wish to thank the Lightning Research Committee of the South African Institute of Electrical Engineers under whose direction this research has been carried out. We are also greatly indebted to Professor B. F. J. Schonland, director of the Bernard Price Institute of Geophysical Research, for his assistance and advice in the preparation of this paper and to the Bernard Price Institute and Professor Paine of the Witwatersrand University for the hospitality extended to one of us (D. J. M.) as a guest researcher.

* These suggestions arose from discussions with Professor Schonland.

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