III. *Investigations on Lightning Discharges and on the Electric Field of Thunderstorms.*

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[Plates 2–5.]

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THE observations discussed in this paper were made at the Solar Physics Observatory, Cambridge, mainly during the summer months of 1917.

I. *Methods of Measurement.*

The method and apparatus used in the measurements are substantially those described in a paper "On Some Determinations of the Sign and Magnitude of Electric Discharges in Lightning Flashes."* The induced charge on an exposed earthed conductor (test-plate or sphere) is used as a measure of the electric field. The test-plate virtually forms part of a flat portion of the earth's surface, and the vertical electric force or potential gradient at ground level is equal (in electrostatic measure) to $4\pi Q/A$, where Q is the charge on its exposed surface and A is its area. The charge Q on the earth-connected sphere of radius R, when exposed at a height h, great compared with R, is a measure of the potential at that height; the zero potential of the sphere being the resultant of the undisturbed atmospheric potential V at the height h and of the potential Q/R due to the charge on the sphere, so that $Q/R = -V$. The earthed conductors can be shielded from the earth's field: the test-plate by means of an earth-connected cover, the sphere by lowering it into a conducting case resting on the ground. The quantity of electricity which flows to earth through the connecting wire on exposing or shielding the test-plate or sphere, is measured by a special type of capillary electrometer in which the readings indicate the total quantity of electricity which has traversed the instrument; the sign and magnitude of the charge on the exposed conductor, and thus of the potential gradient, at the beginning and end of an exposure are thus determined. The sign and magnitude of sudden changes of potential gradient which occur while the conductor is exposed are indicated by the direction and magnitude of the resulting displacements of the electrometer meniscus. The total flow of electricity between the atmosphere and the test-plate or sphere during an exposure is also measured —being given by the difference between the electrometer readings before and after the exposure. The principal improvement introduced has been the provision of apparatus for giving a photographic trace of the electrometer readings; rapid changes in the field occupying less than one-tenth of a second are in this way recorded.

In the observations described in the previous paper the sphere was supported in a manner which did not admit of absolute measurements being made, as the charge measured included that on the upper part of the support as well as that on the sphere itself; in these earlier measurements therefore the sphere was standardised by comparison with the test-plate. The method of supporting the sphere is now such that the charge on the sphere alone is measured, while the disturbing effect of the

* 'Roy. Soc. Proc.,' A, vol. 92, p. 555, 1916.

earthed supporting rod is small, and thus the potential at the level of the earth-connected sphere can be calculated from the charge upon it. The new method of mounting the sphere is shown in fig. 1.

The sphere, 30 cm. in diameter, is supported on an earth-connected brass tube B, 2 cm. in diameter, from which it is insulated by sulphur-coated ebonite E; insulators are indicated in the figure by the dotted areas. The tube is inserted within a wider one C which extends from the top to the bottom of the sphere and which is open below. The supporting tube B is rigidly fixed in a hole bored through the screw cap which closes the upper end of an iron pipe P, 5 cm. in external diameter and 427 cm. long, which can be turned about its lower end from the vertical to a nearly horizontal position as described in the former paper. The length of the brass tube from the top of the iron pipe to the bottom of the sphere is 38 cm. The connection between the sphere and the electrometer is made by means of a tightly stretched wire W supported by quartz insulators. The wire is not attached directly to the sphere but to a brass disc D insulated from the supporting tube and fitting loosely within the wider tube C inside the sphere. The sphere is fixed to the disc by means of a screw which projects from its inner surface and can thus readily be removed to give access to the insulation.

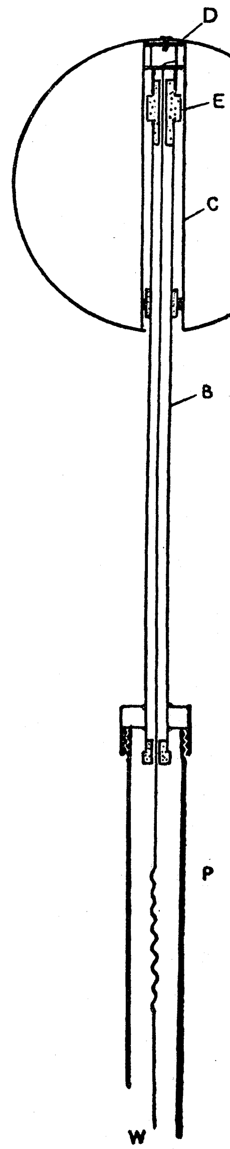


FIG I

When the sphere is exposed by raising the iron pipe to its vertical position the height of its centre above the ground is 480 cm.

The sphere when lowered is received in a metal-lined earthed box resting on the ground; a tightly fitting cover, also metal lined and earthed, protects the sphere from the atmospheric electrical field and from the weather. The charge on the earthed sphere in this position is taken as zero.

The charge Q on an earthed sphere of radius R at a height h above level ground is assumed to be such that $Q/R - Q/2h + V = 0$, where V is the undisturbed air potential at the height h. The presence of the neighbouring hut exerts a disturbing influence which however is not large: the correction to be applied has been estimated by imagining the hut to be replaced by a conducting hemisphere large enough to enclose it. The vertical potential gradient over level ground being assumed uniform throughout a height exceeding that of the hemisphere, the lowering of potential at

a given point by the induced charge on the hemisphere is readily seen to be equal to Va^3/r^3 where a is the radius of the hemisphere and r is the distance of its centre from the given point. In the actual case the correction amounts to 6 per cent.

The charge on the exposed earthed test-plate (the surface of which is at ground level) is similarly diminished by the presence of the hut; the correction to be applied amounts in this case to about 1 per cent. A somewhat larger correction—estimated at 1·5 per cent.—has to be made for the effect of the induced charge of the earth-connected cover and its supporting arm. Apart from these small corrections the relation between the potential gradient F at ground level and the charge Q on the exposed earthed test-plate, of area A, is given by $4\pi Q/A = F$, when the quantities are expressed in C.G.S. electrostatic measure. The effective area of the plate is 2220 sq. cm.

For the measurement of the quantities of electricity which passed between the exposed conductor and earth through the connecting wire, the capillary electrometer described in the previous paper was used. By means of a $\frac{1}{4}$-inch microscope objective, placed with its axis vertical above the electrometer, an image of the meniscus was formed on a horizontal slit. The slit coincided in position with the image of the axis of the capillary tube and was almost in contact with the sensitive surface of a photographic plate kept in uniform motion at right angles to the slit. It was made by ruling a line with a razor blade on an exposed and developed "process" plate; it was protected by a strip of microscope cover-glass cemented with Canada balsam to the gelatine surface—the thin cover glass was next the moving photographic plate and was only a small fraction of a millimetre distant from it. The breadth of the slit was about $\frac{1}{50}$ mm.

The carrier of the photographic plate was clamped to the middle portion of a wire stretched horizontally over two pulleys; a weight was attached to one end of the wire, while the other was attached to a piston, the motion of which in its cylinder caused oil to be driven through a fine hole in a brass disc. By turning the disc any one of a graduated series of holes could be brought into action according to the speed of travel desired.

The light from the source of illumination—a paraffin lamp—could be cut off momentarily by means of a shutter which was worked by a cord from outside the hut. In this way it was possible to record on the photographic plate the times of the beginning and ending of thunder. In the records reproduced (Plates 2 to 5) these momentary interruptions of the illumination are represented by vertical black lines; a single line indicates the beginning, a double line the end of a peal of thunder.

The interval on the photographic record between the vertical portion of the trace, which represents the sudden change of field due to the passage of a lightning flash, and the dark line which marks the moment when the thunder resulting from the flash began to be heard, afford data for obtaining an estimate of the approximate distance of the discharge.

The varying position upon the slit of the image of the meniscus on which the microscope is focussed is represented by the curve separating the dark and light regions of the record. The fine horizontal lines are due to dust particles or to irregularities of the slit; they are useful as reference lines from which the displacement of the meniscus may be measured. The vertical flutings which appear in some of the records are probably due to flickering of the lamp.

Records of the electrical effects of thunderstorms at various distances from the place of observation were obtained on ten different days in 1917. The records were not by any means continuous throughout the whole duration of a storm: comparatively quick runs of the recording apparatus were generally made—varying from 3 to 50 minutes in duration—and some time had to be spent in changing the photographic plates and readjusting the apparatus between the successive runs. Again, the difficulty of estimating the order of magnitude of the electric effects to be expected frequently led to the sphere being exposed when the test-plate would have been more suitable, or *vice versa*; the readings—which are 40 times larger with the sphere than with the test-plate—being in consequence too large or too small to be recorded. Thus the records obtained served rather to sample a thunderstorm at different stages of its history than to give a complete account of the changes in its electric field.

II. *Some Typical Records.*

Enlargements of some of the records are reproduced in Plates 2 to 5. In the original negatives a change of one mm. in the ordinates represented a flow of 24 electrostatic units, or $8 \cdot 0 \times 10^{-9}$ coulomb through the electrometer: a change of potential gradient of 100 or 4000 volts per metre, according as the sphere or the test-plate was used, was required to cause the passage of this quantity of electricity between the exposed conductor and the earth.

A fairly typical fine weather record (May 23, 1917, 14h. 17m. to 14h. 51m. G.M.T.) is shown in fig. 1, Plate 2: the sphere was used as the exposed conductor. The record begins with a horizontal portion traced before the conductor was exposed to the electric field. The small peak near the beginning of the record shows the effect of raising the sphere to its maximum height (480 cm.), and immediately lowering it again into its protecting case; it indicates the existence of a positive potential gradient of 100 volts per metre. The sphere was raised at 14h. 20m., the exposure to the electric field being continued till 14h. 50m. except for regular interruptions at 5-minute intervals when the sphere was momentarily lowered into its case. The depths of the notches in the curve are measures of the potential gradient at the times of lowering the sphere: the potential gradients recorded at intervals of 5 minutes are, in volts per metre, 120 (at 14h. 30m. when the sphere was raised), 110, 120, 90, 75, 80, and finally 90 at 17h. 50m. (when the sphere was lowered).

The difference in the ordinates of the final and initial horizontal portions of the trace (both recorded while the sphere was in its case) is a measure of the integrated

ionization current which has entered the sphere during the 30 minutes' exposure to the atmospheric electrical field. The record shows that this amounted to 21·8 E.S.U., while the mean charge induced on the earth-connected sphere during the exposure amounted to 23 E.S.U.—the equivalent of 96 volts per metre. The mean "dissipation factor" for the period of exposure was thus $\frac{21{\cdot}8}{30} \times \frac{100}{23}$, *i.e.*, about 3 per cent. per minute.

The readings obtained when the sphere is down form a series of points on a curve of which the vertical height above the initial horizontal part of the trace is a measure of the integrated ionization current which has entered the sphere from the atmosphere. This curve forms the zero line for potential gradient, *i.e.*, the differences of the ordinates of this curve and of the actual trace obtained when the sphere is exposed give a measure of the potential gradient at any moment.

In fig. 2 is reproduced the record of May 12, 1917, from 16h. 50m. to 17h. 35m. The sky was overcast and the weather conditions suggested thunder—a storm did in fact occur some hours later. The sphere was momentarily raised at 16h. 51m.; raised again at 16h. 55m., and kept up till 17h. 23m., being however momentarily lowered into its case at 5-minute intervals during this time; it was kept in its case after 17h. 23m. The potential gradient was 150 volts per metre at 16h. 51m.; it gradually diminished till it reached negative values, and continued to be negative from 17h. 12m. 50s. till 17h. 18m. 10s., reaching a minimum of −80 volts per metre at 17h. 16m., becoming positive again and being equal to 260 volts per metre when the sphere was lowered at 17h. 23m. The negative potential gradient coincided in time with the passage overhead of a cloud discharging rain which did not reach the ground. The test-plate was uncovered from 17h. 25m. to 17h. 30m.: the displacement of the meniscus on uncovering and covering the plate is almost too small to be seen in the reproduction of the record but indicates the continuance of a positive potential gradient of about 300 volts per metre. The ionization current from the earth-connected sphere to the atmosphere during the period of negative potential gradient has been sufficient to neutralise approximately the flow from the atmosphere to the negatively charged earth-connected sphere during its exposure to the positive potential gradient.

All the remaining records reproduced in the plates show the effects of lightning discharges (generally at a considerable distance) on the potential gradient.

Fig. 3 (June 13, 1917, 14h. 11m. to 14h. 16m. 30s.).

The sphere was exposed during the whole time represented by the record except at about 14h. 12m. 30s., when it was momentarily lowered; the effect of lowering and raising the sphere is indicated by the prominence midway between 14h. 12m. and 14h. 13m. The potential gradient at that moment was negative and equal to −420 volts per metre. The summit of the prominence gives the zero line of potential gradient. The record begins with a negative potential gradient of about −430 volts

per metre. At 14h. 11m. 10s. distant electrical charges which were responsible for a portion (amounting to 150 volts per metre) of the negative potential gradient at the place of observation were neutralised by the passage of a lightning flash. The negative potential gradient at once began to be regenerated but was again suddenly diminished about 3 seconds later, losing 25 volts per metre by the passage of a lightning flash, probably at a still greater distance. This continuous production of a negative potential gradient and its sudden diminution at intervals by lightning discharges continues throughout the record. At about 14h. 13m. 40s. a sudden change of potential gradient of positive sign occurred, but was followed by one of negative sign and of nearly equal magnitude about 0·4 second later, a small positive change again occurring after another almost equal interval; these changes of potential gradient amount to +240, −220 and +25 volts per metre respectively. Another negative change of potential gradient (about 60 volts per metre) is indicated 10 seconds later. A few seconds after 14h. 16m. the record shows two discharges to have occurred with an interval of 2·4 seconds between them; each produced a change of potential gradient of positive sign, the first amounting to 840, the second to 870 volts per metre.

The potential gradient at any moment may be regarded as being the resultant of several electric fields, including those due to charges concentrated in different thunder-clouds or different centres of activity in the same cloud. The passage of a lightning flash results in the sudden destruction of one of these constituent fields. This at once begins to be regenerated by processes going on in the thunder-cloud at a rate which is indicated by the slope of the curve. The curve of recovery of the electric field (approximately logarithmic) shown after the discharges of 14h. 14m. is quite typical; similar curves appear in most of the records, a specially striking example being that of fig. 11 (Plate 4).

On account of the very short intervals between the successive peals of thunder, the times at which they began and ceased to be heard were not systematically recorded during the record reproduced in fig. 3. The first peal of thunder recorded is marked by the single and double dark lines as beginning at 14h. 13m. 8·9s. and ending at 14h. 13m. 15s., and a second one as beginning at 14h. 13m. 18·4s. and ending at 14h. 13m. 30s. The two peals are taken as being due to the discharges at 14h. 12m. 47·7s. and 14h. 12m. 53·6s. respectively; this gives a distance of 7·1 km. for the first and of 8·3 km. for the second. The first of these discharges produced a total change of potential gradient of 350 volts per metre, but this took place in two stages of 220 and 130 volts per metre which were separated by an interval of about 0·2 seconds; this interval is barely distinguishable in the reproduction. The discharge at 8·3 km. produced a change of about 95 volts per metre. The peal of thunder marked as beginning at 14h. 14m. 9s. probably belongs not to the flash at 14h. 14m., but to an earlier one, possibly the double one at 14h. 13m. 40s.

Fig. 4 (August 9, 1917, 14h. 45m. to 15h. 2m. 30s.).

Here the test-plate was exposed in place of the sphere. The potential gradient

indicated at 14h. 45m. 15s. when the plate was first uncovered is negative (-4570 volts per metre). The principal sudden changes of potential gradient (all in the neighbourhood of 3000 volts per metre) are negative, indicating the destruction of positive fields by the passage of lightning discharges. The times of the beginning and ending of the peals of thunder were in most cases marked as shown by the single and double black lines. The distances indicated by the intervals between the principal discharges and the beginning of thunder are all about 5 km. The characteristic curve of recovery after the passage of each discharge is well shown.

Heavy black clouds were overhead at the beginning of the record and slight rain began about 14h. 48m. 30s. and became heavy at about the time when the record ceased. The effect of the rain is shown by the downward slope of the latter portion of the trace, which indicates a flow of positive electricity from the earth through the capillary electrometer to the test-plate. How much of this positive charge went to increase the induced positive charge on the test-plate (on account of increasing negative potential gradient) and how much to neutralise a negative charge carried down to the test-plate by rain drops, or by ions travelling under the influence of the negative potential gradient, remains undetermined owing to the fact that the cover was not replaced until after the record was completed.

Fig. 5 (June 17, 1917, 20h. 23m. 23s. to 20h. 27m. 29s.).

This is an enlargement of a portion of a record obtained while a severe storm was passing at a distance of 15 to 20 km. Between 20h. 20m. and 20h. 29m. the photographic trace recorded 95 positive discharges (*i.e.*, discharges causing a sudden positive change of potential gradient) and 40 negative discharges. The discharges were visible as vertical flashes passing between a cloud near the N.W. horizon and the earth, many of the flashes being multiple. The storm was seen to travel from W. to N.; newspaper reports show that it passed over St. Ives, which lies from 10 to 11 miles (about 17 km.) to the N.W., damage by lightning occurring there. The mean of the 95 sudden changes of potential gradient of positive sign amounted to 119 volts per metre, that of the 40 of negative sign to -80 volts per metre.

The sphere was used in obtaining this record.

Fig. 6 (June 16, 1917, 19h. 12m. to 19h. 23m.).

The test-plate was used as the exposed conductor.

The potential gradient was negative (-5400 volts per metre) at 19h. 12m. 45s. when the cover was removed, positive ($=1000$ volts per metre) at 19h. 22m. 15s. when the cover was replaced. Rain was falling throughout the duration of the record, and the charge carried down (by rain and ionization current) during the $9\frac{1}{2}$ minutes' exposure was negative and amounted to 16×10^{-12} coulombs per sq. cm., the mean current being thus about 27×10^{-15} ampere per sq. cm. Two of the discharges recorded—at 19h. 17m. 4s. and at 19h. 20m. 55s.—were multiple, as is shown in the enlargements, figs. 18 and 19 of Plate 5. All the sudden changes of

potential were negative—excepting the positive components of the multiple flashes—the largest amounting to -9600 volts per metre. The distance of this discharge, as is shown by the interval elapsing before the thunder began to be heard, was about 4·3 km. The distances of the others ranged between 4·3 and 5·7 km. The peals of thunder, as the intervals between the single and the double black lines show, were very long, some lasting for as many as 40 seconds.

Fig. 7 (June 16, 1917, 19h. 31m. 10s. to 19h. 36m. 45s.).

This is a portion of the record taken with the test-plate next after that shown in fig. 6. Rain continued to fall throughout the time of exposure. The cover was removed from the test-plate at 19h. 31m. 30s.; the potential gradient at that moment was negative, -6500 volts per metre; a lightning discharge had probably occurred immediately before the exposure of the test-plate. The discharge at 9h. 33m. 20s. was really multiple, the sudden changes of potential gradient being -2900, -5100 and $+1300$ volts per metre. The discharge at 19h. 35m. 55s. was negative (change of potential gradient = -4100 volts per metre) and was at a distance of about 5·5 km. The characteristic form of the recovery curve following the discharges is modified by the superposition of a general downward slope which represents an electric current from the ground to the atmosphere; this current was probably mainly carried by falling negatively charged raindrops. The potential gradient when the cover was replaced at 19h. 39m. (beyond the limits of the portion of the record reproduced) was positive and exceeded 2500 volts. The total quantity of electricity transferred per sq. cm. of the test-plate to the atmosphere, during the whole $8\frac{1}{2}$ minutes of exposure, but mainly after 19h. 36m. was the equivalent of 40,000 volts per metre, *i.e.*, $3{\cdot}5 \times 10^{-11}$ coulomb.

Fig. 8 (May 29, 1917, 19h. 4m. 10s. to 19h. 11m. 50s.).

This is the final portion of a record which began at 18h. 44m. The sphere was used as the exposed conductor. The potential gradient had been $+1200$ volts per metre at 18h. 46m. when the sphere was raised; 980 at 18h. 51m. and -1400 at 18h. 56m., at which times the sphere was momentarily lowered. The peak shown in the figure at 19h. 6m. represents the effect of again momentarily lowering the sphere and indicates that the gradient was still negative, being equal to -430 volts per metre. At 19h. 11m. when the sphere was finally lowered the potential gradient had again become positive, being now $+20$ volts per metre.

These comparatively gradual changes of potential gradient accompanied the passage of towering cumulus clouds at no great distance. Superimposed upon them are sudden changes (amounting at most to 150 volts per metre) produced in the field by frequent discharges of more distant thunder-clouds. Some of these are positive, some negative; the discharges of either sign are alike in being followed by the characteristic curve of recovery of the field.

Fig. 9 (May 29, 1917, 17h. 58m. 45s. to 18h. 12m. 30s.).

This is an enlargement of a portion of a record which extended from 17h. 56m. to

18h. 36m.; the sphere was exposed. During the period covered by the portion of the record reproduced the sphere was momentarily lowered at 18h. and at 18h. 5m; it was also lowered at 18h. 10m. and kept in its case till 18h. 11m. when it was again raised. The potential gradient at the times of lowering the sphere amounted to +90, +60 and +40 volts per metre. It is plain from the record that the gradient remained positive throughout: the principal sudden changes of gradient were positive, and amounted to about 150 volts per metre; two, however, at about 18h. 1m. and 18h. 9m. 30s. were negative and equal to about 60 volts per metre. Positive discharges evidently also occurred during both the short periods for which the sphere was lowered.

The characteristic recovery of the field after both positive and negative discharges is well shown. The two peals of thunder recorded probably belong not to the discharges immediately preceding them but to the previous discharges. The discharges were probably at a distance of 20 km. or more.

Fig. 10 (August 15, 14h. 18m. 20s. to 14h. 30m. 15s.).

At 14h. 18m. 30s., when the cover was removed, the potential gradient was negative (=−3600 volts per metre). This negative potential gradient had increased to about −5000 at 14h. 19m. 6s.; at this moment the negative field was nearly destroyed by the passage of a lightning flash at a distance of 4·1 km., the sudden change in potential gradient being +4800. The five subsequent flashes also produced positive changes in the potential gradient; the beginning and ending of the thunder is marked on the record in each case. The magnitudes of the sudden changes of potential gradient vary from 3900 (the third shown in the fig.) to 14,600 volts per metre (the last); the distances of these two discharges were practically the same, 3·7 and 3·8 km.

The striking feature of this record is the abnormal character of the curve of recovery of the field after the passage of every discharge except the last; instead of the rate of recovery of the field being most rapid immediately after the discharge, it is at first zero or very small and gradually increases to a maximum, falling off again with the increasing field as in the normal type. The last discharge shown in fig. 10 as well as all the subsequent discharges of the record of which this is a part were followed by a recovery of the field of the normal type. The recovery curves following the discharges of the immediately preceding record of the same storm were also normal in character.

Rain began about 14h. 20m., became heavy about 14h. 25m., and ceased about 14h. 31m. 30s.

The potential gradient was negative throughout the period covered by fig. 10 until reversed by the last discharge shown. At 14h. 28m., when the cover was momentarily replaced, the potential gradient was −4800 volts per metre. The small hump in the curve at 14h. 24m. 45s. is due to the shielding effect of a horse and cart which passed within a few yards of the test-plate.

In spite of the negative potential gradient, which would tend to produce an

ionization current from the ground to the atmosphere, the total charge received by the test-plate from the atmosphere between 14h. 18m. 30s. and 14h. 28m. has been positive and equal to the charge which a potential gradient of 17,000 volts per metre would have induced on the earth-connected plate. The charge carried by the rain must thus have been positive and must have exceeded to the above extent the negative charge carried by the ionization current. The greater part of this charged rain has evidently fallen between 14h. 26m. and 14h. 28m.

Fig. 11 (June 12, 1917, 16h. 38m. 40s. to 16h. 50m.).

This is a portion of the second record taken on a sultry afternoon with towering cumulus in all directions. The first record ran from 15h. 55m. to 16h. 19m. A cap was seen to form on the summit of a large cumulus cloud in the E.N.E. at 15h. 59m., and another on one of the lower heads of the same cloud now in the N.E., about 16h. 16m. The potential gradient throughout this first record was positive and about 50 volts per metre. No thunder was heard and no sudden changes of the field are shown on the record.

The second record, of which fig. 11 is a portion enlarged, extended from 16h. 27m. to 17h. 4m. The large cumulus cloud was N. by E. with its edge at an elevation of about 60 degrees at 16h. 30m. and due N. about 16h. 50m. The potential gradient diminished from +44 volts per metre at 16h. 30m. to 15 at 16h. 35m. and then became negative, being −29 at 16h. 40m., −175 at 16h. 45m. (all the above being occasions of momentary lowering of the sphere), and −106 volts per metre at 16h. 49m. when the sphere was finally lowered. The field was zero at 17h. 14m., and had become positive at 17h. 16m., when the observations ceased.

All the sudden changes of field observed were positive; two of 18 and 14 volts per metre, both due to flashes at a distance of about 7 km., occurred before the field had become negative. The other two (equal to 120 and 320 volts per metre respectively) are shown in the figure; they both show characteristic recovery curves; in both cases the potential gradient was reversed, in the first by a discharge at a distance of 8·2, in the second by one at a distance of about 7 km.

The discharge at 16h. 45m. 50s. is an interesting one. The negative potential gradient had reached a steady value—about 170 volts per metre—before the passage of the discharge. The discharge—at a distance of about 7 km.—caused the gradient to become positive (=150 volts per metre); the negative field was again re-established, practically exponentially, a steady value being finally reached equal to about 105 volts per metre. The sphere was brought down at 16h. 49m. No thunder was heard after this time.

In Plate 5 are enlargements of small portions of some of the traces, showing details in the changes of potential gradient associated with lightning discharges. In each case the time in seconds is shown, reckoned from the moment at which the discharge, as indicated by the record, began.

The principal discharge of fig. 12 occurred on May 29, 1917, at about 15h. 23m. 10s.; the peal of thunder which followed began 21·5s. later (indicating a distance of about 7 km.) and was audible for about 20 seconds. The sudden change produced in the potential gradient was negative and exceeded 1250 volts per metre. The record shows the characteristic curve of recovery of the field, interrupted at 1m. 50s. after the discharge by the lowering of the sphere. The positive field due to the charge which the flash neutralised was nearly counterbalanced at the place of observation by a negative field, so that the resultant potential gradient before the passage of the discharge was only about +360 volts per metre.

When the sphere was first raised, at 15h. 19m. 30s., the potential gradient was positive—about 150 volts per metre—and it increased up to the moment of the principal discharge. There were, however, during this time, small sudden changes of potential, some positive, others negative, none exceeding 50 volts per metre; they were obviously due to very distant discharges; no thunder was recorded. Throughout the afternoon there were towering cumulus clouds in all directions, rain falling from some of them.

The discharge of fig. 13 occurred about 15h. 9m. 30s. on August 15, 1917. The sphere was lowered at 15h. 10m., the characteristic curve of recovery of the field being thereby interrupted. The peal of thunder began while the sphere was being lowered, *i.e.*, about 40 seconds after the discharge; the beginning is not marked on the record, but the double dark line indicates that the peal of thunder ended about 55 seconds after the discharge. The potential gradient immediately before the discharge had a negative value exceeding 1000 volts per metre; immediately after the discharge the potential was positive and equal to about 300 volts per metre.

The first discharge of fig. 14 occurred at 13h. 50m. on June 13, 1917, just at the moment when the sphere had been raised to its exposed position. The potential gradient before the discharge was negative (= − 690 volts per metre). The discharge was a double one, causing an increase in the negative potential gradient of more than 980 volts per metre, followed by a sudden change of the opposite sign, which brought the potential gradient to within 260 volts per metre of its original value, the total duration of the double discharge being about one-fifth of a second.

Two other double discharges of about the same total duration were recorded about 22 seconds and 87 seconds later, the first giving sudden potential changes of +70 and −30, the second of +100 and −115 volts per metre. The other discharges shown in the figure are noteworthy as not being followed by the usual recovery curve.

The next three figures are further examples of double discharge records of the same type—*i.e.*, of records showing the occurrence within a very short interval of time of two sudden changes of potential of opposite sign. They differ among themselves mainly in the relative magnitudes of the two sudden changes: the first change of

gradient being the greater in fig. 15, the two being approximately equal in fig. 16, and the second being the greater in fig. 17; in the last case the initial change is negative, in the two others positive. The duration of the double discharge is about one-fifth of a second in fig. 15, two-fifths of a second in fig. 16, and two-fifths of a second in fig. 17.

Double discharges consisting of two successive sudden changes of potential gradient of the same sign are also not uncommon. A striking example is that of the last discharge shown in fig. 3, where a sudden positive change of potential of 840 volts per metre is followed 2·4 seconds later by a second change of the same sign amounting to 870 volts per metre. The discharge at 14h. 12m. 50s. (in the same fig. 3) was also really a double one of this type, the interval between the two components of magnitudes, 220 and 130 volts per metre, being about one-fifth of a second.

What have been called above double discharges, it should be noted, are not necessarily discharges along the same track or even from the same thunder-cloud; it may often be observed that lightning flashes from two different centres occur almost simultaneously.

In the last three figures of Plate 5 are reproduced enlargements of records of multiple discharges, *i.e.*, of records showing a rapid succession of changes of potential gradient of opposite sign. These were all obtained during the same thunderstorm, that of the afternoon of June 16, 1917. The first shows sudden changes of potential gradient of −9600, +4350 and −1500 volts per metre, the intervals between the reversals being about one-third of a second. The second shows sudden changes of potential gradiant amounting to −7100, +1700, −1700, +300, −1900, +700, −600, +1000, the total time occupied by the eight reversals being 2·1 seconds. In the third the changes of potential gradient are −1600, +900, −1600, +1200, +700, −700 volts per metre, the total duration being 1·9 seconds.

III. *On the Prevailing Sign of the Sudden Changes Produced in the Potential Gradient by Lightning Flashes.*

The sudden changes produced in the potential gradient at the place of observation by the passage of lightning discharges have been more often positive than negative, *i.e.*, the greater number have consisted in a sudden increase of a previously existing positive potential gradient or a diminution or reversal of a previously existing negative gradient; in other words they might be explained as being due to the discharge of a negatively charged cloud. Discharges producing such a positive change of potential gradient are called in what follows positive discharges.

The number of positive discharges recorded in 1917 was 432, of negative discharges 279. If the observations of 1914 and 1915 are included, the numbers are 528 and 336, the ratio being 1·56. Of the ten days of thunder on which records were obtained in 1917, there were nine on which more positive than negative discharges

were recorded; on the remaining day, however (June 16) about twice as many negative as positive discharges were recorded (74 negative, 38 positive). It is perhaps natural to associate the excess of positive over negative discharges with the excess of positive electricity found by SIMPSON* and others to be carried down in rain, the greater part of the charge transferred from the atmosphere to the earth by the rain of the thunderstorm being perhaps returned in lightning discharges. (See however Sections XIX. and XX.)

IV. *Magnitude of the Changes Produced in the Electric Field by Lightning Discharges at Different Distances.*

The approximate distance of each lightning flash which caused a disturbance on the photographic trace was, when possible, determined by observing the time interval between the discharge and the thunder associated with it. The beginning of each

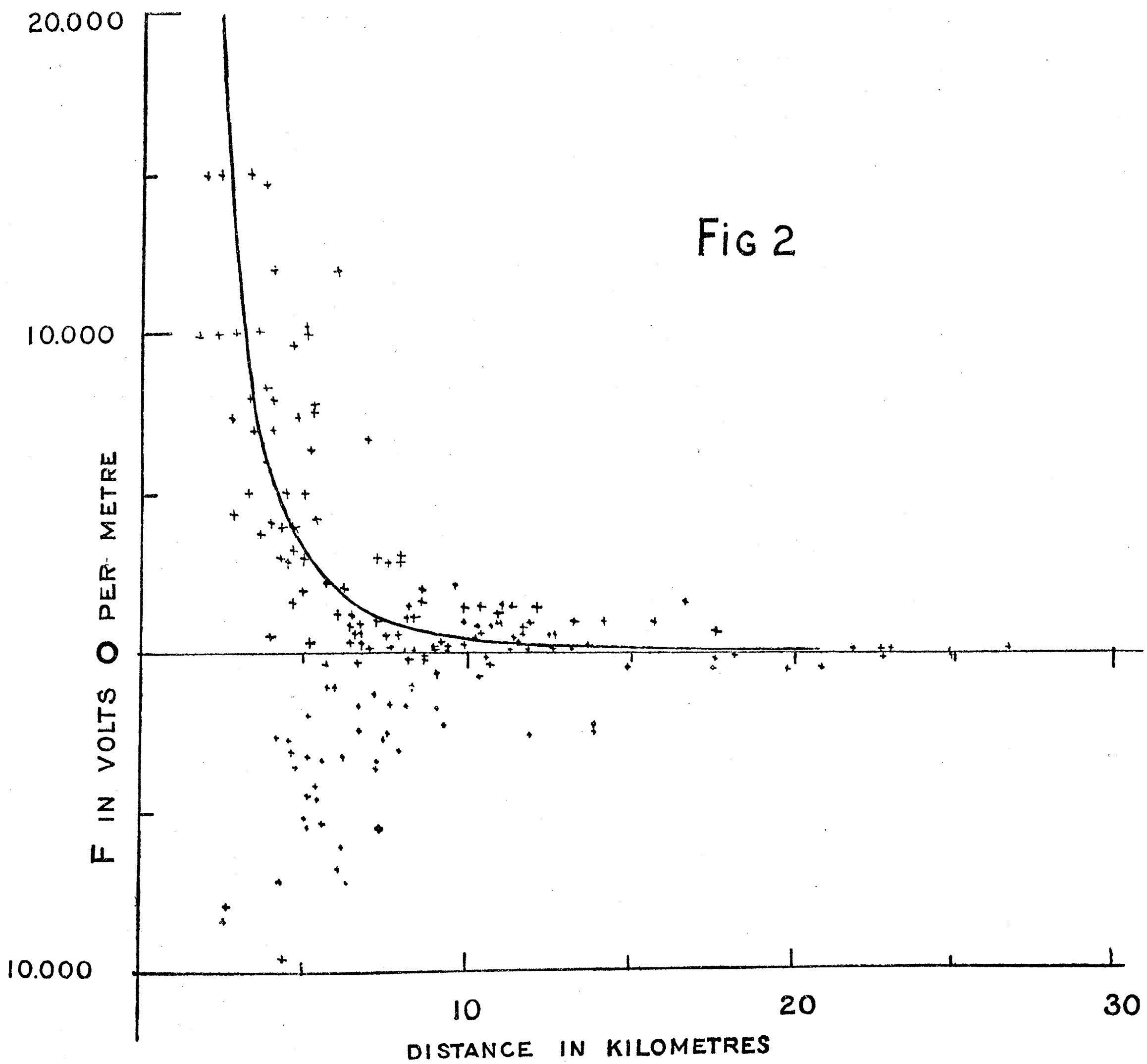


FIG 2

* SIMPSON, 'Phil. Trans.,' A, vol. 209, p. 379, 1909.

peal of thunder heard was marked on the trace by momentarily cutting off the light as described in Section I. It was by no means always possible to be certain which peal of thunder recorded was caused by the lightning discharge responsible for a given sudden disturbance of the field; when the storm was a distant one with very frequent lightning flashes there might be several subsequent discharges between the passage of a flash and the arrival of the sound of its thunder. There appeared to be no ambiguity in the case of about 120 discharges recorded in 1917; the approximate distance L of each of these discharges and the sign and magnitude of the resulting sudden change of field F are shown in fig. 2, which includes also the eye observations of 1914 and 1915. When the records show two or more sudden changes of field within a fraction of a second it is the largest of these which is recorded in fig. 2; it was considered that if the component discharges of the multiple flash were not all at the same distance, the one which produced the largest effect was likely to be the nearest, and therefore that of which the distance was deduced from the interval elapsing between the discharge and the beginning of the thunder.

V. *Effects to be Expected from Different Kinds of Discharges at Different Distances.*

A lightning flash may consist in the passage of a charge Q from a certain region A of the atmosphere to earth, or from a region A_1 to another A_2 both in the atmosphere; A_1 and A_2 may be in the upper and lower parts of the same thunder-cloud with their centres near the same vertical line, or they may be at a considerable horizontal distance apart.

Let a charge Q derived from a certain region A of the atmosphere pass to earth. The change in the electric field may be considered as due to the removal of the charge Q from A and of an equal and opposite charge $-Q$ from A′ the image of A. Just as for many purposes no sensible error is made by assuming the magnetism of a bar magnet to be concentrated at two definite points, the poles of the magnet, so in the present case the charges Q and $-Q$ may be regarded as being concentrated at two points p and p'. These points are situated at a height H above and at an equal depth below the surface of the ground, such that $2QH = 2\Sigma qh = M$, the electric moment of the discharge;* q being the charge derived from a small element of volume at a height h. In calculating the change produced in the electric field at distant points by the passage of the discharge, no sensible error will be made by making this substitution, and even at points at no great distance from the axis pp', the error will be small if there has been any approximation to a symmetrical distribution of the charge in a sphere surrounding p.

* In the present paper $2qh$, not qh as in the previous paper, is taken as the electric moment of the discharge of a quantity q from a height h to earth, the moment with which we are concerned being that of charge q at a height h together with that of its image $-q$ at a height $-h$.

The vertical electric force at a point on the ground is given by

$$F = \frac{2QH}{L^3\left(1+\frac{H^2}{L^2}\right)^{\frac{3}{2}}} = \frac{2Q}{H^2\left(1+\frac{L^2}{H^2}\right)^{\frac{3}{2}}}$$

$\left(\text{becoming } \frac{2QH}{L^3} \text{ and } \frac{2Q}{H^2} \text{ when L is large and small respectively compared with H}\right)$ where L is the distance of the point from the axis pp'. The curve I in fig. 3 represents

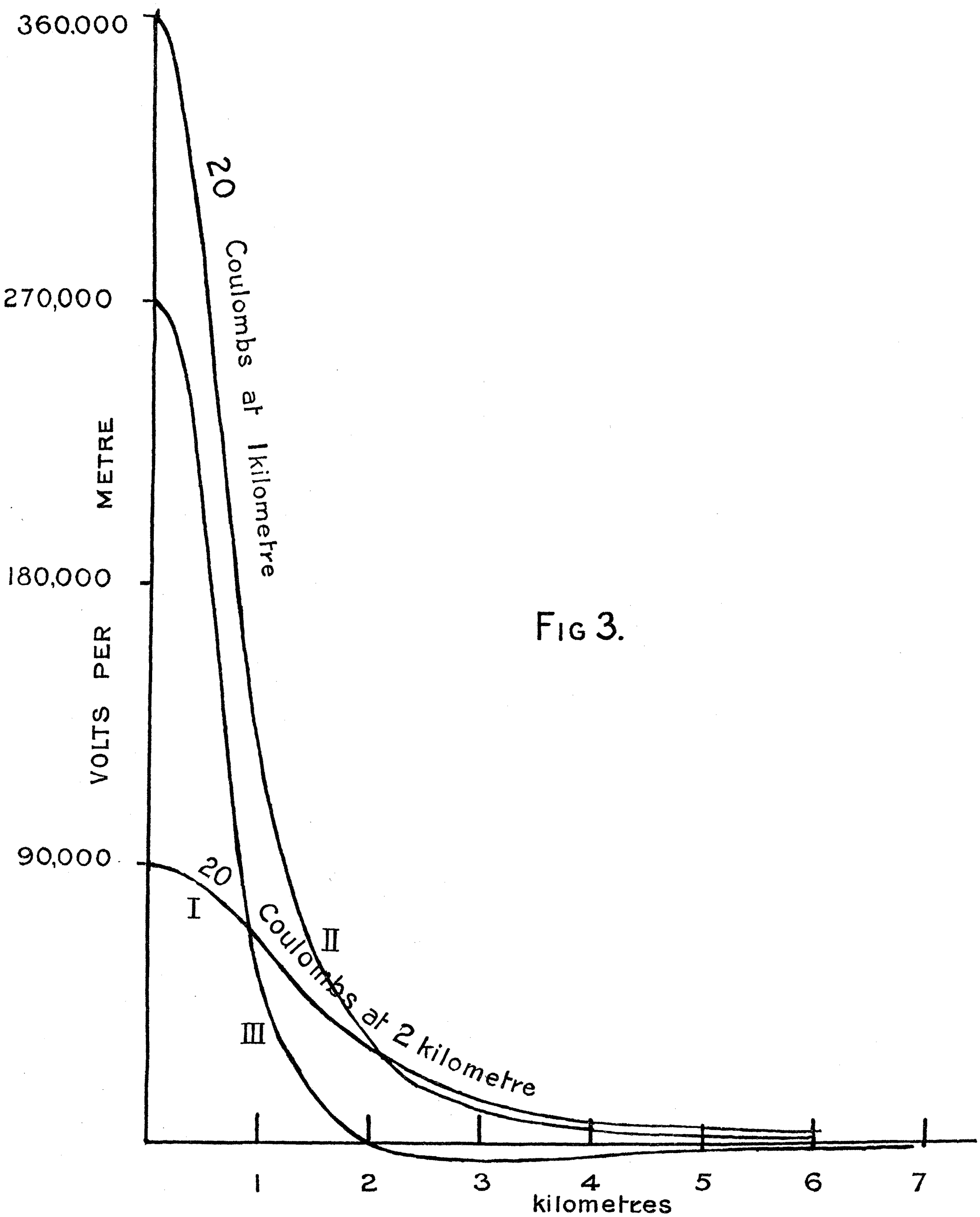


FIG 3.

the potential gradient at the earth's surface at different distances due to a charge Q supposed concentrated at a point at a height of 2 km.: it represents the change produced in the potential gradient by the discharge of 20 coulombs from a height of 2 km. to earth. The curve II. represents similarly the potential gradients due to the same charge at a height of only 1 km. The difference between the ordinates of the two curves (curve III.), represents the change of potential gradient produced by a vertical discharge of the quantity Q from a height of 2 km. to a height of 1 km. The sign of the effect is reversed at a certain distance, the vertical electric force at the surface of the ground being, for a given charge Q at the lower level, greater than for the same charge at the higher level when the distance is small, but less when the distance is great.

For a vertical discharge from a height H_2 to a height H_1, F, when L is large, becomes equal to $2Q(H_2-H_1)/L^3$, so that $FL^3 = 2Q(H_2-H_1)$ which may be defined as the electric moment of such a discharge. Thus when L is large FL^3 is equal to the electric moment of the discharge whether this reaches the earth or not.

The effects at different distances of various kinds of double discharge are also readily obtained from inspection of the two intersecting curves of fig. 3. For example, a discharge from a height of 2 km. to a height of 1 km., followed by an equal discharge from the lower level to earth, would produce at the surface of the ground two successive sudden changes of potential of the same or of opposite sign according as the distance exceeded or fell short of the above limit. Again if we consider a thunder-cloud of which the upper and lower parts are oppositely charged, and suppose that a discharge between the top of the cloud and the ground is followed by one between the ground and the bottom of the cloud, the two successive sudden changes of potential gradient would be of opposite sign, but their relative magnitude would depend on the distance of the place of observation from the discharges; at great distances the longer discharge, at small distances the shorter would produce the larger sudden change of potential gradient; while at some intermediate distance the two effects would be of equal magnitude. The various types of double discharge records shown in Plate 5 may perhaps be explained in this way; a given type of double discharge giving a considerable variety of effects on the trace according to its distance from the recording instrument.

If the effects of individual discharges could simultaneously be recorded at several suitable distributed stations, we should be able to learn much about the quantities of electricity which pass and about the initial and final distribution of charges. It is especially useful to have measurements of the change of field (1) at points at a considerable distance from a discharge, since the electric moment 2QH or $2Q(H_2-H_1)$ may at once be deduced, and also (2) for points nearly below the centres of the regions discharged, where, in the case of discharges to earth, F approximates to its maximum value $2Q/H^2$. Knowing both $2Q/H^2$ and 2QH we obtain both Q and H.

When a single station only is available we have to be content with attempting to

learn something about the average lightning discharge by accumulating measurements of the effects produced by discharges at various distances.

VI. *Electric Moments of the Discharges.*

For each discharge recorded in fig. 2, FL^3, the product of the vertical electric force and the cube of the distance of the discharge, has been calculated. This product, when the quantities are expressed in electrostatic C.G.S. units, may be taken as giving a lower limit for the electric moment $2\Sigma qh = 2QH$, or $2Q(H_2-H_1)$, becoming equal to it when L is large compared with H.

The mean value of FL^3 for the 78 positive flashes for which L could be determined in the 1917 records is $7{\cdot}3 \times 10^5$ in volts per metre × kilometres^3; for the 46 negative flashes the mean value obtained is identical with that found for the positive. We may take this value (the equivalent of $2{\cdot}4 \times 10^{16}$ E.S.U. × centimetres, or about 80 coulomb-km.) as a minimum estimate of the average electric moment of the lightning discharges.

The observations of 1917 give values of FL^3 ranging between 1/20 and 5 times the mean; but in more than half the discharges for which the necessary data are available FL^3 lies between one half and twice this mean value. Some of the eye observations made previously to 1917 lead to higher values, reaching in one case ten times the above mean.

In Table I. are given the mean values of FL^3 for positive and for negative discharges at distances (1) below 5 km., (2) between 5 and 10 km., and (3) exceeding 10 km. The number of observations used in getting the means is in each case inserted in brackets. FL^3 is given in volts per metre × kilometres^3 × 10^5.

TABLE I.

	Below 5 km.		5–10 km.		Above 10 km.	
	Positive.	Negative.	Positive.	Negative.	Positive.	Negative.
1917 only . .	4·5 (17)	3·7 (8)	6·0 (32)	8·2 (29)	11·8 (29)	9·5 (8)
1914, 1915, 1917 . . .	3·7 (37)	3·7 (8)	7·4 (48)	7·8 (33)	14·6 (38)	15·5 (15)

The mean values of FL^3 are not appreciably different for positive and negative discharges.

For discharges at distances between 10 and 15 km., the mean value of FL^3 for the 24 positive discharges of 1917 is $10{\cdot}8 \times 10^5$; if the 5 discharges of previous years

are included the mean is $11 \cdot 8 \times 10^5$ volts per metre × kilometres³. Data for negative discharges between 10 and 15 km. are almost lacking.

These numbers leave little room for doubt as to the order of magnitude of the average electric moments of the discharges. Distances below 5 km. are too small in comparison with the probable lengths of the discharges for FL^3 to serve as a measure of the electric moment. We may assume that the value of FL^3 for a discharge at a distance of 10 km. or more approximates to its electric moment. The mean value of the electric moment for both positive and negative discharges may be taken as not differing much from 10^6 in volts per metre × kilometres$^3 = 3 \times 10^{16}$ E.S.U. × centimetres or about 100 coulomb-km.

Higher values for the mean electric moment are obtained, as is evident from Table I., if the data from discharges at greater distances than 15 km. are used. The records of discharges at great distances may possibly give disproportionately large values for the mean electric moment for two reasons: (1) because at these distances discharges of small electric moment are unrecorded on account of the small magnitude of the charges of potential gradient produced by them; and (2) because it is only at great distances that discharges, which do not reach the earth and which may be of great vertical length and have large electric moments, produce effects proportional to their moments. The sign of the effect of such discharges is in fact reversed at small distances, and the magnitude of the sudden change of potential gradient produced becomes more nearly proportional to the height of the lower end of the discharge than to its vertical length (fig. 3).

Some additions to the data of Table I. were furnished by the storm of June 17, 1917, in which the distance and frequency of the flashes were too great to admit of the distances of the individual discharges being estimated. There was in this case (see p. 80) independent evidence as to the approximate distance of the storm when the trace containing records of 95 positive and 40 negative discharges within 10 minutes was obtained. Assuming the distance of the discharges to have been 17 km. we obtain for the mean value of FL^3, in volts per metre × kilometres³, $5 \cdot 8 \times 10^5$ for the 95 positive discharges and $3 \cdot 9 \times 10^5$ for the 40 negative, corresponding to electric moments 2QH of $1 \cdot 9 \times 10^{16}$ E.S.U. × centimetres = 63 coulomb-km. and $1 \cdot 3 \times 10^{16}$ E.S.U. × centimetres = 43 coulomb-km. respectively. The discharges were observed to be approximately vertical and to pass between the base of the cloud and the earth.

VII. *Quantity of Electricity Discharged in an Average Lightning Flash.*

When the electric moment of a discharge is known, the order of magnitude of the quantity of electricity which passes in the discharge may be roughly estimated. We may assume that the average vertical length of any ordinary discharge is likely to be between 1 and 5 km. Thus if the average electric moment 2QH is 100 coulomb-km., we may estimate the average quantity discharged in a flash as being between 10 and 50 coulombs.

We get some further information about the discharges by considering the way in which F varies with L (fig. 2). The charge which feeds a lightning flash is evidently not generally derived from a widely extended horizontal sheet, as is shown by the rapid falling off in F at comparatively short distances from the discharge.

The curve shown in fig. 2 represents the relation which would hold between F and L in the case of the discharge of 20 coulombs to earth from a point at a height of 2 km.; the charge may be considered to have been distributed symmetrically within a sphere around this point. The curve represents the mean of the observations fairly well, except in the case of discharges at great distances.

The average magnitude of the sudden change of field produced by lightning discharges at any distance may be roughly calculated by assuming that the average lightning flash consists of a discharge of 20 coulombs to earth from a height of 2 km.

The average change produced in the potential gradient by a discharge at a distance of 10 km. is, it will be noticed, of the order of 1000 volts per metre, and for moderate distances beyond this it probably falls off approximately according to the inverse cube law. (It should perhaps be pointed out that the change of field referred to here is merely the difference between the initial and final values, before and after the passage of a single discharge. At distant points the amplitude of the short period oscillations will greatly exceed the difference between the initial and final magnitudes of the field. Such oscillations—the ordinary "atmospherics" or "strays"—are of too short period to be recorded by the methods of this research).

Discharges may be expected to occur (1) between the ground and the lower part of a thunder-cloud; (2) between the upper and lower parts of the cloud; (3) between the upper part of the cloud and the ground; and (4) upwards from the top of the cloud. Great differences in the vertical lengths and in the electric moments of discharges are therefore to be expected, and the manner in which F varies with L in the different storms furnishes some evidence of such differences. When, as in the records of June 12, 1917, FL^3 varies little with the distance and is besides relatively small, one is tempted to conclude that the vertical length of the discharges was small, that, for example, they passed between the ground and the base of the cloud. When on the other hand, as on August 15, 1915, or August 15, 1917, FL^3 continues to increase with increasing distance and reaches very high values, great vertical lengths would appear to be indicated for the discharges. Possibly the discharges of greatest vertical length may be those between the top of a thunder-cloud and higher levels of the atmosphere.

It is unfortunate that no records were obtained of the effects of discharges from clouds immediately overhead; such observations of the maximum values of F would have given useful evidence bearing on the height from which the discharges came. A discharge of 20 coulombs from a height of 2 km. would cause at the ground a maximum change of potential gradient of nearly 100,000 volts per metre.

Comparatively few determinations appear to have been made of the dimensions of

lightning flashes. A few are quoted by HANN,* the length of vertical flashes to earth generally ranging from 1 to 3 km. It is only rarely, in the photography of lightning, that the distance of the flash has been recorded, so that its length may be deduced. Fig. 4 is a reproduction of a photograph taken with this object in view

Fig. 4.

and for which the necessary data are available; it is, moreover, of interest in other ways. It was taken on May 22, 1918, at about 22h. 45m., the camera pointing north. The interval between the lightning flash and the moment when the thunder began to be heard was 35 seconds, corresponding to a distance of 11·7 km. Two flashes are shown in the photograph, both passing between the cloud and the earth; they must have been nearly simultaneous, since the camera lens was covered as soon as a flash was observed. One discharge has initially passed upwards from the cloud and reached the ground by a curved path at a horizontal distance of nearly 4 km. from its starting point. The other has taken a nearly vertical course to the ground, its image is somewhat faint and ill-defined in the photograph: the discharge was probably within a heavy rain shower, a considerable thickness of which had to be traversed by the light on its way to the camera. The starting points of the two discharges in the cloud are comparatively close together, suggesting (as indeed does

* HANN, 'Lehrbuch der Meteorologie,' p. 632, 1901.

the picture as a whole) that a charge of electricity had been concentrated in a comparatively small volume in the head of the cloud, and that the discharges took place approximately along lines of force.

The mean height of the upper ends of the two discharges—the height of the centre of the charged cloud-head according to this view—must have been just under 2 km., if its horizontal distance from the camera is taken as 11·7 km. The distance and height may in fact have been somewhat greater, since the track of the long flash may at some point of its course have been nearer the camera than the vertical flash, and the distance deduced from the interval between the lightning and thunder is that of the nearest point of the discharge.

VIII. *Electric Field of a Thunder-cloud.*

It is much more difficult to obtain direct information about the electric field of a thunder-cloud than about the sudden changes produced in the field by lightning discharges. The observed field may be the resultant of the fields of several thunder-clouds superimposed upon the normal electric field; while a single instantaneous change in the field will in general be due to the passage of one lightning flash, of which the approximate distance may frequently be determined. Nothing approaching a direct survey of the electric field of a thunder-cloud has yet been attempted: some general conclusions may be reached by a study of the photographic records of the potential gradient in thunderstorms.

It might perhaps naturally have been thought that the actual field due to a distant thunder-cloud would greatly exceed in magnitude the sudden changes due to the lightning discharges from it, each flash removing from the cloud only a small part of its whole charge. This is disproved by the observations; only when there has been, in addition to the more distant thunder-cloud, a heavy shower-cloud overhead or in the immediate neighbourhood of the place of observation, has the actual potential gradient greatly exceeded the instantaneous changes; the main part of the observed field has in all such cases obviously been due to the nearer cloud and not to the comparatively distant thunder-cloud which was in action at the time. The potential gradient due to a distant thunder-cloud has apparently never greatly exceeded in magnitude the sudden changes produced in the field by the lightning discharges from the cloud. Very frequently each discharge has approximately destroyed or even reversed the previously existing potential gradient, the field has then been rapidly regenerated, to be again nearly neutralised or reversed by the next discharge. The magnitude of the vertical electric force at the ground due to a thunder-cloud at a given distance is thus probably of the same order as has been found for the change produced by the average lightning discharge at the same distance.

Potential gradients exceeding 30,000 volts per metre (*i.e.*, $\frac{1}{100}$ of the sparking value) have not been recorded: it is doubtful, however, if any of the records were obtained when the centre of a storm was nearly overhead.

There can be little doubt that it is by the agency of precipitation that the separation of positive and negative charges in a thunder-cloud and consequent production of an electric field is effected, the larger raindrops or hailstones carrying down a charge of one sign while the charge of opposite sign is attached to small drops or cloud particles carried up in the ascending air stream. It is not proposed to discuss here how the large and small particles may acquire charges of opposite sign: whether for example the thunder-cloud is essentially a frictional electrical machine (disruption of drops, which SIMPSON* regards as the important factor, being included under this head) or an influence machine as ELSTER and GEITEL† contend.

It is obvious that any view that places the seat of electro-motive force of a thunder-storm within the thunder-cloud implies that the cloud is essentially bipolar, equal and opposite charges being in any given time transferred from within the cloud to its upper and lower portions. The actual charges residing at any moment in the positive and negative portions of the cloud will in general be quite unequal, since the conditions determining the rates of dissipation of the charges at the top and bottom of the cloud will be very different; an important part of the loss of charge from the lower part of the cloud is obviously the charge carried down to the ground in rain-drops. The lower charge may indeed to a large extent reside on rain-drops falling from the cloud, and may thus extend all the way to the ground. Rain may not however reach the ground, or may lose a large part or the whole of its charge before reaching it by processes to be considered later.

Consider a cloud in which there is an upward stream of charged cloud particles or small drops and a downward stream of oppositely charged large drops; the total vertical electric current is the sum of the currents carried by the upward and downward streams. If the density of electrification of the two streams were the same and uniform throughout the greater part of the vertical thickness of the cloud, then the whole of this portion of the cloud would be electrically neutral. Above a certain level however the small drops alone will remain, and again it is only the large drops which fall below the lower margin of the cloud; equal and opposite charges will in this way be liberated in the upper and lower portions of the cloud. The assumption of uniform density of electrification in the two streams is of course an extreme and improbable one, and the concentration of the charges in the upper and lower parts of the cloud alone is not likely to be so complete as this supposition would imply; it serves, however, to indicate the possibility of the positive and negative charges of a cloud being separated by a considerable vertical thickness of electrically neutral cloud.

The factors which determine the rates of dissipation of the upper and lower charges and the magnitudes of the maximum charges are considered in a later

* SIMPSON, *loc. cit.*

† ELSTER and GEITEL, 'Wied. Ann.,' 25, p. 116, 1885; 'Physikal. Zeitschr.,' 14, p. 1287, 1913; GEITEL, 'Physikal. Zeitsch.,' 17, p. 455, 1916.

section. The electric field at the ground due to a cloud of this kind will be the resultant of the fields of the upper and lower charges.

In the ordinary thunder-cloud or cumulo-nimbus cloud we are concerned with rapidly ascending air currents of comparatively small horizontal dimensions. The heads of such clouds generally reach to heights of several kilometres: according to WEGENER* the top of a thunder-cloud may reach almost to the upper limit of the troposphere (about 10 km.). The average height of the bases is probably about 1 km.

If we suppose a cumulo-nimbus cloud to have charges Q_2 and Q_1 of opposite sign in its upper and lower portions, we may, for the purpose of calculating its electric field at a distance, treat these charges as if they were concentrated at definite "poles" at heights H_2 and H_1. The effect of the charges induced on the surface of the ground is the same as if they were replaced by charges equal and opposite to Q_2 and Q_1 and at depths H_2 and H_1 below the surface. The problem is then the same as that of finding the magnetic field due to two bar magnets of lengths $2H_1$ and $2H_2$ and moments $2Q_1H_1$, $2Q_2H_2$, placed so that their centres coincide, the axes being vertical and their polarities opposed.

The vertical electric force due to the cloud at a point on the ground at a distance L from the axis is

$$F = \frac{2Q_2}{H_2^2\left(1+\frac{L^2}{H_2^2}\right)^{\frac{3}{2}}} - \frac{2Q_1}{H_1^2\left(1+\frac{L^2}{H_1^2}\right)^{\frac{3}{2}}}.$$

Immediately below the cloud, where $L = 0$, the second term (representing the effect of the lower charge) will be the greater unless the ratio of Q_2 to Q_1 exceeds H_2^2/H_1^2, and for distant points the first term (representing the vertical force due to the upper charge) will be the greater unless Q_1/Q_2 exceeds H_2/H_1. Thus the surface of the ground may generally be divided into two areas, an inner and outer, in which the electric field due to the cloud has opposite signs; in the central area the effect of the lower pole of the cloud predominates and determines the sign of the potential gradient and of the charge on the ground, while in the outer area the effect of the upper pole of the cloud is the greater.

The maximum intensity of the resultant field anywhere near the centre of the inner area will generally greatly exceed the maximum reached in the outer area. The curve III., fig. 3, represents the resultant potential gradient produced at the ground by equal and opposite charges of 20 coulombs at heights of 1 and 2 km. The inner area has a radius of approximately 2 km., the maximum potential gradient at the centre amounts to 270,000 volts per metre, while the maximum reached by the potential gradient of opposite sign in the outer area is less than 10,000 volts per metre. Greater differences in heights of the two poles are probable in actual

* WEGENER, 'Thermodynamik der Atmosphäre,' p. 210.

thunderstorms, and the difference in the intensities of the electric fields in the inner and outer areas is likely to be even greater than in the example given. As represented in fig. 5 lines of force from the central area end on the lower charged portion of the cloud, those from the outer area on the upper charge, others again connect the upper and lower charges.

Thus far no account has been taken of the conducting layer in the higher levels of the atmosphere, to the existence of which the phenomena of terrestrial magnetism seem to point.

The normal potential gradient at the surface of the ground in clear weather is of the order of 100 volts per metre, falling off with increasing height and becoming negligible above 10 km.; thus the potential in the conducting layer over regions of fine weather is not likely to exceed a value of the order of 1,000,000 volts. If we assume, in accordance with modern theories of terrestrial magnetism,* that the conductivity of the upper atmosphere is high enough to prevent any large potential differences within it, then even above a thunderstorm the potential in the conducting layer may not greatly exceed 1,000,000 volts. The potential in the head of a thunder-cloud probably reaches values 1000 times as great.

One important effect of the conductivity of the upper atmosphere is to cause a portion of the lines of force from the head of the thunder-cloud to end in the conducting layer. The effect will be more marked than that which would be produced by a solid conducting sheet since ions of opposite sign to the charge on the head of the cloud will be dragged down out of the conducting layer to form an expansion of it extending downwards towards the thunder-cloud. The charge on these ions (which constitutes the induced charge on this protuberance from the conducting layer) will partially neutralise the electric field produced at the ground by the charge in the head of the cloud; in other words lines of force from the head of the cloud which would otherwise have ended on the ground are now diverted upwards into the conducting layer.†

The considerations brought forward in this section suggest that the electric field of a cumulo-nimbus cloud may be regarded as due to charges, generally unequal, in the upper and lower parts of the cloud (falling rain being included as part of the cloud) and to the charges induced by these on the ground and on the conducting layer of the upper atmosphere. Thus the lines of force of the cloud may be divided into four classes, connecting (a) the ground and the lower charge of the cloud, (b) the lower charge and the upper charge, (c) the upper charge and the

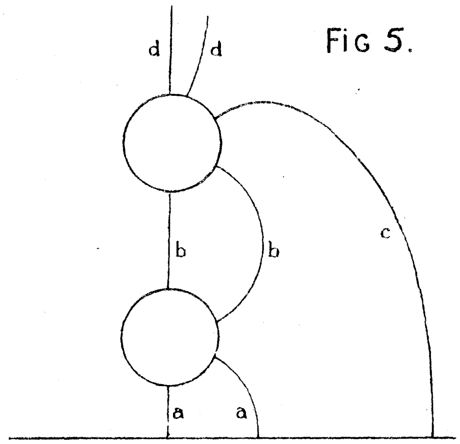
* SCHUSTER, 'Phil. Trans.,' A, vol. 208, p. 163, 1907; S. CHAPMAN, 'Phil. Trans.,' A, vol. 218, p. 1, 1919.

† In the absence of a previously existing conducting layer a thunderstorm would itself produce ionization in the upper atmosphere; this is readily seen to follow from the values found for the electric moments of lightning flashes.

ground, (*d*) the upper charge of the cloud and the conducting layer of the atmosphere.

If uniform stratiform conditions over a wide area be assumed, the conditions are simpler than in the case of the cumulo-nimbus cloud. The field at the ground below such a cloud, if the effects of the conducting layer be ignored, would be the difference

FIG 5.



between the fields due to the upper and lower charges, and its sign would be that of the field due to the larger charge. The effect of the conducting layer, as in the case of the cumulo-nimbus cloud, is to reduce the potential gradient produced at the ground by the upper charge of the cloud: firstly by the action of the opposing field of the charge induced on the conducting layer above the cloud, and secondly by the actual diminution of the cloud charge by the ionization current from the conducting layer.

IX. *Conditions Determining Discharge.*

In order that a lightning discharge may begin, it is clear that the electric force must somewhere exceed the sparking limit, which amounts at the ordinary atmospheric pressure to about 100 electro-static units or 3,000,000 volts per metre; it is not necessary that the electric force along the whole length of the path of discharge should previously have approached the sparking limit. As LARMOR has pointed out,* if we suppose that an initial discharge occurs along a narrow line of length equal to the distance (possibly very small) over which the sparking value of the electric force was originally exceeded, and that this approximately equalises the potential along its path, there will be concentration of charge and intense local fields at the ends of this line; the discharge will thus be lengthened. The conditions are in fact momentarily much the same as if a conducting wire were placed along the path of this initial discharge. The maximum value of the electric force at the ends of the conducting track of the initial discharge will thus greatly exceed the critical

* Sir JOSEPH LARMOR and J. S. B. LARMOR, 'Roy. Soc. Proc.,' A, vol. 90, p. 312, 1914.

value and will continue to do so as the track lengthens, so that the discharge may finally extend far beyond the boundary of the region in which the critical electric force was originally exceeded. Consider a stratiform cloud in which vertical separation of positive and negative electricity is taking place so that opposite charges are accumulating in the upper and lower portions of the cloud. Let us suppose that these charges remain approximately equal. There will be a vertical electric force within the cloud reaching a maximum in the central neutral zone of the cloud; the vertical electric force at the ground will be small and the conditions for discharge will be first reached within the cloud. Discharge will occur when the maximum vertical electric force within the cloud reaches its critical value; this amounts to about 30,000 volts per centimetre (= 100 electrostatic units) at a pressure of one atmosphere and is proportional to the pressure.

It is perhaps doubtful whether the vertical potential gradient within a cloud has necessarily to reach the above value of 3,000,000 volts per metre, in order that a discharge may begin, since an electric force amounting to one-third of this would be sufficient to bring the maximum electric force at the surface of a suspended drop, assumed spherical, to the above value. It must however be remembered that the critical value of the electric force at a curved surface of a conductor increases rapidly with the curvature and that only drops of the largest size will have any marked effect in assisting discharge.*

The discharge may extend considerably beyond the limits of the zone in which the vertical electric force originally reached the critical value. It is possible that it might extend even beyond the upper and lower boundaries of the cloud, for the ends of a linear vertical discharge would, as it lengthened, be continually penetrating into regions of a greater potential difference until they reached the limits of the charged portions of the cloud, so that the density of electrification and maximum electric force at the ends of the conducting track, and the consequent tendency to further lengthening of the discharge, would be increasing up to this point.

The end of an initial discharge which has penetrated into a region where there is little electric force to guide it will tend to branch or to expand into a brush. The potential may thus finally be approximately equalised throughout a considerable volume at each end of the discharge, the effective electric capacity of the expanded ends of the discharge and the original difference between the potentials of the regions thus connected will determine the quantity of electricity discharged by the complete flash.

If the lower charge of the stratiform cloud reaches nearly or quite to the ground

* The electric force at the surface of a conducting sphere 6 mm. in diameter has to reach about 260 E.S.U. (a value equal to nearly three times the sparking limit for a uniform field) in order that a spark may pass. (SCHUSTER, 'Phil. Mag.,' vol. 29, p. 182, 1890.) Drops of this size—which is little short of the maximum attained by rain drops—will only slightly assist discharge in an electric field in which they are suspended, and drops smaller than 3·5 mm. will not assist discharge at all.

(as will generally be the case when rain is falling), or if its charge is considerably smaller than the upper charge, then the initial discharge is likely to extend downwards till it reaches the ground; it will form then a conducting path for the main discharge, which may be regarded as reducing approximately to zero the whole discharge track and its ramifications.

If the potential gradient at the ground reaches a value amounting to any considerable fraction of that in the cloud, if for example, the upper and lower charges of a stratiform cloud are very unequal, then the critical value of the electric force is likely to be first reached, and the initial discharge to begin, at the surface of a projecting earth-connected conductor.

Let us next assume—and this perhaps represents more nearly the conditions which hold in an ordinary thunder-cloud—that the vertical separation of the centres of the charges is as great as the horizontal dimensions of the charged portions of the cloud.

Consider for example a charge to accumulate in the head of a cumulo-nimbus cloud until the conditions for the passage of a lightning discharge are reached. To get an idea of the order of magnitude of the quantities involved let us assume that the charge is distributed symmetrically about its centre within a sphere of radius R, the maximum electric force being at the boundary of the sphere. If the total charge of the sphere is Q, the radial electric force exerted at its surface by the charge is Q/R^2 and is there a maximum. A radial discharge will therefore begin at a point on the boundary of the sphere when F exceeds the critical value and will be continued inwards towards the centre and outwards approximately along a line of force. The charge of opposite sign in the lower part of the cloud will increase the electric force below and diminish it above the upper charge; the effect will however be small if the lower charge is small or if it is situated at a height small compared with that of the upper charge; in the latter case the effect of the lower charge is largely neutralised by the force due to its image. On the other hand on account of the diminished pressure at the greater height a smaller electric force is required to start a discharge from the upper than from the under side of the upper charged portion of the cloud.

Thus discharges may be expected to start not only downwards but also upwards and laterally from the charged head of a thunder-cloud. The path of discharge is likely to follow approximately a line of force which may belong to any of the classes of Section VIII. Discharges such as that of fig. 4, or even discharges upwards into a cloudless sky, such as have sometimes been observed, are not unlikely occurrences.

If an initial discharge from the charged head of a cloud reaches the ground, thus opening up a conducting path to earth, an approach to complete discharge is probable, so that the quantity of electricity which passes in the lightning flash may be taken as a measure of the charge which had accumulated in the head of the cloud.

A discharge originating in the region surrounding the lower pole of a cumulo-nimbus cloud is more likely to begin in the lower rather than the upper boundary of the charged region; since the electric force below will be increased, and that above

diminished by the action of the induced charge, *i.e.*, virtually by the image of the lower charge. An extreme case is that in which the lower charge, carried largely by rain below the actual cloud, extends to the ground. Here the maximum value of the electric force would be at the surface of the ground; and, if the charge be assumed to be distributed uniformly throughout a region of which the vertical and horizontal dimensions are approximately the same, the maximum vertical electric force would not differ much from $2Q/R^2$, where R is the height of the centre of the lower charge. In this case the field will be locally intensified at the surfaces of projecting parts of earth-connected conductors, and discharges (not necessarily developing into lightning strokes) will occur from such points long before the electric force over flat ground reaches the sparking limit.

X. *Dimensions of the Regions Discharged by Lightning Flashes.*

It has been shown that the quantity of electricity which passes in an average lightning discharge—if the thunderstorms investigated may be taken as typical—is of the order of 20 coulombs. In this and the following sections, X. to XVII., are considered some of the consequences which follow if the quantity discharged by a lightning flash is taken as 20 coulombs.

Consider a thunder-cloud of the bipolar type and assume that a discharge takes place when the electric force at the boundary of either the upper or the lower charge reaches the sparking limit F_0. To get an idea of the order of magnitude of the effects, let us assume that the charge is contained within a sphere of radius R, at a distance from the ground and from other charged masses, and that it is distributed symmetrically in such a way that the maximum radial electric force is at the boundary. A discharge will occur when $Q/R^2 = F_0$. Thus, if $Q = 20$ coulombs $= 6 \times 10^{10}$ E.S.U. and $F_0 = 30{,}000$ volts per centimetre $= 100$ E.S.U. (its value at ground level) then $R = 250$ metres. If $F_0 = 50$, its value at a pressure of half an atmosphere, $R = 350$ metres. If an equal and opposite charge (the other cloud-charge or the image of the first in the ground) were similarly distributed within a sphere of the same radius in contact with the first, we should have at the moment of discharge $2Q/R^2 = F_0$; and the values found for R would be $\sqrt{2}$ times as great as in the case considered, *i.e.*, 350 and 500 metres respectively.

A similar result is obtained if, instead of assuming the charge to have been distributed in a sphere, we suppose the vertical thickness of the charged portion of the cloud to have been small compared with its horizontal dimensions. Consider for example the case in which there are frequent flashes between the earth and the base of the cloud. We may picture the charged rain escaping from the base of the cloud as forming a charged layer which increases in thickness at a rate equal to the downward velocity of the drops. The vertical electric force at the upper and lower boundaries of the charged layer, due to its charge, will amount to $2\pi\rho d$ where ρ is the

charge per unit volume and d is the vertical thickness. On this will be superimposed the electric force due to the upper charge of the cloud and that due to the induced charge on the ground; the first of these will increase the electric force at the upper surface and diminish that at the lower surface, while the second will increase the electric force at the lower and diminish that at the upper surface of the charged layer. If we assume the electric force below the lower charge to be greater than above it—as may easily be the case if the vertical thickness of the cloud (of cumulo-nimbus type) is great in comparison with the height of the lower charge—its magnitude will be between $2\pi\rho d$ and $4\pi\rho d$. A flash will occur when the vertical electric force reaches the sparking limit, *i.e.*, about 100 in electrostatic measure. If we assume the boundary of the lower charge to be a circle of radius r, and the quantity discharged to be 20 coulombs $= 6 \times 10^{10}$ E.S.U., r is between 350 metres and 500 metres, these being the limits obtained by putting $F_0 = 2\pi\rho d$ and $F_0 = 4\pi\rho d$ respectively.

It has thus far been assumed that the horizontal dimensions of the charged portions of the cloud are less than the distance apart of their centres, and that the greater part of the whole upper or lower charge of the cloud is neutralised by each discharge. Let us now suppose that there has been a uniform stratiform distribution of charges over a wide area. Take as an example the cases in which the upper and lower charges of the cloud are equal, the other extreme case in which one of the charges is very small compared with the other is not essentially different—the charge on the ground taking the place of the second cloud-charge. There will be a discharge when $4\pi\sigma = F_0$, σ being the total charge in a vertical column of unit area extending throughout the whole thickness of either charged portion of the cloud. If 20 coulombs are discharged in a lightning flash, and the whole thickness of a limited area of the charged portion of the cloud is discharged by the flash, the area A, discharged is such that $AF_0/4\pi = 20 \times 3 \times 10^9$; if the area discharged be assumed circular, and F_0 be taken as 100, the radius of the area discharged must be approximately 500 metres.

XI. *Maximum Potential Attained before the Passage of a Lightning Flash.*

The potential at the surface of the sphere, considered in Section X., will immediately before discharge be approximately $Q/R = F_0R$; other terms being relatively small may be neglected in estimating the order of magnitude of the potential. The potential at the centre of the sphere will exceed that at the boundary, the excess lying between zero and F_0R—these being the values in the limiting cases (1) in which the radial electric force within the sphere is zero, the charge being confined to the boundary, and (2) in which the radial electric force within the sphere reaches everywhere the sparking limit. (The case of uniform distribution of the charge within the sphere is intermediate, the excess being $\frac{1}{2}Q/R$). The potential at the centre thus lies between $Q/R = F_0R = \sqrt{QF_0}$ and twice this value.

If $Q = 20$ coulombs $= 6 \times 10^{10}$ E.S.U. and $F_0 = 50$ E.S.U. the potential at the surface of the sphere before discharge must reach $1{\cdot}7 \times 10^6$ E.S.U. $= 5 \times 10^8$ volts.

We may take 10^9 volts as giving the order of magnitude of the potential reached in a thunder-cloud before the passage of a discharge of 20 coulombs.

The order of magnitude of the potential required to cause a discharge remains the same even if the spherical distribution of the charge is departed from: the horizontal dimensions might, for example, considerably exceed the vertical so long as they did not much exceed the height of the charge above the ground.

Suppose next that there is a stratiform distribution of charges over a wide area, so that the lines of force are vertical. The conditions of discharge have already been discussed in Section IX.

If we assume that the mean vertical electric force along the whole length of the line of discharge initially approached the value F_0 (= about 3×10^6 volts per metre) and that this length is 2 km., the potential difference between the levels connected by the discharge must have been about 6×10^9 volts. But, as was pointed out in Section IX., the discharge may extend much beyond the regions in which the vertical electric force had originally attained the sparking limit F_0; the discharge might, for example, extend from the region of the upper charge of the cloud to the ground, although the electric field did not originally extend to the ground. The potential difference required to produce a vertical lightning flash 2 km. long from a cloud of this type may thus be considerably less than 6×10^9 volts, but it is not likely to be so small as 10^9 volts.

XII. *Mean Density of the Charge in a Thunder-cloud immediately before Discharge.*

If we assume that a charge of 20 coulombs is concentrated within a sphere 500 metres in radius, the charge per cubic metre is about 120 E.S.U.

In the case of a stratiform distribution of charges we have immediately before discharge $4\pi\sigma = F_0$ (Section X.). If uniform density ρ be assumed for the charge throughout a layer of thickness d, then $\rho d = F_0/4\pi =$ about 8 E.S.U. If d be taken as equal to 1 km., $\rho = 8 \times 10^{-5}$ E.S.U. per cubic centimetre (= 80 E.S.U. per cubic metre). Concentration of the charge within a smaller thickness is probable, with a corresponding increase in the density of the charge.

The mean density of the charges in thunder-clouds is thus likely to reach values of the order of 100 E.S.U. per cubic metre.

XIII. *Charge Associated with 1 c.c. of Water.*

If the amount of water in the charged portion of a thunder-cloud were no greater than in ordinary clouds (about 4 gm. per cubic metre), the average charge per gramme of water would be about 25 E.S.U.; the force exerted on each gramme of water by

the electric field where it approached the sparking limit, 100 in E.S. measure, would amount to 2500 dynes, *i.e.*, to more than twice its weight. As pointed out by SIMPSON,* 10 E.S.U. is the largest charge per cubic centimetre of water consistent with its falling in an opposing electric field of 100 E.S.U. (on one occasion rain actually was found by him to carry a charge exceeding 10 E.S.U. per cubic centimetre). In the same paper SIMPSON draws attention to the very considerable accumulation of water that must occur in thunder-clouds through lagging of the larger drops behind the uprushing air. Thus the charge per cubic centimetre of water does not necessarily reach the above high values: and indeed the electric force opposing the fall of the large drops associated with the lower pole of the cloud cannot, as a rule, exceed their weight, since it is by the fall of these drops that the field is maintained. But there will be less concentration of water on the smaller drops associated with the upper charge, and densities exceeding 10 E.S.U. per cubic centimetre in the upper part of the cloud are not unlikely.

The drops in the head of a thunder-cloud may thus in virtue of their mutual repulsion have radial velocities which near the boundary may be comparable with the terminal velocity which the drops would acquire if falling freely through the air. Drops of 10^{-3} cm. in radius would have a maximum radial velocity of a few centimetres per second: if the radius were as large as 5×10^{-3}, the charge per cubic centimetre of water remaining the same, the radial velocity would be of the order of 1 metre per second. The characteristic bulging form of the heads of a developing cumulo-nimbus cloud may possibly be partly due to mutual repulsion of the charged droplets.

XIV. *Disruption of Drops by the Electric Field.*

It was shown by Lord RAYLEIGH† that a charged spherical drop must become unstable if Q^2 exceeds $16\pi a^3 T$, where Q is the charge, a the radius of the drop and T the surface tension. If the charge per cubic centimetre of the water in the cloud is ρ and is equally distributed among the drops, so that $Q = \frac{4}{3}\pi a^3 \rho$, then the spherical form will be stable so long as $\rho^2 a^3$ does not exceed $9T/\pi$, *i.e.*, about 225 in the case of water drops. The limit fixed in this way for the maximum charge per cubic centimetre of water, even for rain-drops as large as $\frac{1}{3}$ cm. in radius (for which it amounts to more than 70 E.S.U.), is too high to be of importance in the thunder-cloud problem.

Of much greater importance is the effect, upon the stability of the drops, of the electric field in which they are suspended, or in other words of the induced charges on the two halves of each drop.

If it is as a result of the electric force within or at the boundary of a cloud that a lightning flash occurs, then it becomes an interesting question whether under certain conditions disruption of the drops may not occur before the conditions for

* SIMPSON, *loc. cit.*

† RAYLEIGH, 'Phil. Mag.,' vol. 14, p. 184, 1882.

discharge are reached. ZELENY,* who has made a very interesting series of investigations on the stability of electrified liquid surfaces, found that in air at atmospheric pressure the potential required to cause a discharge from the surface of a drop of water at the end of a capillary tube exceeds, though only by a few per cent., that required to produce instability and disruption of the drops. He points out that it would follow from his experiments that a discharge of minute electrified drops, constituting an upward shower, would take place from the edges of the wet leaves of a tree in a thunderstorm, before the electric force at the surface of the tree reached the sparking limits.

It seems not unlikely that under certain circumstances a similar process may occur in a cloud, droplets suffering disruption where the field approaches the sparking limit. Consider a developing cumulus head in which a charge is accumulating, and suppose that the radial electric force near the edge of the cloud-head reaches the value required to cause disruption of the drops before it reaches the sparking limit. The induced charges on the two halves of the drop will then be separated and will tend to travel in opposite directions along a line of force.

The magnitude of the induced charge on each half of a spherical drop of radius a in a field F is $3\pi a^2 \mathrm{F}/4\pi = \frac{3}{4}\mathrm{F}a^2$, and when F approaches the sparking value this will generally greatly exceed any resultant charge of the drop. The charge per cubic centimetre of water for each half of the drop $= \frac{3}{4}\mathrm{F}_0 a^2 / \frac{2}{3}\pi a^3 = 9\mathrm{F}_0/8\pi a$; if $\mathrm{F}_0 = 100$ and $a = 1$ mm. the charge per cubic centimetre of water for each half of the drop is 360 E.S.U. Thus if the original drop of 1 mm. in radius were divided into two oppositely charged halves, the force acting on each of the new drops would in a field of 100 E.S.U. amount to 36 times its weight.

If the drop is drawn out by the action of the field into an ellipsoidal or cylindrical form before disruption, the induced charges will be considerably greater. Separation of the charges by division of the drop will thus give rise to oppositely charged portions each having a charge much greater than that of the original drop. The two portions will tend to travel in opposite directions along the line of force with velocities greatly exceeding the original radial velocity of the drop from which they were derived.

The outward moving products of disruption of the drops in the head of a cumulo-nimbus cloud may possibly constitute "false cirrus." These particles are more likely to freeze than those constituting the original head of the cloud; (1) because the stretching of the water drop into a filament itself causes cooling; (2) the conversion of a water filament into an ice crystal is not accompanied by a large increase of surface, and one of the main obstacles in the way of the freezing of small drops is thus removed; and (3) the charged particles are still further cooled through being driven by the action of the field into the colder and drier air outside the original cloud.

Ice needles formed under the above conditions would not only be charged but also

* ZELENY, 'Proc. Cambridge Phil. Soc.,' vol. 18, p. 71, 1914.

electrically polarised (the induced charges of the original conducting filament remaining when the filament freezes), and will thus tend to remain with their long axes parallel to the direction of the electric force. A study of the optical phenomena of "false cirrus" would be of interest in this connexion, as would also an experimental investigation of the effects of an electric field on super-cooled drops.

XV. *Pressure Within a Charged Portion of a Cloud.*

The pressure within a charged cloud—like that within a charged soap bubble—must be less than the pressure outside. If the whole charge be supposed to lie near the surface of a sphere the analogy with the soap bubble is complete, and this case may be considered in finding the order of magnitude of the effect. The reduction of pressure within the cloud by the charge is $2\pi\sigma^2 = F^2/8\pi$ where σ is the charge per unit area of the surface of the sphere and F is the radial electric force immediately outside. Just before the passage of a discharge $F = F_0$ = about 100 in electrostatic measure, so that $F^2/8\pi$ is about 400 dynes per square centimetre, *i.e.*, about $\frac{1}{2500}$ of an atmosphere.

If we consider the charge to be distributed uniformly in a horizontal layer of thickness which is small compared with its horizontal dimensions, the diminution of pressure midway between the top and bottom of the charged layer, due to mutual repulsion of the charged drops, is again $F_0^2/8\pi$ dynes per square centimetre.

XVI. *Thunder Resulting from Sudden Contraction due to Loss of Charge.*

Thunder is generally regarded as entirely due to the sudden expansion of the air along the track of a lightning flash. It is evident however that the sudden contraction of a large volume of air (the contraction corresponding to an increase of pressure of some tenths of a millimetre of mercury) must furnish a by no means negligible contribution to the thunder which follows the discharge.

XVII. *Energy Dissipated in Lightning Discharges.*

If we take the estimates arrived at above ($V = 10^9$ volts, $Q = 20$ coulombs) for the order of magnitude of the potential in the charged portions of a thunder-cloud immediately before the passage of a flash, and of the quantity discharged in the flash, we obtain for the order of magnitude of the energy dissipated in an average discharge, $\frac{1}{2}QV = 10^{10}$ joules $= 10^{17}$ ergs.

We may also arrive at an upper limit for the energy if we assume that the distribution of the charges is stratiform and that the vertical electric force is uniform and equal to F_0 throughout the height H through which the discharge extends. From the value found for the average electric moment, 2QH, since V must

now be equal to F_0H, we have for the energy dissipated, $\frac{1}{2}QV = \frac{1}{2}QF_0H$, about 10^{11} joules.

The rate at which electrical energy would be going to waste in a storm in which one such discharge occurred in every 10 seconds would amount to 10^{16} ergs per second or 1,000,000 kilowatts. It is of interest to compare this with the total power which would be available if it were possible to catch the rainfall of a thunder-shower before it fell and utilise the water power thus stored. The rate of rainfall in a severe thunderstorm may reach values approaching 10 cm. per hour. The water power available if it were possible to catch the rain at a height of 1 km. would amount to 3×10^{15} ergs per sq. kilometre per second. Thus a rainfall of the above amount over an area of about 3 sq. km. if intercepted at a height of 1 km. would furnish sufficient power to produce the required electrical energy. The total power available for the production of lightning flashes may obviously greatly exceed the above estimate based on the rainfall.

XVIII. *Interpretation of "Recovery" Curves.*

In a typical record of the changes of the vertical electric force due to a distant thunderstorm each vertical portion of the trace—representing the sudden change produced by a discharge—is followed by a characteristic "recovery" curve. This may be interpreted as follows:—The charge in the head or base of the thunder-cloud—or in both—is suddenly destroyed by the passage of a lightning flash. The field at once begins to be re-established at a rate represented by the initial steepness of the curve immediately after the discharge. But as the charge increases, its field tends to diminish the rate of increase of the charge in two ways: (1) by hindering the separation of oppositely charged rain-drops and cloud particles; and (2) by producing an ionization current which tends to neutralise the charge and increases with the increasing intensity of the field. Unless the field previously reaches the sparking limit, a steady condition will finally be approached when the two opposing processes, which tend respectively to increase and diminish the field, balance one another.

The initial rate of increase of the field immediately after the passage of a distant discharge is thus an important quantity. It is proportional to the rate at which a charge destroyed by the flash is regenerated by the action of the thunder-cloud, *i.e.*, it is proportional to the vertical electric current which is carried through the thunder-cloud by the convection of charged masses. If the distances and height of the charge destroyed are known, the vertical electric current may at once be deduced from the initial rate of increase of the field. If this information is not available the ratio of the current to the quantity which passed in the previous discharge can always be obtained from the record.

The value of $T = F\bigg/\frac{dF}{dt}$, where F is the instantaneous change recorded and dF/dt the initial rate of recovery immediately after the discharge, has been deduced from the recovery curves in the case of 34 discharges. We may regard T as the time which would have been required to re-charge the cloud to the sparking limit had there been no neutralising process due to the action of the electric field of the cloud. The values of T vary between 1·5 seconds and 30 seconds, the mean of 64 measurements giving 6·9 seconds; in more than half the cases examined T lies between 4 and 10 seconds. These times are generally only a small fraction of the actual intervals between the flashes: on June 17, however, in a record (Plate 3, fig. 5) showing more than 100 flashes in 10 minutes—so that the average interval between the flashes was less than 6 seconds—the average value of T exceeded half this interval.

Some of the recovery curves, as, for example, that of June 12, shown in Plate 4, fig. 11, approximate very closely to the exponential form, so that the charge which has been regenerated when a time t has elapsed after the discharge may be represented by $Q = Q_0(1-e^{-\lambda t})$. Such a curve suggests that the charge of the thunder-cloud is being regenerated at a constant rate, and that it is at the same time being dissipated at a rate which is at any moment proportional to the charge. It might also however be interpreted as representing the regeneration of the charge by a constant E.M.F. in the cloud, the current through the cloud being proportional to the difference between this E.M.F. and the opposing potential difference produced by the charges separated; there would be no current when the charges reached a steady value. If dissipation of the accumulated charges is taken into account the recovery curve still remains of the same type; if the dissipation is large, or, in other words, if the internal resistance of the thunder-cloud, regarded as a generator of constant E.M.F., is large compared with that of the external circuit, the current through the cloud is constant, and we have again the case first considered.

The rate of regeneration of charge per second, in other words the vertical current through the cloud, immediately after a discharge varies between $\frac{2}{3}$ and $\frac{1}{30}$ of the charge removed by the flash, the mean being about $\frac{1}{7}$. If we assume a discharge to convey a quantity of the order of 20 coulombs, the mean current through the cloud, immediately after a discharge, is of the order of 3 ampères.

It is not at all impossible that this is also the order of magnitude of the vertical current through a thunder-cloud at other times than immediately after a lightning discharge, and even when an approximately steady condition of the field has been reached. Consider, for example, the charge in the head of a thunder-cloud which reaches to a great height. The conductivity of the atmosphere has been found by GERDIEN and by WIEGAND* to increase rapidly with the height, the former having found at 6 km. a conductivity more than 20 times as great, and the latter at 8865 metres a conductivity about 40 times as great as the normal conductivity near

* WIEGAND, 'Deutsch. Physik. Gesellschaft,' February 29, 1914.

the ground. A charged body suspended in the atmosphere under the conditions found by WIEGAND at 8865 metres would lose about $\frac{1}{15}$ of its charge per second. Thus a charge of 20 coulombs in the head of a thunder-cloud at this height should lose more than 1 coulomb per second: to keep the charge constant the vertical current through the cloud would have to exceed 1 ampère. The presence of such a large charge would, it is true, not leave the conductivity of the surrounding atmosphere unaltered: it would tend to increase it by dragging down ions from upper layers of still greater conductivity.

XIX. *Electrical Currents Maintained in the Atmosphere by Thunder-clouds and Shower-clouds.*

Consider a cumulo-nimbus cloud of the type imagined in Section VIII. containing upper and lower charges—the latter being partly or, it may be, mainly carried by the rain below the cloud. Such a cloud may be regarded as an electric generator—whether essentially of the frictional type or of the influence machine type need not at present be discussed—capable of maintaining a potential difference between its poles of the order of 10^9 volts.

As pointed out in Section VIII. the potentials in the conducting layer of the upper atmosphere is likely to be insignificant in comparison with that in the head of a thunder-cloud, and the potential difference between them may thus be of the order of 10^9 volts.

There will be a flow of electricity along the lines of force belonging to the various groups enumerated in Section VIII. and indicated in fig. 5. The upper pole will continually be losing charge by currents flowing (1) to the lower pole; (2) to the earth's surface (this portion of the current reaching the outer zone (Section VIII.) where the potential gradient is unlikely to reach high values); and (3) to the upper atmosphere.

Unless the field in the shower-cloud approaches very near to the sparking limit, the conductivity within the cloud is likely to be small, since any ions liberated soon lose their mobility by becoming attached to cloud particles. The electrical resistance of the atmosphere between the upper pole of the cloud and the conducting layer of the upper atmosphere will be much less than that between the upper pole and the earth's surface; for the free ions will be dragged out of the conducting layer, and their mobility throughout the greater part of their course will greatly exceed that of the ions in the lower layers of the atmosphere. A large part of the current from the upper pole must thus go to the upper atmosphere.

Consider now the lower oppositely charged pole of the cloud. Part of the charge is continually being neutralised by the direct return current between the poles, but this, as has already been pointed out, is likely to be small. The greater part of the charge lost by the lower pole will reach the ground. If no rain reaches the ground the loss of charge will be due to ions moving under the action of the electric field

of the cloud. If the normal rate of production of ions in the air below the cloud had alone to be taken into account, the current would be small; but we have to add the ions supplied by evaporation of charged drops falling from the cloud and those (of opposite sign) due to point discharges from earth-connected conductors, such as the leaves of trees or even the tips of blades of grass, under the action of the intense electric field of the central area below the cloud. If the rain reaches the ground the former of these sources of ionization is absent, but there is a further source of ionization in the splashing of the rain on the ground. In addition to the ionization current we have also the convection current carried to the ground by charged rain-drops. The total current between the lower pole of the cloud and the ground now consists of the convection current carried by the falling charged drops and the conduction current carried mainly by the upward stream of ions set free by point discharges and splashing at the surface of the ground. The ratio of the convection current to the conduction current will be less near the ground than higher up, since the falling drops will lose more and more of their charge as they penetrate farther into the stream of upward moving oppositely charged ions; these again as they are carried upwards by the electric field are continually diminished in number by union with the drops. The greater the supply of ions from the ground the smaller will be the charge retained by the drops; if the current carried by the upward stream of ions is sufficient, the drops may lose the whole of their charge or even have it reversed before they reach the ground. The charge carried to the ground by rain-drops is thus by no means necessarily a true measure of the vertical current in a shower: nor does the sign of the charge carried by the drops when they reach the ground necessarily indicate the sign of the current between the ground and the base of the cloud.

Thus a large part of the current from the upper pole of a cumulo-nimbus cloud is likely to reach the conducting layers of the upper atmosphere, while that from the oppositely charged lower pole goes mainly to earth. A current is thus maintained from the earth through the cloud to the upper atmosphere or in the reverse direction according to the sign of the polarity of the cloud.

Discharges between the ground and the lower pole of the cloud and between the upper pole and higher portions of the atmosphere contribute to the total current between the ground and the upper atmosphere; discharges between the two poles or between the upper pole and the ground diminish the electric field which maintains the vertical current without contributing anything to the current.

XX. *Differences Between the Electrical Effects of Shower-clouds of Positive and Negative Polarity.*

We may define the polarity of a shower-cloud as being positive when the upper charge is positive, negative when the upper charge is negative, the current through it being upward in the former case, downward in the latter.

It was first proved by SIMPSON,* and has been confirmed by many observers, that rain on reaching the earth's surface is much more often positively than negatively charged. This, as we have seen, does not necessarily imply that shower-clouds are always or even prevailingly of negative polarity. It is therefore of interest to consider some of the differences to be expected between the electrical effects of clouds of positive and of negative polarity.

Recent experiments have shown† that the carrier of negative electricity in hydrogen, helium and nitrogen even at atmospheric pressure is the free electron, and that its mobility is some hundreds of times that of the carrier of positive electricity, the positive ion. In ordinary atmospheric air, as the pressure is reduced, the average mobility of the carriers of negative electricity increases relatively to that of the positive ions; quite an appreciable proportion of the negative carriers, consisting, according to WELLISCH,‡ of free electrons when the pressure is reduced to 8 cm. of mercury, the proportion increasing rapidly as the pressure is further reduced.

Thus, while the carriers of positive electricity dragged out of the conducting upper atmosphere by a cloud of negative polarity consist of ordinary ions, the negative carriers dragged down by a cloud of positive polarity are originally to a large extent free electrons, and a considerable proportion are likely to remain in this condition till quite moderate elevations are reached. The conductivity of the air between a shower-cloud and the upper atmosphere will thus be considerably greater if the cloud is of positive than if it is of negative polarity.

Let us compare two shower-clouds which differ only in the sign of their polarity and consider the effect of the greater conductivity of the atmosphere above the cloud of positive polarity. Let us suppose that the two clouds act as generators capable of maintaining equal potential differences between their poles. Let V_2, $-V_1$ be the potentials of the upper and lower poles of the cloud of positive polarity, and $-V_2^1$, $+V_1^1$ the potentials of the upper and lower poles of the cloud of negative polarity, let $V_2-V_1 = V_1^1-V_2^1$. Then the current from the ground to the upper atmosphere maintained by the cloud of positive polarity will be greater than that from the upper atmosphere to the ground maintained by the cloud of negative polarity, since the total resistance of the circuit is less in the former case.

The ratio V_2/V_1 is less than V_2^1/V_1^1, the upper and lower potentials being proportional to the resistance of the portions of the circuit above the upper and below the lower pole respectively.§ Thus V_2^1 is greater than V_2 and V_1 is greater than V_1^1; in other words the potential (and charge) of both the upper and the lower pole is greater when negative than when positive.

* SIMPSON, *loc. cit.*

† FRANCK and POHL, 'Verhandl. Deutsch. Physik. Gesellschaft,' 9, p. 69, 1907.

‡ WELLISCH, 'Phil. Mag.,' vol. 34, p. 33, 1917.

§ The potential of the conducting layers of the upper atmosphere is assumed to remain small in comparison with the E.M.F. of the thunder-cloud.

The potential gradient (negative) in the central area below the cloud of positive polarity will be greater than the positive potential gradient in the corresponding area below the cloud of negative polarity, the central positively charged area below the cloud of positive polarity being also larger than the negatively charged area below the cloud of negative polarity. Again, the positive potential gradient at the ground in the outer zone will be less (on account of the smaller charge on the upper pole) in the case of the cloud of positive polarity than the negative potential gradient in the corresponding region due to the cloud of negative polarity. Thus in each area negative potential gradients tend to be greater than positive.

The electric field in the central area below the lower pole being stronger in the case of the cloud of positive polarity, the current carried by the stream of positive ions from the ground will be increased, and therefore also the tendency to neutralisation or reversal of the negative charge on the falling rain-drops.

If lightning discharges occur, they are more likely to pass between the ground and either the upper or the lower pole if this is negative than if it is positive, since the charge of the pole is greater when negative. Thus discharges carrying positive electricity from the earth to the atmosphere will be more frequent than negative discharges. Discharges will tend to occur especially between the ground and the upper, negative, poles of clouds of negative polarity and the lower, negative, poles of clouds of positive polarity. In the latter case the discharges are an additional source of loss or reversal of the negative charge on falling rain-drops.

Essentially similar results are reached if, instead of assuming the same potential difference to be maintained between the poles, whether the clouds are of positive or of negative polarity, we assume that the same vertical current is maintained in both cases.

Thus, if we assume that shower-clouds may have polarity of either sign, the differences in the mobilities of the positive and negative carriers of electricity in the higher portions of the atmosphere will account for the preponderance in showers: (1) of negative potential gradients; (2) of upward or positive lightning discharges; and (3) of positively charged rain. It also affords (4) a possible explanation of the normal positive potential gradient of fine-weather regions.

XXI. *The Normal Potential Gradient and Air-earth Current of Fine Weather.*

A thunder-cloud or shower-cloud is the seat of an electromotive force which must cause a current to flow through the cloud between the earth's surface and the upper atmosphere. In the case of thunder-clouds the records of the changes produced in the electric field by the passage of lightning flashes give us means of forming some estimate of the magnitude of such currents, and it would appear from them that the current through a few square kilometres of the surface of the ground below a thunder-cloud may amount to some ampères. In shower-clouds in which the

potentials fall short of what are required to produce lightning discharges, there is no reason to suppose that the vertical currents are of an altogether different order of magnitude. If any considerable proportion of shower-clouds are of positive polarity the upper atmosphere will receive an excess of positive electricity which may possibly be sufficient to maintain the positive potential of the conducting layers and to supply the normal downward current of the fine-weather regions. The total current which must be supplied for this purpose is, as SIMPSON* has pointed out, of the order of 1000 ampères for the whole earth.

It is not necessary to suppose that only isolated clouds of the cumulo-nimbus type contribute to the current between the ground and the upper atmosphere. If we consider a cloud from which heavy rain is falling and assume that the conditions are uniform over a large area, the case is in fact somewhat simpler than that of the cumulo-nimbus cloud; the general results are the same.

We may suppose that a steady condition is reached in which the vertical electric field within the cloud (and thus the potential difference between its upper and lower surfaces) has a value which depends on the rate of rainfall and other factors; it is assumed to be independent of the sign of the polarity. Even if this potential difference is only $\frac{1}{10}$ or $\frac{1}{100}$ of that reached in thunder-clouds the effects may be important: the E.M.F. which tends to drive a current between the ground and the upper atmosphere is still from 10 to 100 times the normal potential of the upper atmosphere above fine-weather regions.

The difference between the mobilities of the positive and negative carriers dragged out of the conducting upper atmosphere will again cause clouds of positive polarity to differ from those of negative polarity in (1) the greater magnitude of the vertical current (positive for the cloud of positive polarity); (2) the smaller magnitude of the potential (positive) at the upper surface and greater magnitude of the potential (negative) at the lower surface of the cloud; and thus (3) the greater intensity of the potential gradient (negative for the cloud of positive polarity) below the cloud, this again tending to cause a larger part of the vertical current below the cloud to be carried by ions liberated at the ground and thus to produce a more complete discharge of the (negatively-charged) rain.

XXII. *Influence of the Nature of the Earth's Surface below a Thunder-cloud or Shower-cloud.*

The dissipation of the lower charge of a thunder-cloud or other rain-cloud by the upward stream of ions liberated by point discharges or by splashing at the earth's surface must depend largely on the nature of that surface, on whether for example it consists of desert, snowfield, grassland, forest, lake or sea; and again the effect of the nature of the covering of the earth's surface may depend on the sign of the electric field.

* SIMPSON, 'Nature,' December 12, 1912.

Point discharges will occur most frequently and give rise to the largest currents over forests and lands covered with vegetation; also on mountain summits and ridges, owing to the increased intensity of the electric field through proximity to the charged cloud. Ionization by splashing of rain on the ground and the relative number of positive and negative ions liberated thereby is likely to be very different over the various surfaces. Of special interest is the question of the amount and nature of the ionization at the surface of the ocean under heavy rainfall.

Over an area in which the surface ionization was large we should expect an increased vertical current, a diminution of the charge carried to the ground by rain, a diminution in the intensity of the electric field of the cloud, and in consequence a diminution in the tendency for lightning discharges to occur.

The holding up of charged rain-drops by the electric field and the diminution of the field by the dissipation of cloud charges by forests and other sources of surface ionization are perhaps not negligible factors in the local distribution of rainfall. Mr. L. F. RICHARDSON,* describing some of the phenomena observed during the passage of a line squall in France, on September 6, 1917, remarks "the cloud was noticeably darker over the Forest of Argonne than over the grasslands of Champagne."

XXIII. *Secondary Thunder-clouds.*

It has thus far been assumed that the source of E.M.F. is within the cloud in which the lightning discharges and other electrical effects are manifested. It is easy however to imagine conditions in which a cumulo-nimbus cloud, which acts as electric generator, may supply electrical energy to quiescent clouds and produce in them intense electrical fields and even lightning discharges.

Consider for example a horizontal stratiform cloud which intersects lines of force connecting the poles of a cumulo-nimbus cloud; the stratiform cloud might be a lateral extension of the shower-cloud. The electrical conductivity within the stratiform cloud will, through capture of the ions by cloud particles, be very small compared with that of the free air above or below the cloud. The current from the poles of the primary thunder-cloud will cause an accumulation of charges of opposite sign at the upper and lower surfaces of the stratiform cloud. This accumulation of charge will continue—unless the field within the cloud previously reaches the sparking limit—until a steady condition is reached, when the vertical field within the cloud is sufficient to maintain a current equal to that which enters its upper and lower surfaces. The potential difference finally existing between the upper and lower surfaces of the stratiform cloud might amount to a considerable fraction of that between the top and bottom of the shower-cloud, the ratio being that of the resistance of that portion of a tube of flow which lies within the cloud to the resistance

* RICHARDSON, 'Quart. Journ. Roy. Meteor. Soc.,' 45, p. 112, 1919.

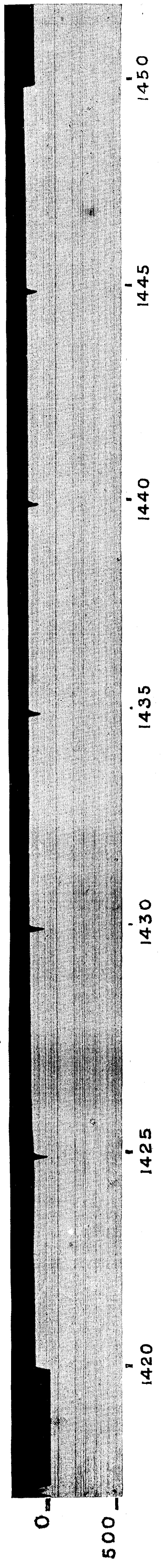


Fig. 1, May 23, 1917.

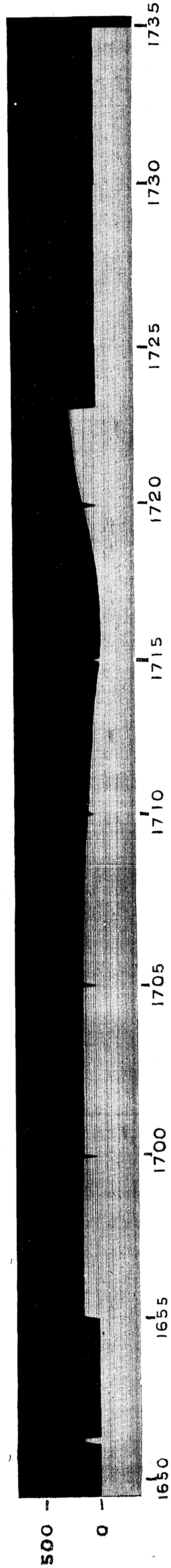


Fig. 2, May 12, 1917.

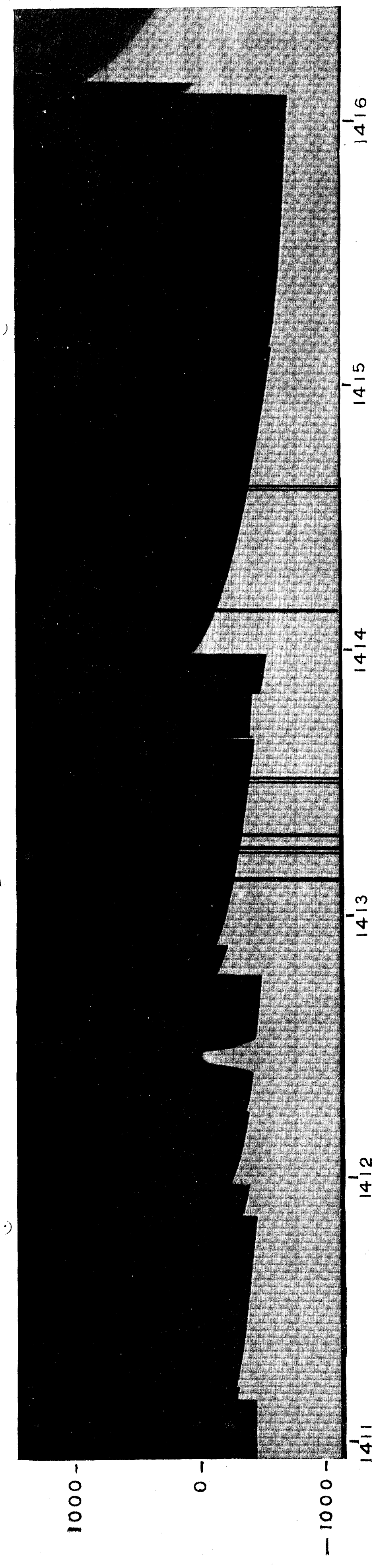


Fig. 3, June 13, 1917.

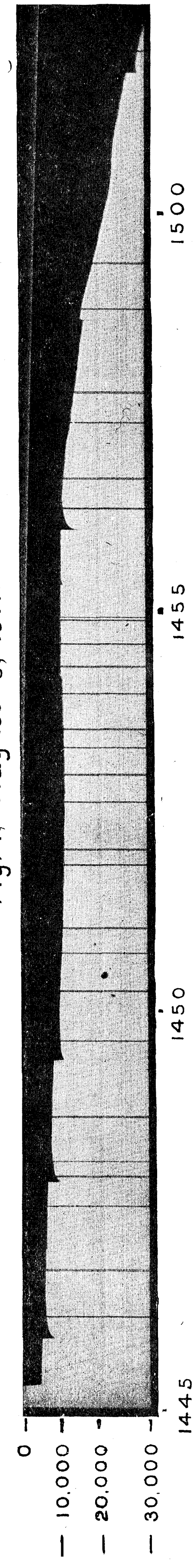


Fig. 4, August 9, 1917.

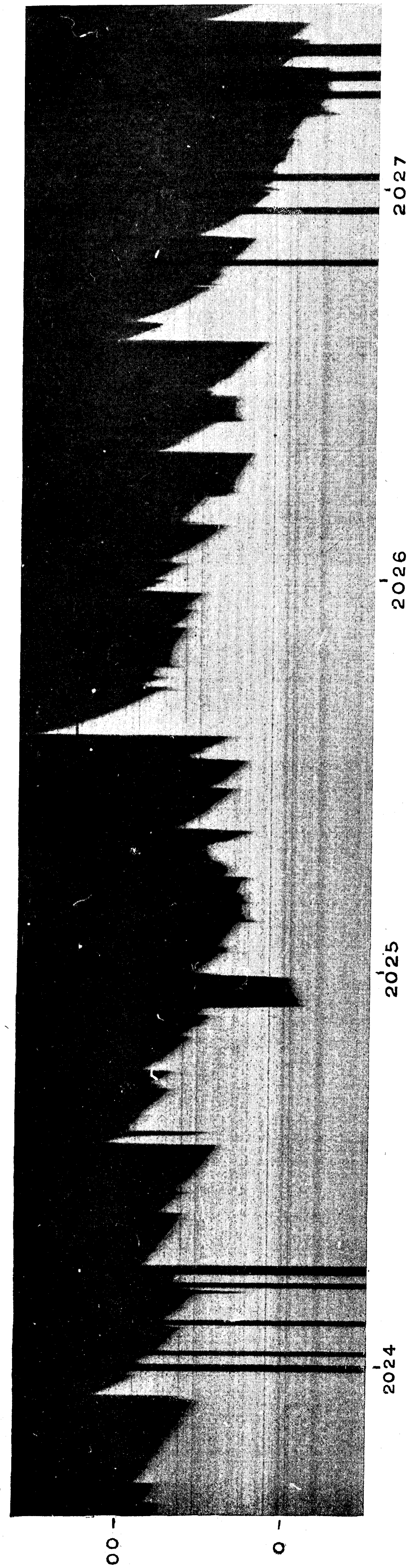


Fig. 5, June 17, 1917.

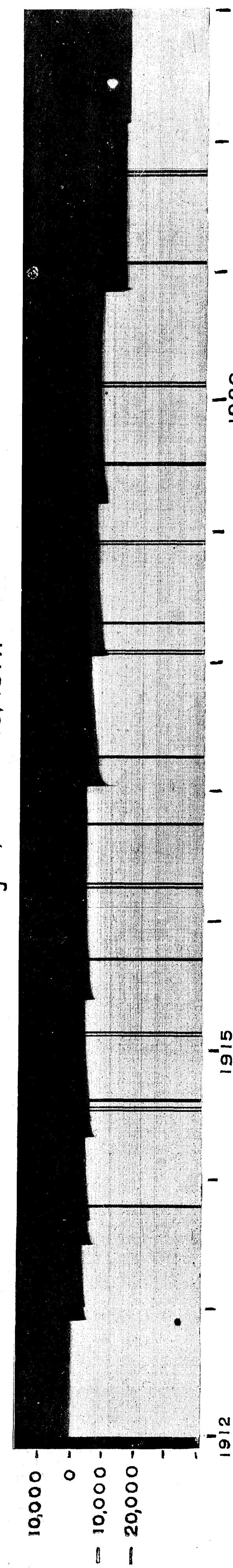


Fig. 6, June 16, 1917.

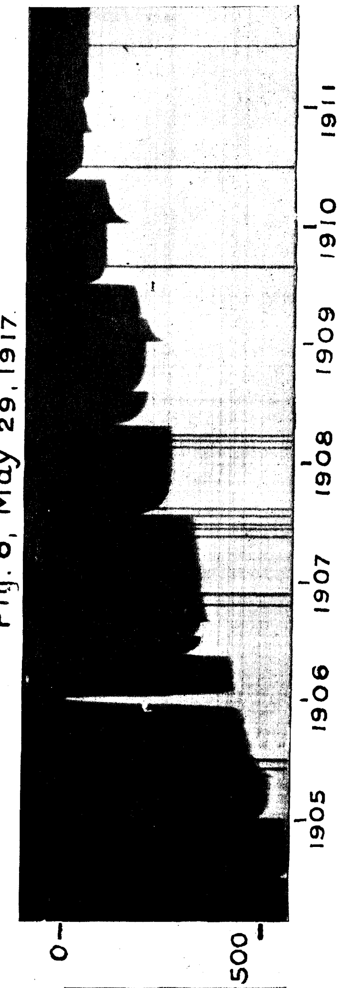


Fig. 8, May 29, 1917.

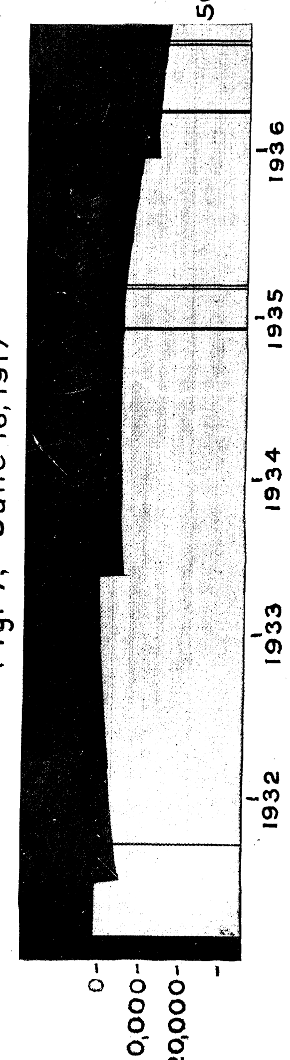


Fig. 7, June 16, 1917

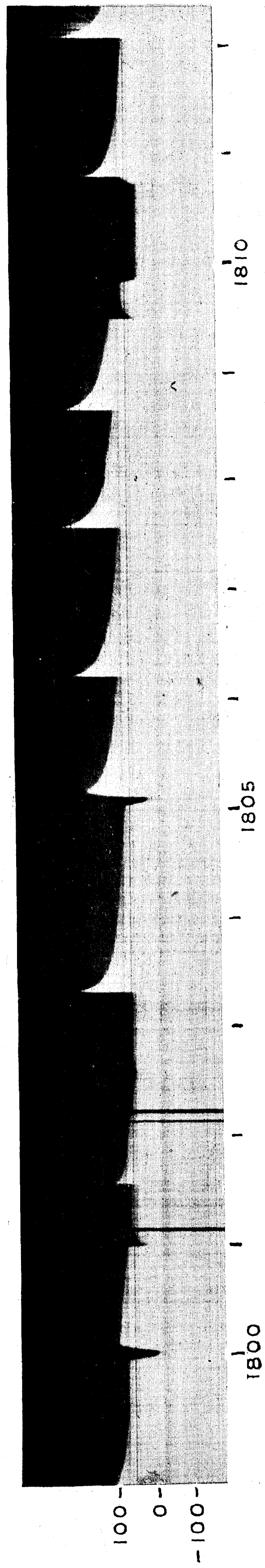


Fig. 9, May 29, 1917.

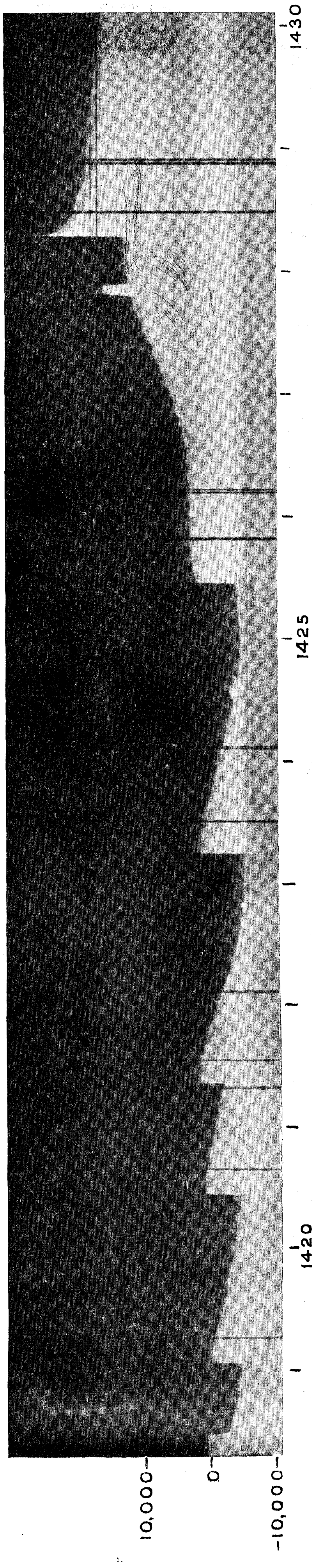


Fig. 10, August 15, 1917.

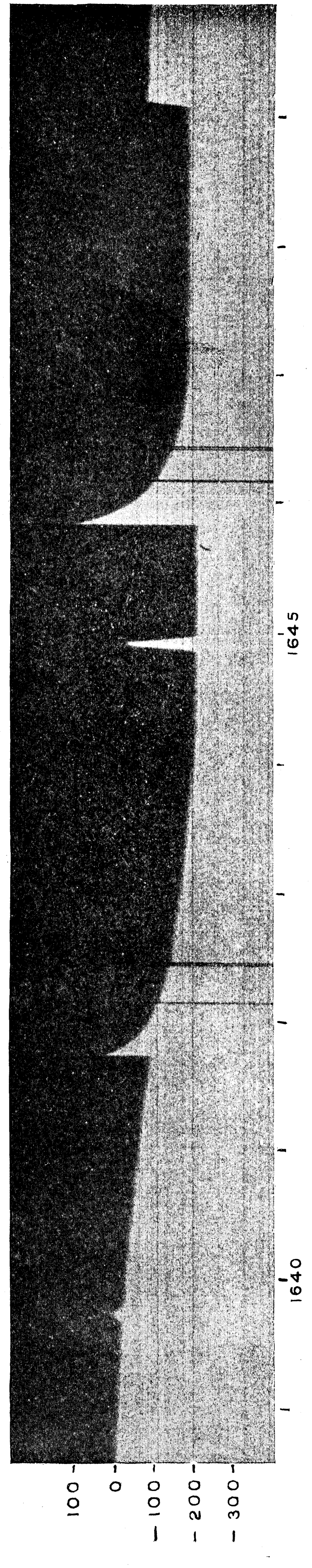


Fig. 11, June 12, 1917.

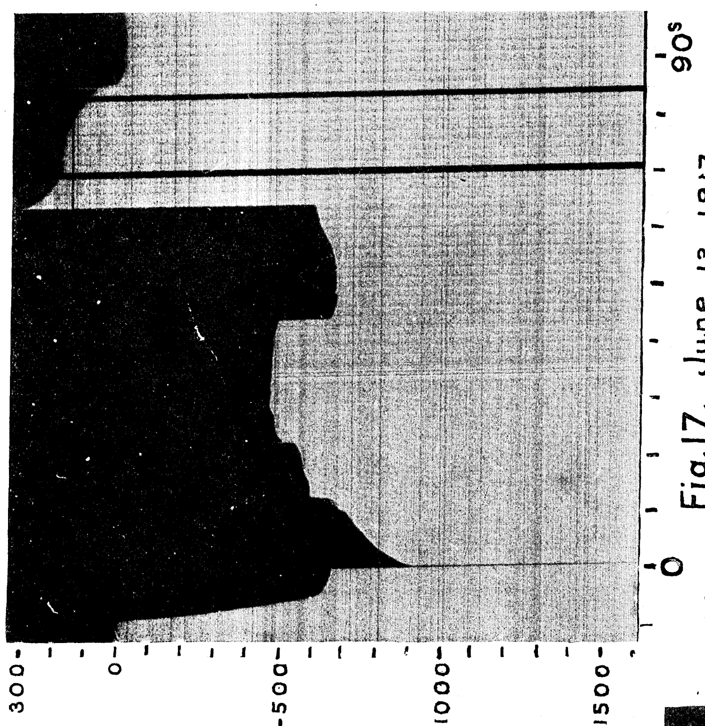


Fig. 14, June 13, 1917

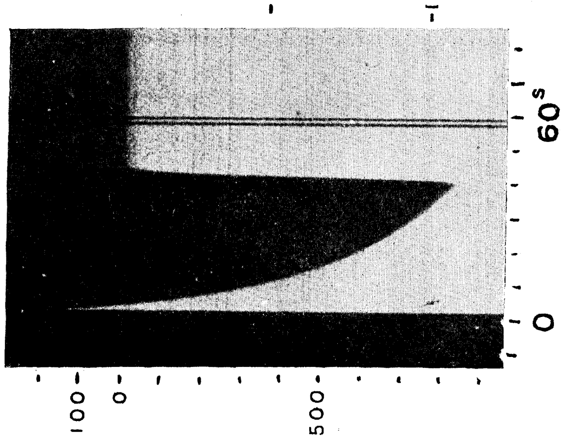


Fig 13, Aug. 15, 1917

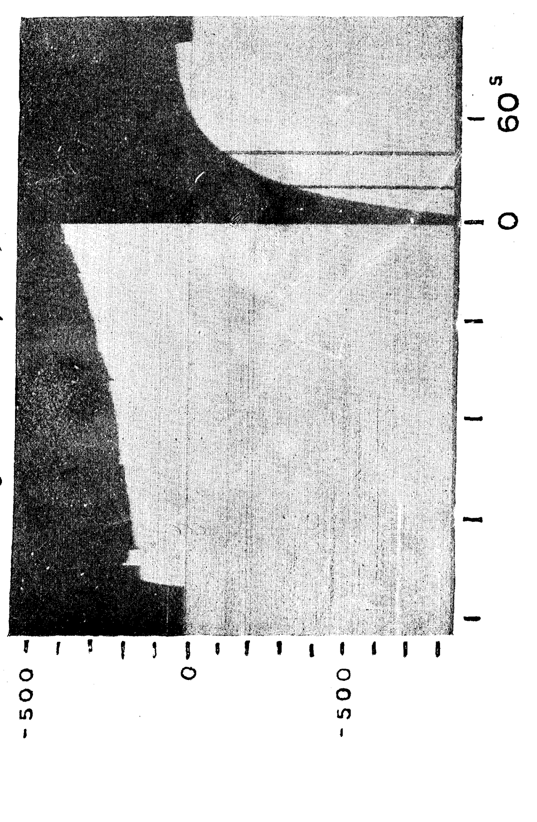


Fig. 12, May 29, 1917

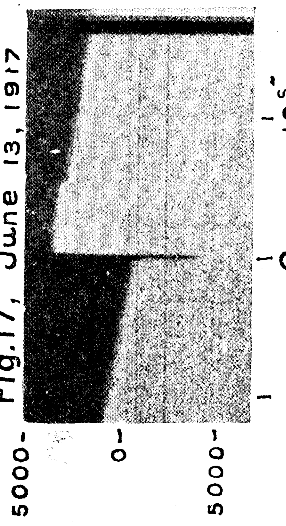


Fig. 17, June 13, 1917

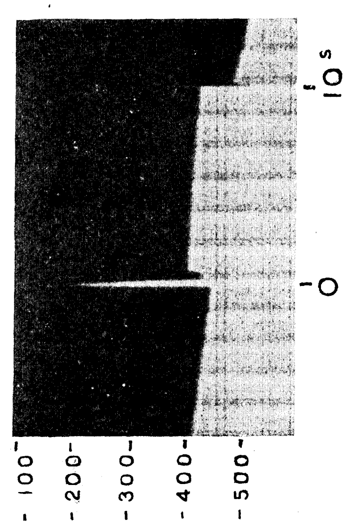


Fig. 16, June 13, 1917

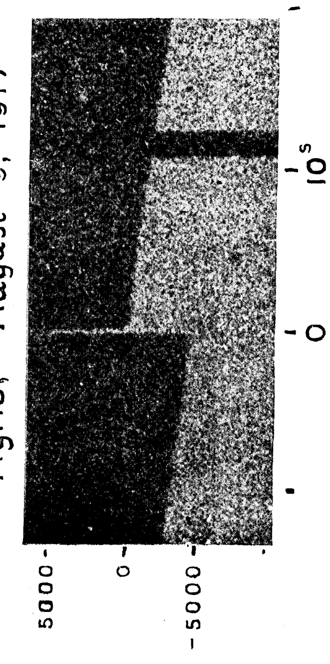


Fig. 15, August 9, 1917

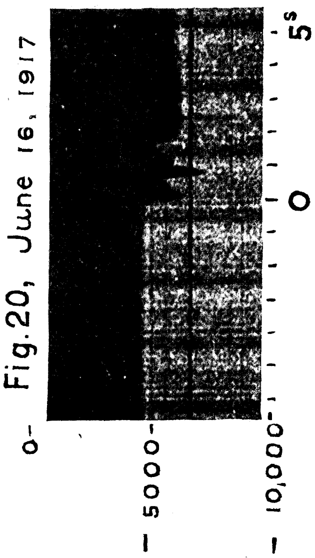


Fig. 20, June 16, 1917

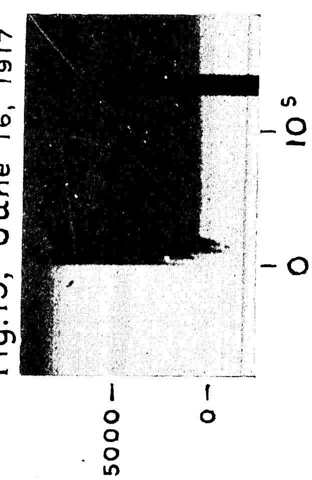


Fig. 19, June 16, 1917

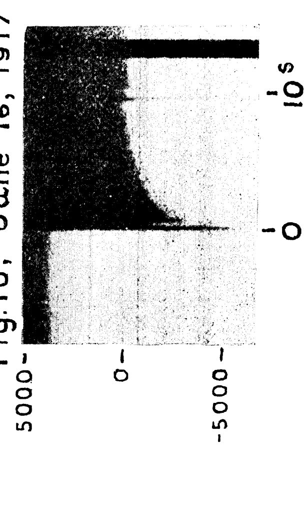


Fig. 18, June 16, 1917

of the whole tube.* If the thickness of the stratiform cloud were small, intense fields might result within the cloud and discharges might even occur; each flash would discharge only a small area of the cloud, of dimensions comparable with the thickness of the cloud.

The characteristic striated and mammatiform appearances frequently observed on the lower surfaces of stratiform clouds associated with thunderstorms may be due to intense electric fields produced as above suggested, the electrical attraction between the upper and lower charges giving rise to convection currents.

If the ionization above and below a stratiform cloud in the field of a primary thunder-cloud is unequal, the cloud will acquire unequal upper and lower charges and thus carry a resultant charge. For example, a stratiform cloud above a cumulo-nimbus cloud will intercept the flow of ions from the upper atmosphere and become charged with electricity of opposite sign to that of the upper pole of the shower-cloud, a steady condition not being reached until a potential difference between the thunder-cloud and the upper atmosphere is concentrated almost entirely in the region below the stratiform cloud. Lightning discharges between the stratiform cloud and the head of the primary thunder-cloud below will be likely to occur.

In the absence of any such cloud above the primary thunder-cloud, the great diminution of the mobility of ions or electrons dragged out of the conducting layers as they penetrate into the denser regions of the atmosphere will have a very similar effect; the concentration of charge will be greatest where the change of conductivity with the height is most rapid. We may in fact, as suggested in Section VIII., consider that the conditions are much the same as if a conducting protuberance were drawn out from the conducting layer towards the summit of the thunder-cloud. It does not seem unlikely that discharges may sometimes occur between this protuberance and the top of the thunder-cloud. In a previous paper some evidence was obtained suggesting the occurrence of discharges of very great vertical length; possibly these may have been of the type we have been considering.

* This action of a layer of cloud, in particular of a ground fog, in increasing the vertical electric field within it has long been recognised in the case of the potential gradient of fine weather. ELSTER and GEITEL, 'Meteor. Zeitschr.,' 17, p. 230, 1900; GEITEL, 'Physikal. Zeitschr.,' 17, p. 455, 1916.

Fig. I, May 23, 1917.

Fig. 2, May 12, 1917.

Fig. 3, June 13, 1917.

Fig. 4, August 9, 1917.

Fig. 5, June 17, 1917

Fig. 6, June 16, 1917.

Fig. 7, June 16, 1917

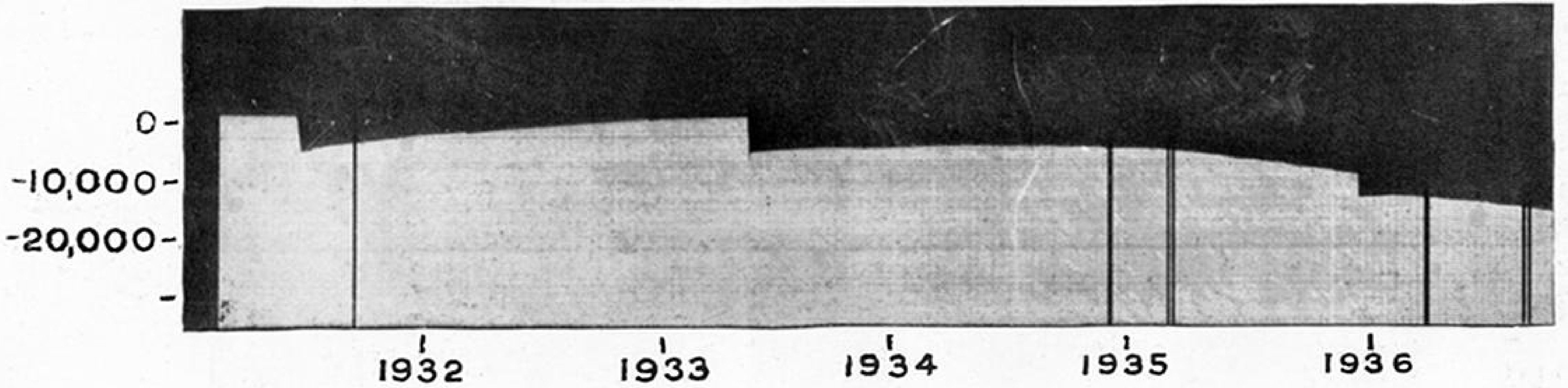
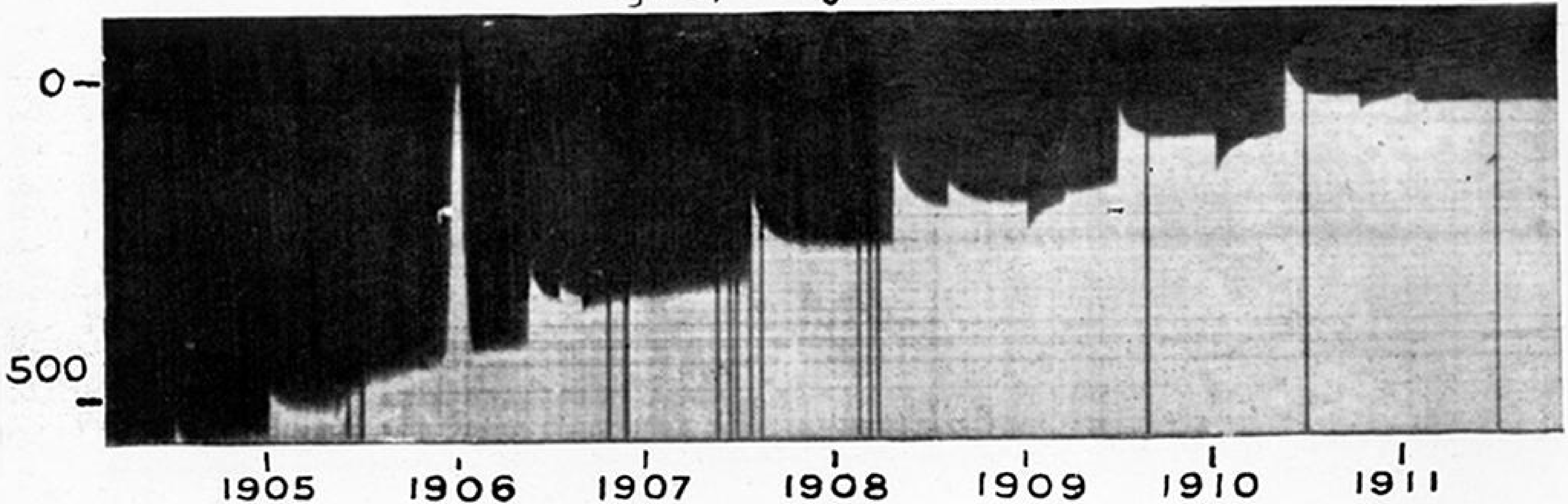


Fig. 8, May 29, 1917.



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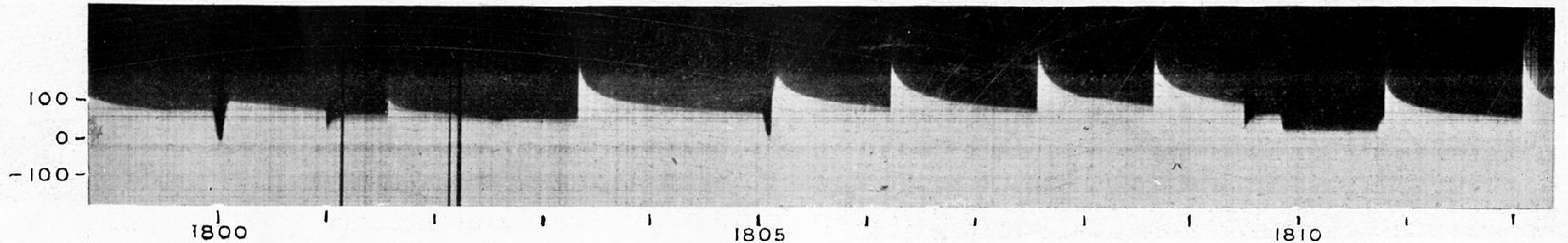
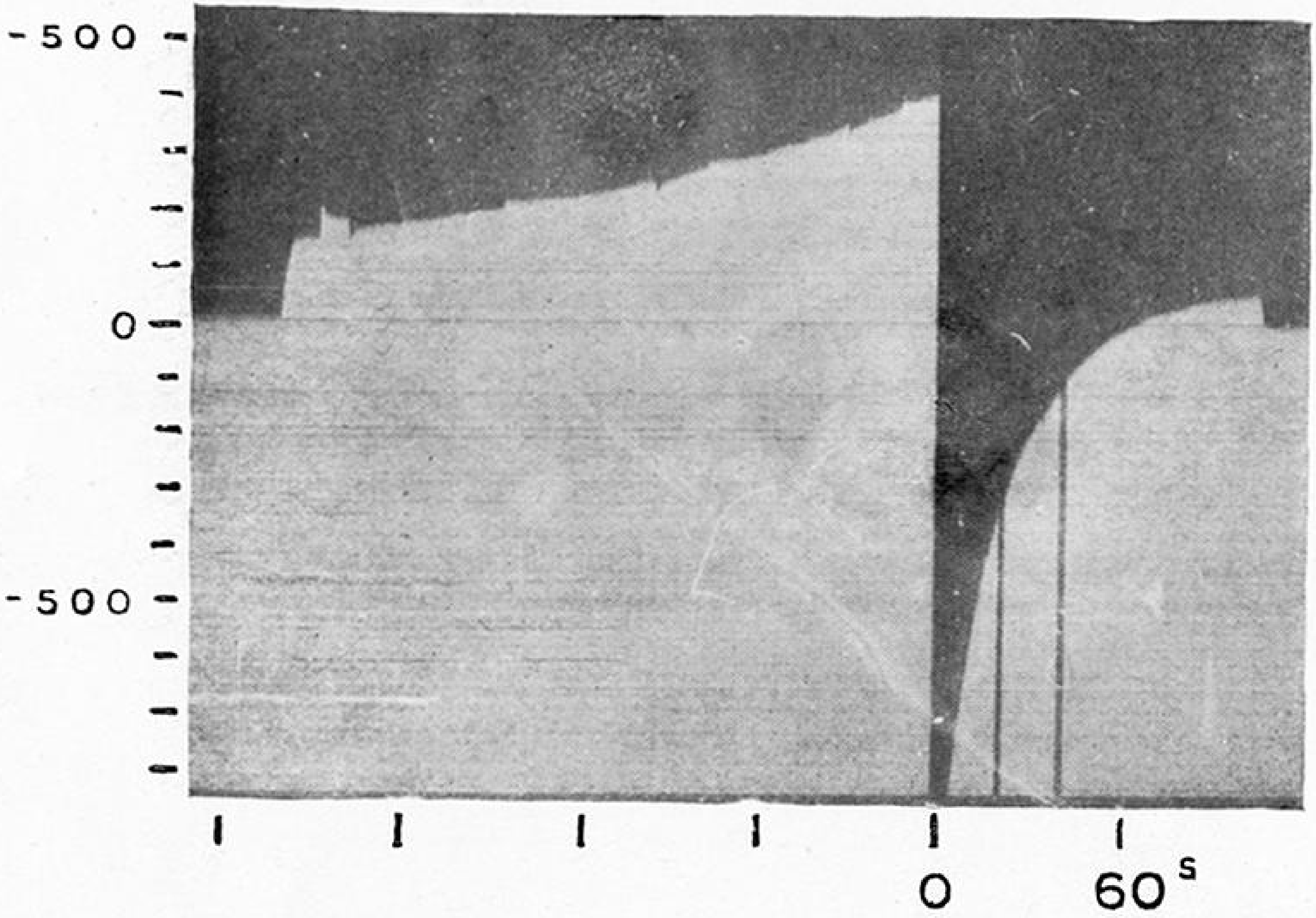


Fig. 10, August 15, 1917.

Fig. 11, June 12, 1917.

Fig. 12, May 29, 1917



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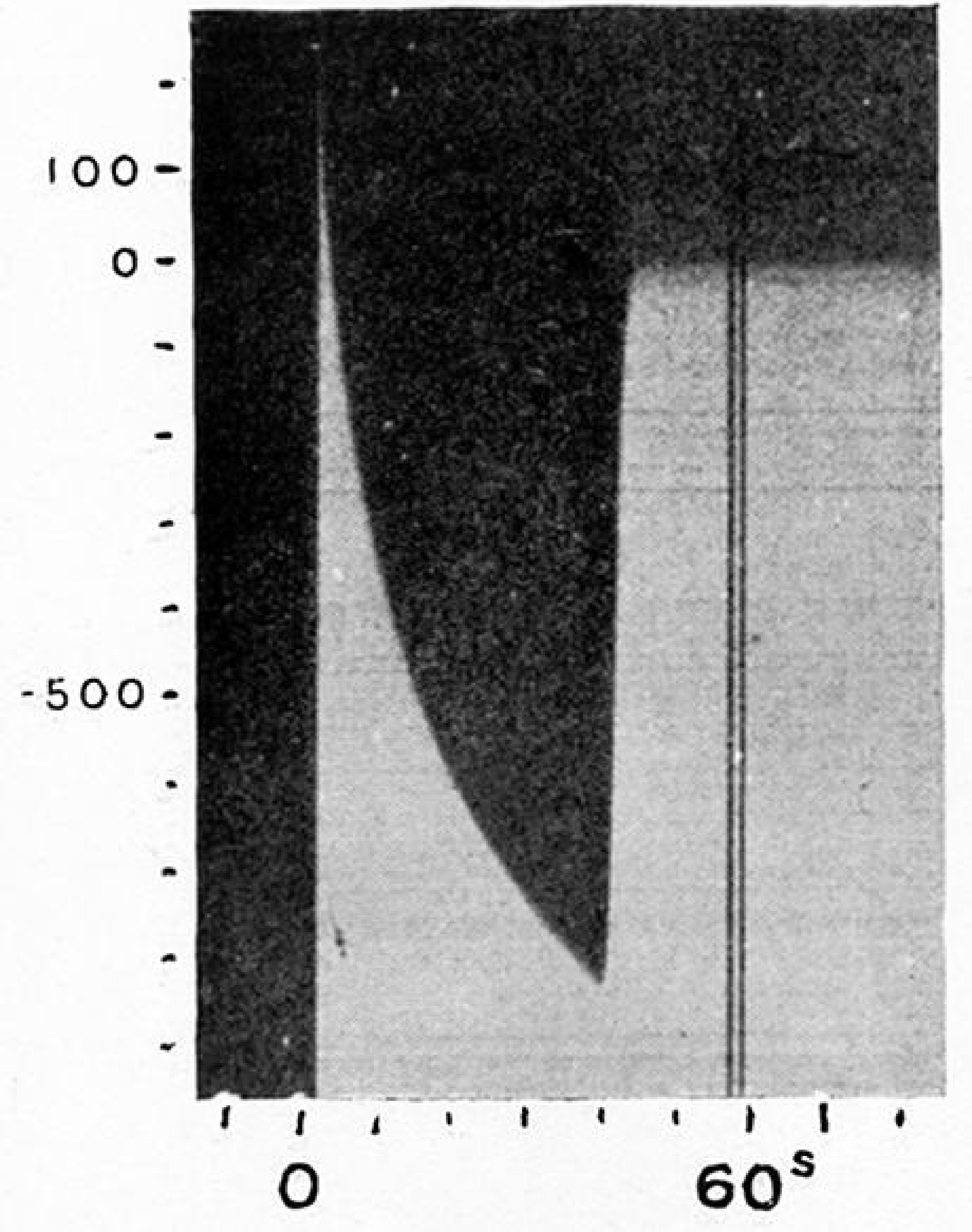

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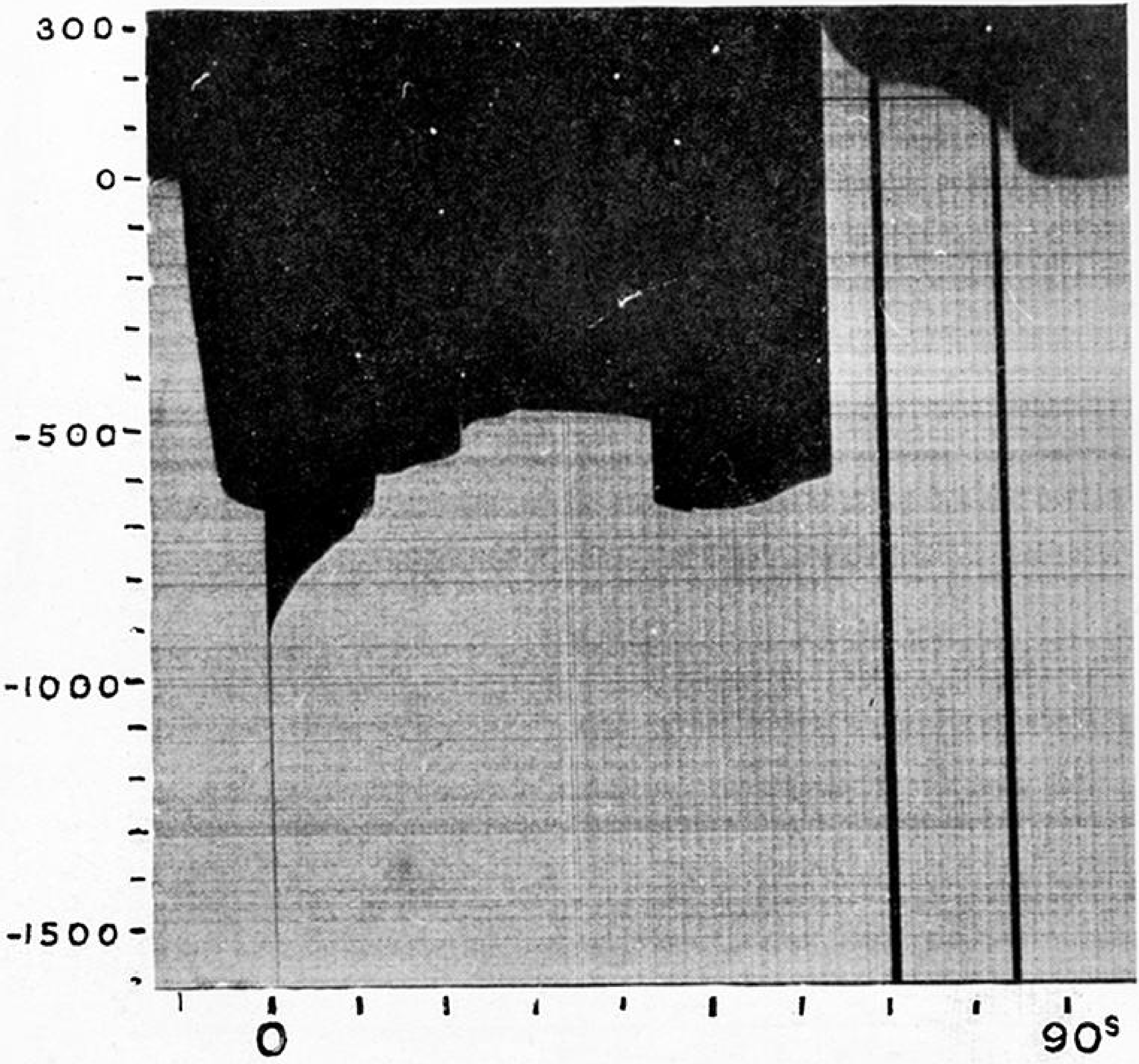
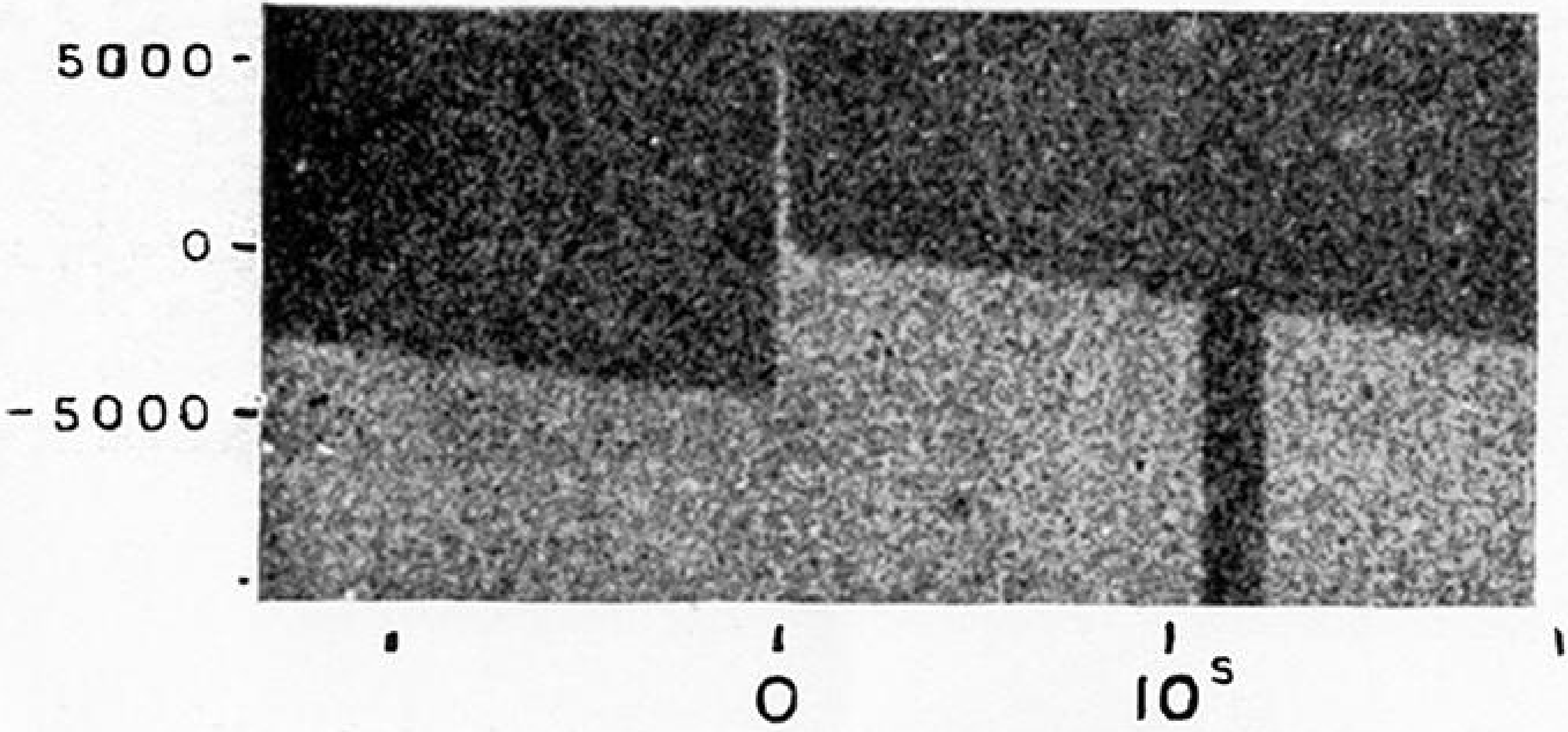


Fig. 15, August 9, 1917



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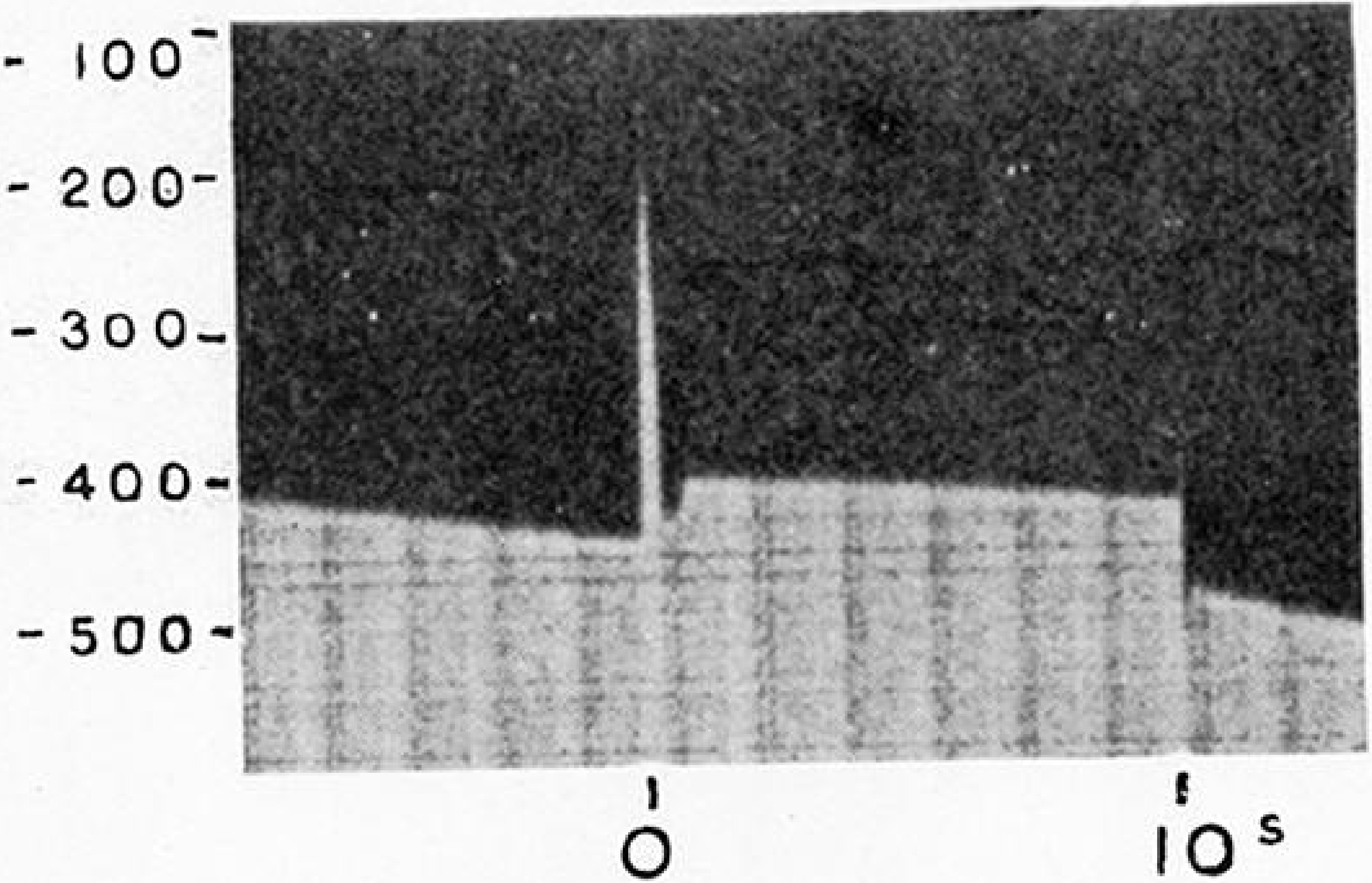

Fig. 17, June 13, 1917

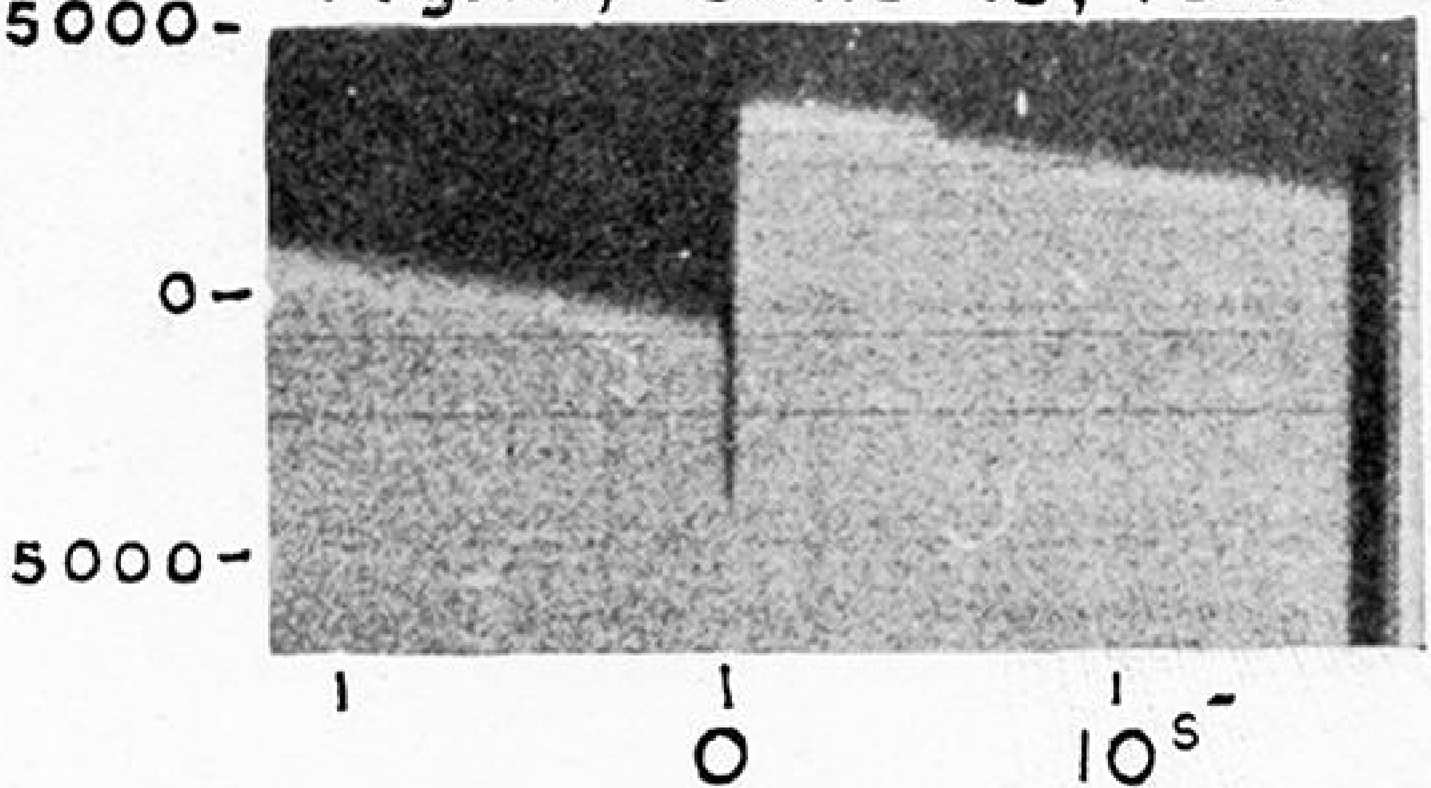

Fig. 18, June 16, 1917

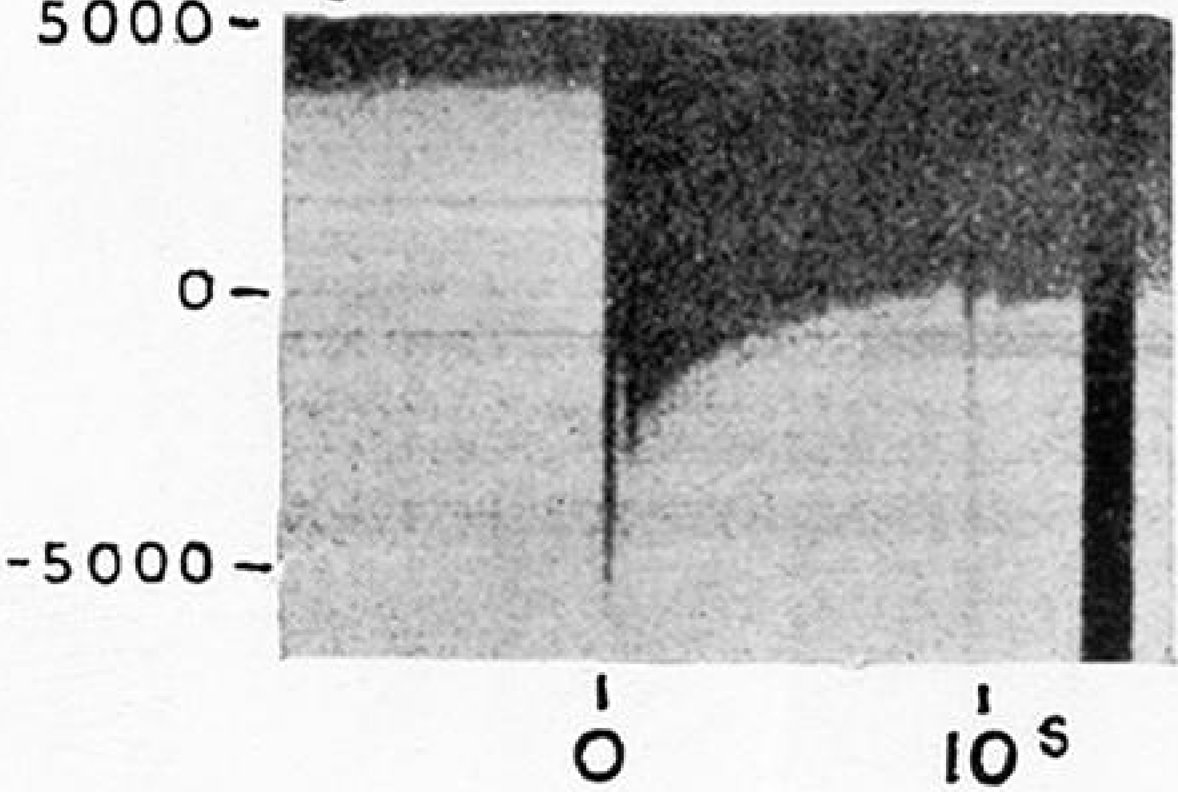

Fig. 19, June 16, 1917

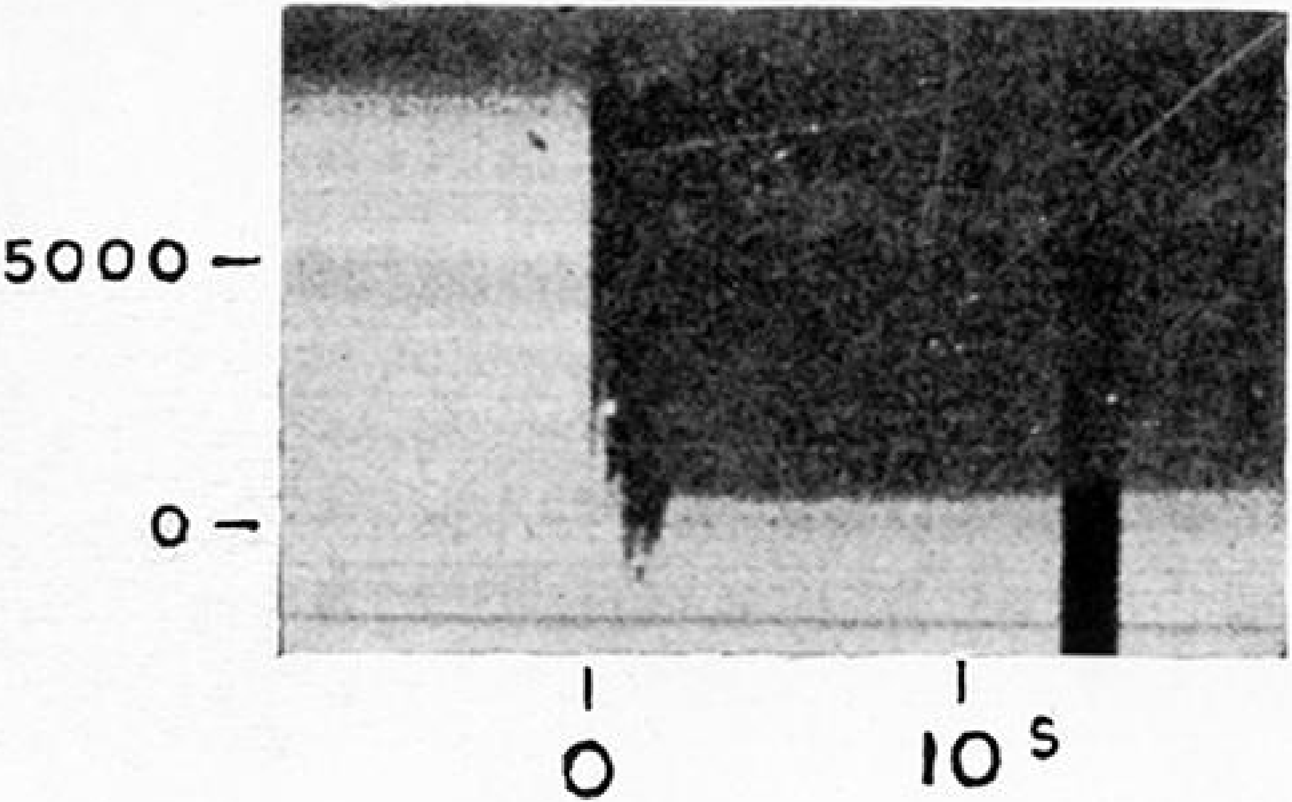

Fig. 20, June 16, 1917