ELECTRIC CHARGES OF RAIN-DROPS.

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(*Received May 22; read August 3, 1951.*)

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Introduction.

In spite of the many investigations that have been made on the origin of electricity of rain there are many points which remain as obscure as ever. Simpson's 'Breaking Drop' theory was at one time considered to describe a major process which was in operation in the production of electricity of cloud. In Simpson's experiments drops of distilled water were allowed to fall through a nozzle and these were broken in a vertical blast of air. In 1938, the senior author showed that the results of these experiments were not directly applicable to breaking of drops in the atmosphere. In the laboratory experiments, the reaction between the liquid and the nozzle makes the drops leave the nozzle with an initial positive charge and give the nozzle a negative charge, with the result that while the drops after being broken by the air current get a charge of 0·023 e.s.u./c.c., the total charge in the air is less than half this amount. In the atmosphere there is no nozzle; the drops may form on ions or nuclei, and may have an initial positive or negative charge, but if they are broken in a current of air, the total charge in the air which will be derived from 1 c.c. will be about minus 0·0092 e.s.u. and the charge acquired by the drops by this operation will also be equal to this amount but positive in sign. Rain-drops always contain a certain amount of impurities; when evaporated to dryness, 100,000 parts of rain-water will give about 0·34 parts of solid matter and most of this consists of sodium chloride and organic matter. This is equivalent to a concentration of $3{\cdot}4\times10^{-4}$ per cent. Experiments show that when drops are broken in a vertical blast of air or by striking against each other, they become negatively charged when the concentration exceeds 5×10^{-5} per cent. The concentration of impurities in rain-drops is so near the transition point that we can develop very little positive charge by the breaking of drops.

The alternative theory of 'carriers' proposed by Wilson (1929) has recently been subjected to experimental tests by Gott (1933). In as much as the process outlined therein involves the capture of ions of either sign by a falling drop in a pre-existing electric field, the growth of charge in the drop, starting from the neutral state, is explained, but the field sets a limit to the charge which the drop can acquire in this way. It is shown that in the presence of ions of both signs carrying equal currents, the drop collects no net charge in fields greater than a certain critical field. In fields less than the critical field it collects more ascending than descending ions and so gains a net charge, which does not increase indefinitely but tends to a limiting value. The limiting charges observed are, for a field of 143 volts/cm., $0{\cdot}58 \times 10^{-2}$ e.s.u. and for a field of 196 volts/cm., $0{\cdot}81 \times 10^{-2}$ e.s.u., while in a field greater than 536 volts/cm., the charge acquired is negligible. The largest charge observed in the course of the experiments described by Gott was equal to about 10^{-2} e.s.u. per drop and since the volume of a drop was $4{\cdot}2 \times 10^{-2}$ c.c., this is equal to 0·2 e.s.u. per cubic centimetre. This maximum charge is slightly smaller than the actual average charge observed on rain-drops.

There can be little doubt that the processes suggested by Wilson and Simpson are both in operation in clouds, in which a strong vertical motion exists. Probably also the collisions of drops, as outlined in Elster and Geitel's theory, come into operation in some way in producing a separation of charge. Furthermore, in the upper parts of a thunder-cloud above the freezing level, the striking of ice particles against each other must make them negatively charged, the positive charge being given to the air. It is, therefore, necessary to find out the relative importance of these various processes by studying the nature of the charges collected by individual drops in thunder-storm or non-thunder-storm rain and also whether these processes by themselves are sufficient to explain the full charges on such drops and if not whether other, and more fundamental, processes come into operation.

The main difficulties in understanding the mechanism of generation of electricity have been that no detailed analysis has hitherto been made of the charge on individual drops of rain. The observations described in this paper[1] were made in the years 1931 and 1932 in the Colaba Observatory at Bombay, and in 1935 and 1936 at Poona. In addition to the Simpson's apparatus for recording the charge of rain collected every two minutes, an apparatus was set up in 1930 in the Colaba Observatory, Bombay, for recording the charge on individual drops of rain. These observations indicate that both positively and negatively charged drops are present in the rain falling from the different parts of a thunder-cloud or an ordinary cloud. When the rain collected in any particular interval of two minutes is positively charged, the result merely means that there is an excess of positively charged drops. Similarly when the rain as a whole in any small interval is negatively charged, there is an excess of negatively charged drops. The average positive charge per drop is about 0·021 e.s.u. and the average negative charge per drop is about 0·023 e.s.u. in non-thunder-storm rain. In thunder-storm rain, the average positive charge per drop is 0·051 e.s.u. and the average negative charge is 0·057 e.s.u. The average radius of rain-drops whose charges were measured is about 0·12 cm. In the classical experiments of Millikan, the oil drops were of radius 2×10^{-4} cm., and on the average there were about 10 ions in a drop. In freshly formed clouds and in fogs, the particles have diameters of the order 10^{-3} cm. Assuming that in a cloud-particle of this size there are 50 ions on the average and assuming that a rain-drop of radius 0·1 cm. has been formed by coagulation of the cloud particles, the total charge on the rain-drop will be about 0·023 e.s.u., that is to say, of the order actually observed. The number of ions in a Millikan drop has been found to vary from 1 to 130, and on the assumption of a similar variation, the charge on a rain-drop supposed to have been formed by coagulation of cloud particles should be expected to vary within wide limits. Since the charge of an ion is $4{\cdot}7 \times 10^{-10}$ e.s.u., there must be in an average positively or negatively charged drop about 10^8 positively or negatively charged ions. Any satisfactory theory of generation of electricity in rain must explain how this enormous number of positive or negative ions attach themselves to rain-drops. Before we proceed to examine this and other points it is necessary first to analyse and collect together the observed results.

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[1] The publication of this paper has been unavoidably delayed, and in the meantime a paper by Hutchinson and Chalmers has appeared in *Quart. Journ. Roy. Met. Soc.*, Vol. 77, 1951

A preliminary account of these experiments was published in *Nature*, Vol. 130, p. 998-999, Dec. 1932.

Although all the experiments were completed in 1935-36, the publication of this paper has been long delayed. This was partly due to the fact that the observations taken at Poona showed that the charges on individual drops recorded at Bombay were about ten times larger than expected, and this was subsequently traced to an unfortunate mistake in the computation of the capacity of the recording system in electrostatic units, which gave its value ten times more than its real value. Owing to this mistake, the figures for charge per drop in e.s.u. would be one-tenth of those given in the above-mentioned article in *Nature*. The delay in publication is also partly due to my preoccupation during the War years.

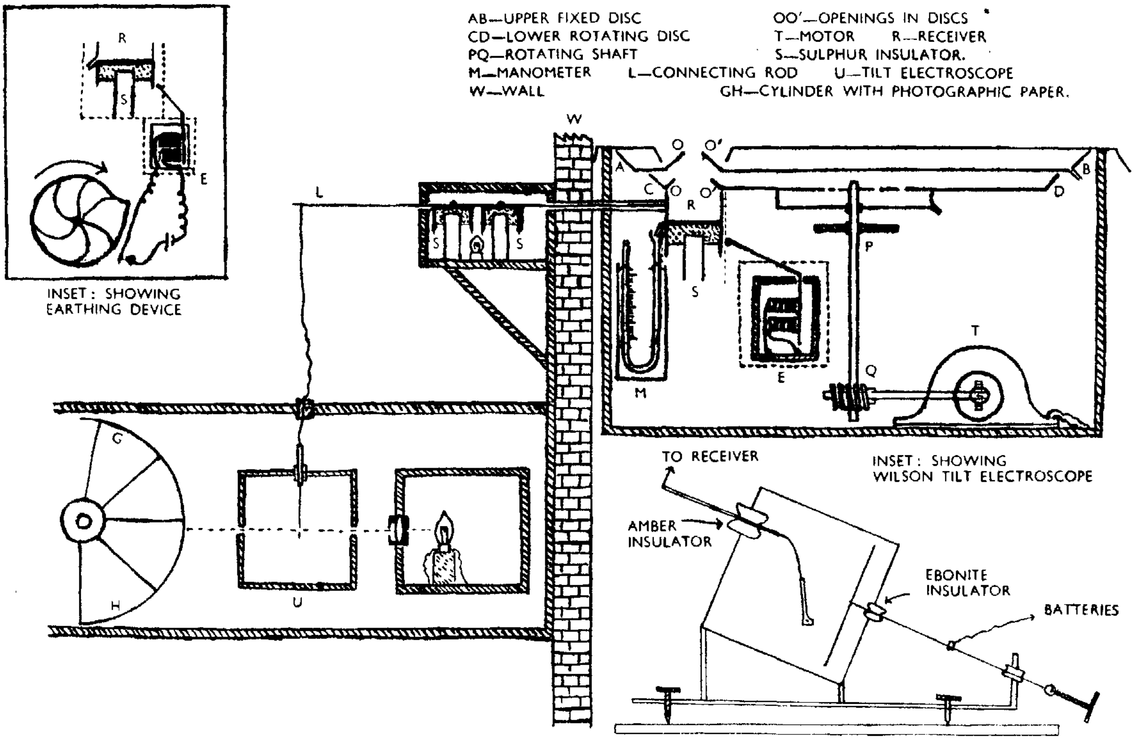

FIG. 1.

2. EXPERIMENTAL ARRANGEMENT FOR RECORDING CHARGE ON INDIVIDUAL DROPS OF RAIN.

In designing a suitable experimental arrangement for recording the charge on individual drops of rain, it is necessary to take every precaution with a view to avoid all spurious effects. The arrangement must be such that a drop enters the receiver without splashing on the side, and that a second drop has no access into the receiver until the charge of the first has been recorded and the apparatus earthed. The electrometer for recording the charge must not only be highly sensitive but also dead-beat so that it can record the charge of drops in quick succession without introducing free vibrations of the system into the record. In practice, it is not easy to satisfy all these conditions rigidly.

The apparatus used, although somewhat imperfect, is shown diagrammatically in figure 1 and is divided into three parts, namely (1) the receiving system, (2) the insulated connecting system, and (3) the recording system. The receiving system consists of an upper fixed disc of diameter 32 cm. with an opening in the form of a cylindrical funnel near the periphery. This opening, which can be adjusted to different sizes to suit different intensities of rain, is provided with trap arrangement, as shown in the diagram, so that a drop striking the sides is caught and led away. It has on the average a diameter of 1·4 cm. Below this disc, there is a disc of diameter 27 cm., rotating uniformly round its central axis once in about 25 seconds. The rotation was maintained by a small alternating current electric motor, the speed being reduced by double worm gears. Near the periphery of the rotating disc, there is a cylindrical opening with trap arrangement and of diameter 2·4 cm. Once during each rotation, this opening comes directly below the opening in the upper fixed disc. The diameter of the opening in the upper disc has been determined by trial so that with moderate intensity of rain only a single drop will pass through both openings. A cylindrical vessel of diameter 7·8 cm. and of height 5·6 cm. resting on double jacket sulphur insulators as shown in the diagram is placed directly below the two openings and receives the drop. A manometer is attached to the receiving vessel and gives a measure of the size and number of drops. The manometer is usually read by eye but a recording arrangement is easily made by making a beam of light focus the meniscus of the coloured oil column (a solution of Iodine in Turpentine) in the outer limb of the manometer on the same sheet of photographic paper which records the charge of the drops. It is not easy to arrange the experimental condition so that each drop after entering the receiver flows into the manometer. If the level is suitably adjusted and a small quantity of water is allowed to remain in the receiver, then after one, two or three drops, depending upon their size, enter the receiver, a corresponding quantity of water flows into the manometer. Careful eye observation is necessary to find out how many drops have entered the receiver before water has flown into the manometer. If the drops are of very small size, the arrangement is not very sensitive and no displacement of the manometer occurs until 3 or 4 drops have entered the receiver. The shaft which rotates the disc also works a contact arrangement. As soon as the charge of the drop has been recorded, an arm attached to the axle makes an electric contact and excites an electro-magnet. The electro-magnet thus attracts an earth connected lever which by making a momentary contact earths the receiver. The electro-magnet and the contact arrangements and all other parts except the end of the earthing lever were covered by earth-connected metal-sheets.

The receiving apparatus was placed on a bracket fixed to the outer wall of a photographic room and covered all round by earth-connected metal sheets leaving on the top sufficient opening for the rain-drop to enter the receiver. The wire connecting the receiver with the recorder was made to pass through a hole in the wall. An earth-connected metal tube was placed concentrically around the wire in order to protect it from stray electric fields. The insulators used in leading the wire from the receiver to the recorder were of sulphur and of the design shown in the diagram.

Before the records were started all insulations were scraped and heated by heating lamps. But when the instrument was in operation all heating lamps were disconnected in order to avoid the effect of artificial fields. The recording apparatus consisted of a Wilson tilt electroscope. The gold-leaf was of length 3·8 cm. and of breadth 1 mm. except at the lower end which was a rectangular piece of breadth 3 mm. and length 2 mm. This rectangular piece was twisted at right angles and a fine pin-hole made at its centre. Light from a point source (a Pathé-Baby Projector lamp) was passed through a small slit and focussed by means of a short focus lens placed just outside the window of the electroscope, and was then allowed to fall as a transverse beam of length of about 1 mm. over the pin-hole. The transmitted light through the pin-hole formed a sharp point on a photographic paper placed 12 cm. away from the gold-leaf. A large magnification of the movement of the gold-leaf was obtained in this way. The photographic paper was wrapped round a cylinder which was rotated round a spiral by clockwork so as to give a speed of 1·2 cm. per minute on the photographic paper. The driving clock was a pendulum one and gave uniform speed, the time marks were obtained by cutting off the light at known instants. As each rain-drop entered into the receiver, a displacement of the speck was obtained either to the right or to the left of the zero (earthed) position according to the sign of charge and as the system was earthed immediately afterwards, the speck came back to zero. The intensity as well as the sign of the charge of drops was, therefore, given by the successive displacements either to the right or to the left.

The capacity of the receiver and the recording system was 60 cm. Two volts applied to the receiver produced a deflection of 0·9 cm. Therefore, 1 cm. of deflection was equivalent to

$$\frac{2\times 60\times 10}{300\times 9} \text{ or } 0{\cdot}44 \text{ e.s.u.}$$

Test experiments.

The following test experiments were made. A number of drops were allowed to fall on the receiving apparatus from an insulated metal funnel in which a coil of wire was inserted, and which was charged to a known potential with respect to earth. The diameters of the drops were determined by collecting a certain number of them and measuring the volume. Knowing the potential and the volume of each drop the charge per drop is easily obtained. The deflection produced on the photographic paper as the cumulative effect of a definite number of charged drops falling on the receiver is measured under a microscope and from this the charge corresponding to 1 cm. of deflection on the photographic paper is readily calculated. For instance, in one experiment the following results were obtained:—

Volume of 200 drops	24	c.c.
∴ radius of each drop	0·3	cm.
Voltage to which the drops were charged ..	80	volts.
∴ the charge on each drop	0·008	e.s.u.
48 drops produced deflection of	0·88	cm.
The charge corresponding to a deflection of 1 cm. is ..	0·44	e.s.u.

The results of the calibration experiments are summarized in Table I.

Simultaneously with the apparatus described above for recording the charge on individual drops of rain an apparatus for recording the charge collected every two minutes was maintained in continuous action. This was of the usual Simpson type.

An electrograph recording potential gradient, with an 'ionium' collector was also maintained in continuous action.

3. GENERAL DISCUSSION OF THE CHARGE OF RAIN-DROPS.

The kind of records obtained on account of communication of charge into the apparatus by successive drops and the earthing of the system, as soon as the charge of each drop is recorded, is shown in Plate II. In this Plate typical records showing the charge of thunder-storm rain-drops and of non-thunder-storm rain-drops have been reproduced. It will be seen that each drop produces an appreciable deflection and that in thunder-storm rain the

TABLE I.

Plate voltage of tilt electroscope	190	volts.
Radius of an average drop	0·3	cm.
Charge per drop	0·008	e.s.u.

Drops charged to + 80 volts.			Drops charged to −80 volts.		
No. of observations.	No. of drops entering the receiver.	Deflection in cm.	No. of observations.	No. of drops entering the receiver.	Deflection in cm.
1	40	0·76	1	40	0·79
2	40	0·73	2	40	0·71
3	40	0·71	3	40	0·74
4	40	0·73	4	40	0·71
5	48	0·88	5	48	0·85
6	48	0·88	6	48	0·88
7	48	0·88	7	48	0·85
8	48	0·88	8	48	0·94
9	48	0·91	9	48	0·91
10	48	0·88	10	48	0·88
11	48	0·85	11	48	0·88
12	48	0·88	12	48	0·88
13	76	1·38	13	76	1·44
14	76	1·44	14	76	1·41
15	76	1·38	15	76	1·41
16	76	1·47	16	76	1·38
17	88	1·62	17	88	1·62
18	88	1·62	18	88	1·59
19	88	1·62	19	88	1·68
20	88	1·62	20	88	1·62
21	97	1·79	21	97	1·79
22	97	1·79	22	97	1·79

Mean deflection per drop = 0·018 cm.
1 cm. of deflection = 0·44 e.s.u.

Mean deflection per drop = 0·018 cm.
1 cm. of deflection = 0·44 e.s.u.

drops are slightly more intensely charged than in non-thunder-storm rain. It will be observed that if the rain-drops are of diameter 0·2 cm., and if the centre of any drop falls anywhere within 0·1 cm. of the periphery of the adjustable upper opening of 1·4 cm. in diameter, then it will strike the side and get discharged. If, however, its centre falls anywhere within the circle of radius 0·6 cm., then it will pass through. The chance of a drop of this size striking the side is, therefore, $2\pi \times 0{\cdot}7 \times 0{\cdot}1 : \pi \times 0{\cdot}6 \times 0{\cdot}6$ or 14 : 36.

It would be wrong to conclude from this that on the average every third drop will reach the receiver with no charge on it, because the rotating disc below the upper opening completely modifies the condition. The rotating disc closes the upper opening in less than half a second. A drop which will strike the periphery of the upper opening will almost in every case be caught by this rotating disc. It is clear that only those drops which fall through near the centre of the upper opening will have a chance of passing through the opening in the rotating disc. It is, therefore, found in practice that a comparatively small number of drops reach the receiver without any charge. The general characteristic of the charge of thunder-storm and non-thunder-storm rain-drops can be clearly seen from Table II which has been based on the measurement of charges on 2,500 drops. In making the tabulations all drops were neglected whose charge was less than 0·006 e.s.u.

TABLE II.

	Charge per drop (e.s.u.)					
	Positively charged drops.			Negatively charged drops.		
	Mean.	Mean Max.*	Absolute Max.	Mean.	Mean Max.*	Absolute Max.
Thunder-storm rain ..	0·055	0·194	0·244	0·061	0·226	0·374
Non-thunder-storm rain	0·041	0·118	0·195	0·045	0·122	0·241

* Average of maximum reached on different dates.

It is to be noted that a drop of radius 0·1 cm. and having 0·05 e.s.u. has a potential of 150 volts while if it has a charge of 0·25 e.s.u. its potential is 750 volts. It was noticed that when all drops whose charge is less than 0·006 e.s.u. are neglected in making the tabulations, the number of drops neglected is considerably more in non-thunder-storm rain than in thunder-storm rain. The results given above in respect of thunder-storm and non-thunder-storm rain-drops are, therefore, not strictly comparable with each other. Another table was consequently prepared in which all drops whose charge was less than 0·001 e.s.u. was neglected; this was the limit up to which tabulation was possible under the microscope, with the sensitiveness adopted in the recording system.

The results are shown in Table III.

TABLE III.

	Charge per drop (e.s.u.).					
	Positively charged drops.			Negatively charged drops.		
	Mean.	Mean Max.*	Absolute Max.	Mean.	Mean Max.*	Absolute Max.
Thunder-storm rain ..	0·051	0·194	0·244	0·057	0·211	0·374
Non-thunder-storm rain	0·021	0·118	0·195	0·023	0·122	0·241

* Average of maximum reached on different dates.

Note :

Thunder-storm rain.

Number of positive drops tabulated	600
Number of negative drops tabulated	790
Number of drops neglected	23 (percentage 1·6)

Non-thunder-storm rain.

Number of positive drops tabulated	1,070
Number of negative drops tabulated	1,288
Number of drops neglected	297 (percentage 12)

It will be seen that even with the limit of 0·001 e.s.u. the percentage of drops neglected in the case of non-thunder-storm rain was 12, while in the case of thunder-storm rain, it was only 1·6. It is probable that a certain number of these neglected drops reached the receiver discharged as a consequence of their striking the periphery.

An analysis of the records shows that both positively and negatively charged drops are present in the rain received from any part of the cloud. When the Simpson apparatus shows that the rain received during any interval is positively or negatively charged as a whole, it is found that there is an excess of positively or negatively charged drops. When we analyse the figures given in Table II or Table III we find that both in thunder-storm and non-thunder-storm rain, the negative drops are slightly more intensely charged than the positive drops. The mean charge per drop in thunder-storm rain is considerably greater than the mean charge per drop in non-thunder-storm rain. The mean charge per drop in the case of non-thunder-storm rain would probably become slightly less than the figure given if all the drops could be included in the tabulation. The absolute maximum value of charge per drop obtained during the period of observation in the case of thunder-storm rain considerably exceeds that in the case of non-thunder-storm rain. In order to bring out more conspicuously the differences in the charges of drops in the case of thunder-storm and non-thunder-storm rain Table IV has been prepared.

At Poona, a Lindeman electrometer was used. The potentials applied to the plates were +30 volts and −30 volts. With these imposed potentials, the deflection per volt as observed through the microscope was 5·5 divisions. The receiving system although of the same pattern was redesigned, using the minimum amount of metal, so as to have as small a capacity as possible. The capacity was 8 cm., so that a deflection of 1 division was equivalent to $4{\cdot}8\times10^{-3}$ e.s.u. (or approximately 5×10^{-3} e.s.u.). Of the 320 drops whose charges were measured, 151 were positively charged and 169 negatively charged. The following table gives an analysis of the charges obtained in these measurements :—

	Charge per drop (e.s.u.)					
	Positively charged drops.			Negatively charged drops.		
	Mean.	Mean Max.	Absolute Max.	Mean.	Mean Max.	Absolute Max.
Thunder-storm rain ..	0·046	0·120	0·125	0·062	0·165	0·192
Non-thunder-storm rain	0·020	0·065	0·120	0·048	0·080	0·105

At Poona, the charges brought down by rain, as observed in these experiments were preponderatingly negative.

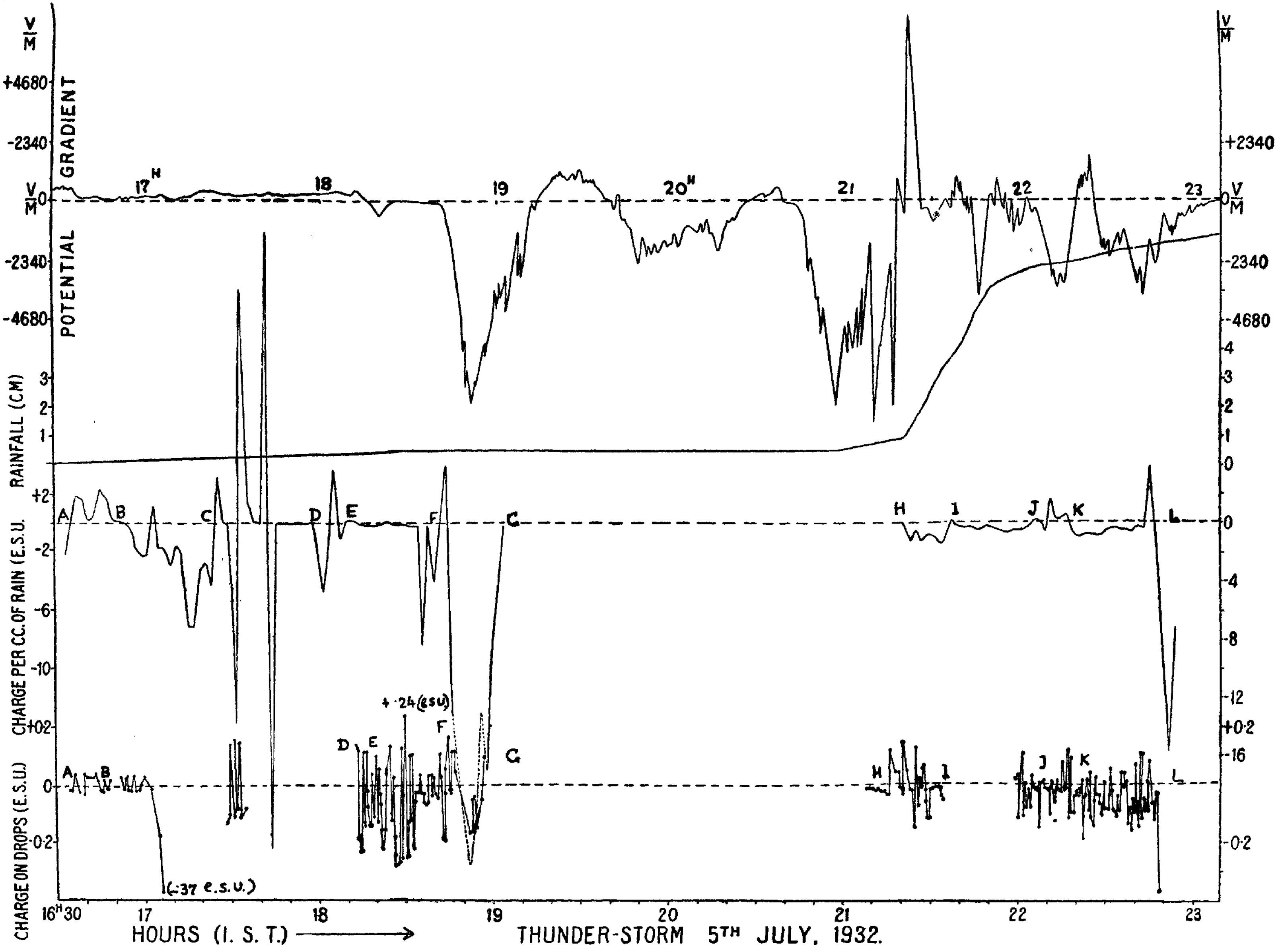
V/M
+4680
-2340
V/M 0
-2340
-4680
GRADIENT
POTENTIAL
RAINFALL (CM)
3
2
1
+2
-2
-6
-10
CHARGE PER CC. OF RAIN (E.S.U.)
+0·2
0
-0·2
CHARGE ON DROPS (E.S.U.)
17H
18
19
20H
21
22
23
+2340
0 V/M
-2340
-4680
4
3
2
1
0
0
-4
-8
-12
+0·2
-16
-0·2
A
B
C
D
E
F
G
H
I
J
K
L
+ ·24 (esu)
(-·37 e.s.u.)
16H30
17
18
19
20
21
22
23
HOURS (I. S. T.) ⟶
THUNDER-STORM 5TH JULY, 1932.

Fig. 2.

TABLE IV.

	Total No. of drops analysed.	Percentage of drops with charge.											
		Of 0·2 e.s.u. or more.		Between 0·1 e.s.u. and 0·2 e.s.u.		Between 0·05 e.s.u. and 0·1 e.s.u.		Between 0·01 e.s.u. and 0·05 e.s.u.		Between 0·005 e.s.u. and 0·01 e.s.u.		Between 0·001 e.s.u. and 0·005 e.s.u.	
		Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.	Pos.	Neg.
Thunder-storm rain	600 Pos. 790 Neg. without charge 23	0·28	1·4	4·0	7·6	12·3	14·4	20·9	28·0	3·2	2·5	1·9	2·1
Total ..	1,413											below 0·001 e.s.u.	1·6%
Non-thunder-storm rain.	1,070 Pos. 1,288 Neg. without charge 297		0·5	2·0	2·4	4·2	5·3	13·4	16·0	6·8	7·1	14·4	17·0
Total ..	2,655											below 0·001 e.s.u.	11·1%

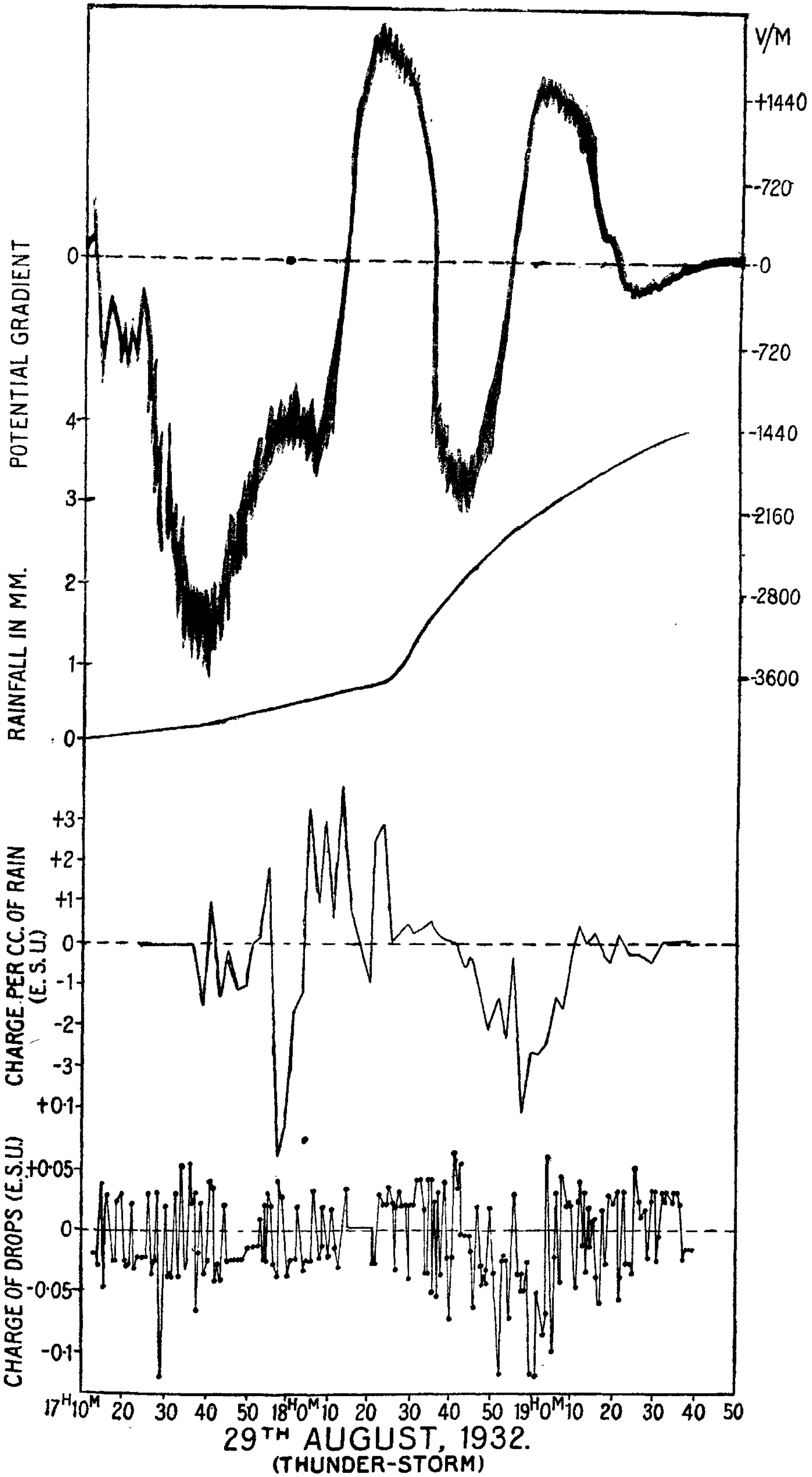
V/M
+1440
+720
0
-720
-1440
-2160
-2800
-3600
POTENTIAL GRADIENT
RAINFALL IN MM.
0
4
3
2
1
0
CHARGE PER CC. OF RAIN (E.S.U.)
+3
+2
+1
0
-1
-2
-3
CHARGE OF DROPS (E.S.U.)
+0·1
+0·05
0
-0·05
-0·1
17H10M
20
30
40
50
18H0M
10
20
30
40
50
19H0M
10
20
30
40
50
29TH AUGUST, 1932.
(THUNDER-STORM)

Fig. 3.

4. Discussion of the charge on thunder-storm rain-drops.

The general relationship between the charge on individual drops of rain, and the charge of rain collected every two minutes by Simpson recorder and their dependence on the electric field can best be discussed with reference to individual thunder-storm. The records obtained during the passage of the line squall thunder-storm over Bombay on the 5th of July, 1932, have been reproduced in fig. 2. The thunder-storm commenced at about 16 hours and continued until midnight. From 16 hours to 20 hours the cloud was diffused; the main thunder-cloud passed over the station after 20 hours. The potential gradient record indicates that the front part of this main cloud was negatively charged, the central part generally positively charged and the rear negatively charged. Very light rainfall occurred during the passage of the diffused cloud, but heavy rainfall occurred for about half an hour during the passage of the central part of the main cloud.

If we consider the charge per c.c. of rain as given by Simpson record we find that during the time marked *AB*, the charge was preponderatingly positive. The drop records indicate that, during the period, drops with positive charge were larger in number than drops with negative charge. During the subsequent period *BC*, the charge of rain was on the whole negative and of the drops whose charge was recorded at the time, a larger number had negative charge. During the period marked *DE*, the rain was for some time positive and for some time negative and, therefore, collectively had very little charge, and if at all, it was slightly negatively charged. We see that during the period the negatively charged drops are slightly in excess of the positively charged drops. On the other hand, during the period marked *EF*, the charge of rain was preponderantly negative, and 17 drops were recorded with negative charge and 12 drops with positive charge. Similar remarks apply to the charge records during the passage of the main thunder-cloud.

We thus see that both positively and negatively charged drops are present in the rain received from any part of the cloud. When the rain from any part of the cloud is on the whole positively or negatively charged, there is an excess number of positively charged drops or negatively charged drops as the case may be. During the period light rain or drizzle occurred the drops were smaller in diameter and carried in general greater charge.

We take another example, namely, that of a 'Heat' thunder-storm, which developed over the hills to the east of the Colaba Observatory on the 29th August, 1932, and passed over it between 17 hours and 20 hours. This thunder-storm was a typical thunder-storm of the 'unitary type' and the relationship between the electric field and the charge of rain as given by the Simpson recorder, as well as the charge on individual drops of rain are shown by the curves in fig. 3. It will be seen that the portion marked *AB*, in the Simpson record is predominantly negative. Of the drops received during the interval, 24 had negative charge, and 12 only positive charge. Then again during the interval *BC*, the charge was predominantly positive, 24 of the drops, whose charges were recorded during the interval had positive charge and 17 had negative charge. During the interval *CD*, the charge was again predominantly negative; 31 drops were received negatively charged and 12 positively charged. This storm, therefore, confirms like the previous one that both negatively and positively charged drops are present in the rain received from any part of the cloud, but when the rain received during any interval is preponderantly positive, there is an excess of positively charged drops. In the same way when the rain is preponderantly negative, there is an excess of negatively charged drops.

No conspicuous lightning or thunder was observed during the passage of the disturbance on the 4th September, 1932, (fig. 4) but the cloud was intensely charged. Very little movement could be observed in the cloud; it was apparently moving very slowly. It caused heavy rainfall and during the passage of its rear part, the field was intensely negative. The '2-minutes' charge record shows

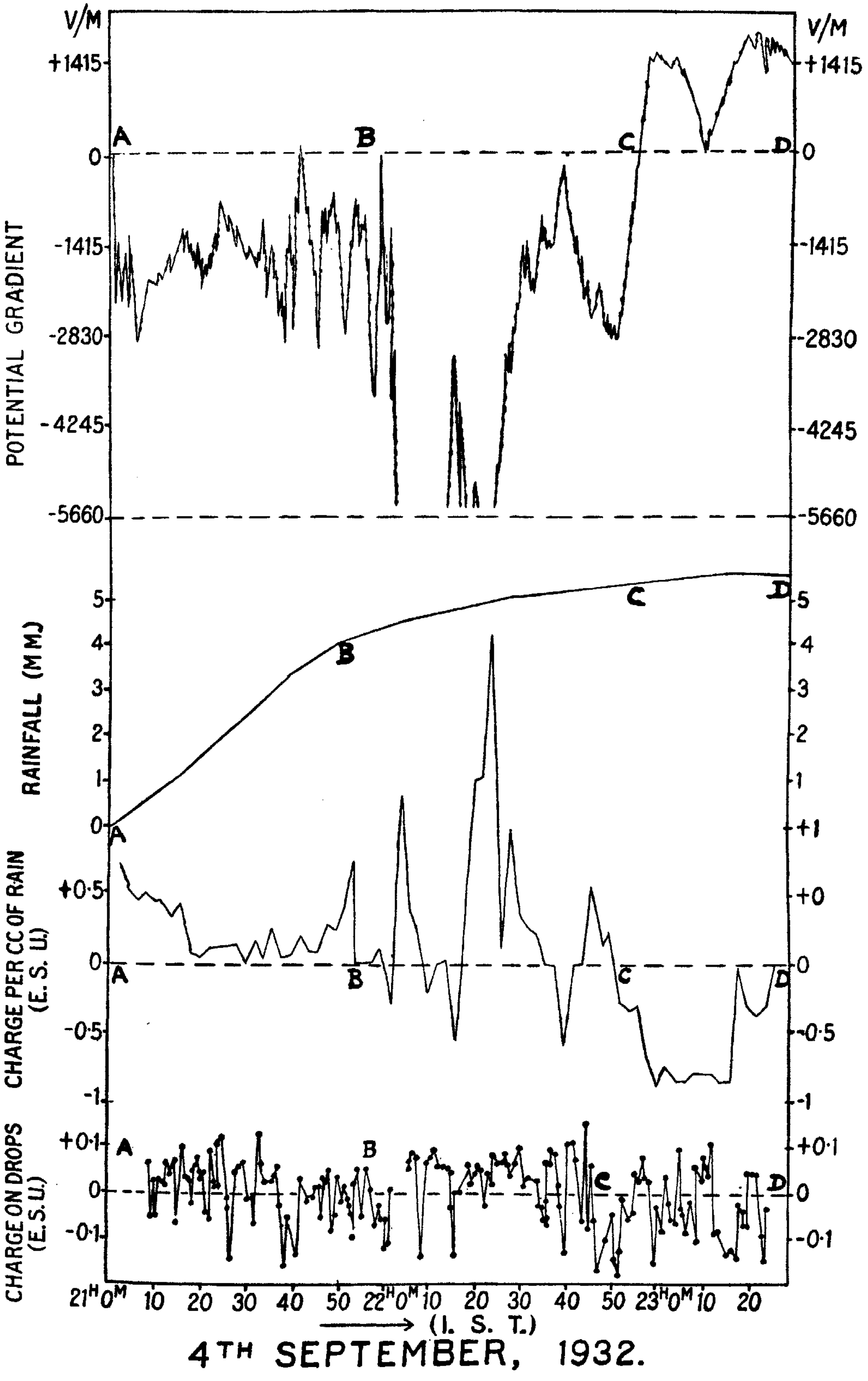
V/M
V/M
+1415
0
-1415
-2830
-4245
-5660
POTENTIAL GRADIENT
A
B
C
D
RAINFALL (M M)
5
4
3
2
1
0
+1
+0·5
+0
-0·5
-1
CHARGE PER CC OF RAIN (E. S. U.)
CHARGE ON DROPS (E.S.U.)
+0·1
-0·1
21H 0M 10 20 30 40 50 22H 0M 10 20 30 40 50 23H 0M 10 20
(I. S. T.)
4TH SEPTEMBER, 1932.

FIG. 4.

that the heavy rainfall (represented by the portion *AC*, on the rainfall curve) was on the whole positively charged. During the interval 82 positively charged drops and 48 negatively charged drops were recorded. The intense negative field which was attained during the interval *BC*, was clearly due to the removal of large quantities of positive charge by rain. This was followed by a decrease in the intensity of rain and the drops brought down an excess of negative charge. During the interval *CD*, 16 positively charged drops and 30 negatively charged drops were photographed. The removal of the excess negative charge, accompanied probably with a regeneration of positive charge, made the field to become gradually positive.

5. DISCUSSION OF THE CHARGE ON NON-THUNDER-STORM RAIN-DROPS.

The electrical records of non-thunder-storm rain may be divided into three distinct classes, namely,

(*a*) Those associated with intense negative gradient,
(*b*) Those associated with comparatively feeble negative gradient,
(*c*) Those associated with an increase in the positive gradient, large or small.

Examples of all these types are met with during the South-West monsoon. Production of negative gradient is, however, more common during a shower than the production of an increase in the positive gradient. We will now proceed to discuss the essential features of the various types.

(*a*) *Non-thunder-storm rain associated with intense negative gradient.*

A typical example of this is furnished by the record obtained during the passage of a nimbus cloud on the 23rd June, 1932 (fig. 5). The sky was overcast and rainfall of about 5 mm. was recorded. As soon as the shower commenced the field decreased in intensity, became negative and reached a negative value of about 850 V./M. The records show that during this period the rain was on the whole positively charged; of the drops whose charges were recorded during the period, 20 were positively charged and 14 negatively charged. Increase in the negative gradient was clearly due to the removal of positive charge in excess of negative, thus making the cloud to have a growing increase of negative charge. Ultimately the excess of negative charge was so great, that the process was reversed and more drops with negative than positive charge fell and consequently the rain was on the whole negatively charged. The removal of the excess negative charge gradually led to a reversion of the field towards positive. It is remarkable how the fluctuation of the field responds to removal by rain of excess positive or excess negative charge. During the period marked *PQ* in the potential gradient record, a fairly large number of drops with positive charge fell, and the intensity of the field tended twice to increase towards negative. Similar remarks apply to the portion *LM* of the potential gradient record.

Another example of comparatively large negative gradient attained during shower is furnished by the records obtained on the 2nd September, 1932, (fig. 6). The fluctuation of the gradient is more complex in this record than in the previous one. This nimbus cloud appears to be a remarkable one, because the 2-minutes charge record shows that throughout the passage of the cloud, the rain was positively charged. This is confirmed by the drop records. During the period 66 drops were recorded with positive charge and 26 with negative charge. The fluctuation in the field in this, as in the previous case is easily seen to be dependent, to a large extent, on the rate at which positive or negative charge was being removed by the rain, the increase towards positive associated with the peak *P* in the potential gradient record followed the removal of a certain quantity of negative charge and so also in the case of the peak *Q*. The maximum negative gradient

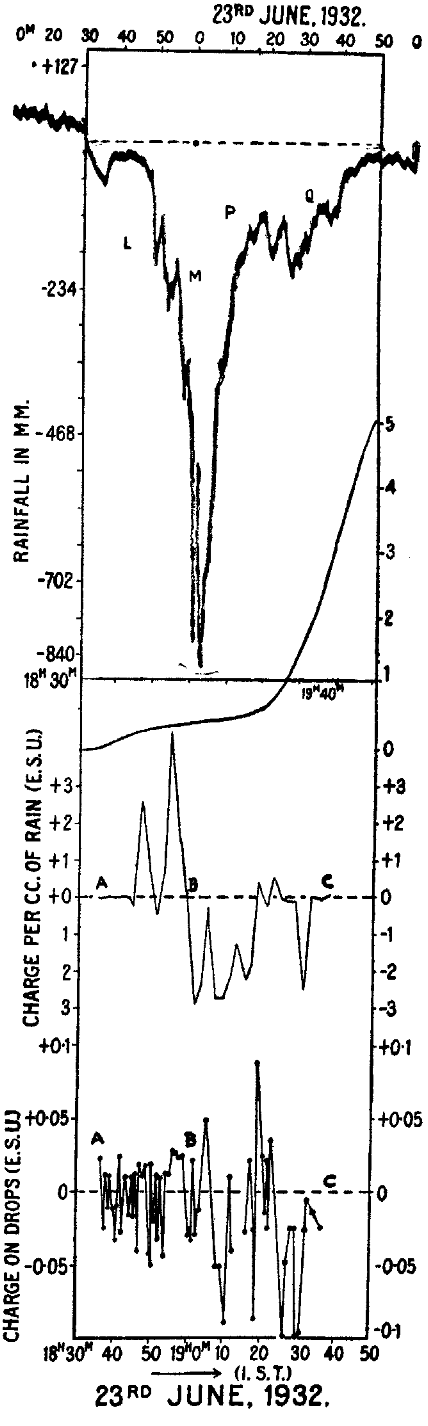
23RD JUNE, 1932.
0M 20 30 40 50 0 10 20 30 40 50 0
+127
-234
-468
-702
-840
RAINFALL IN M.M.
L
M
P
Q
18H 30M
19H40M
5
4
3
2
1
0
CHARGE PER CC. OF RAIN (E.S.U.)
+3
+2
+1
+0
1
2
3
A
B
C
+3
+2
+1
0
-1
-2
-3
+0·1
+0·05
0
-0·05
-0·1
CHARGE ON DROPS (E.S.U.)
A
B
C
18H30M 40 50 19H0M 10 20 30 40 50
(I. S. T.)
23RD JUNE, 1932.

FIG. 5.

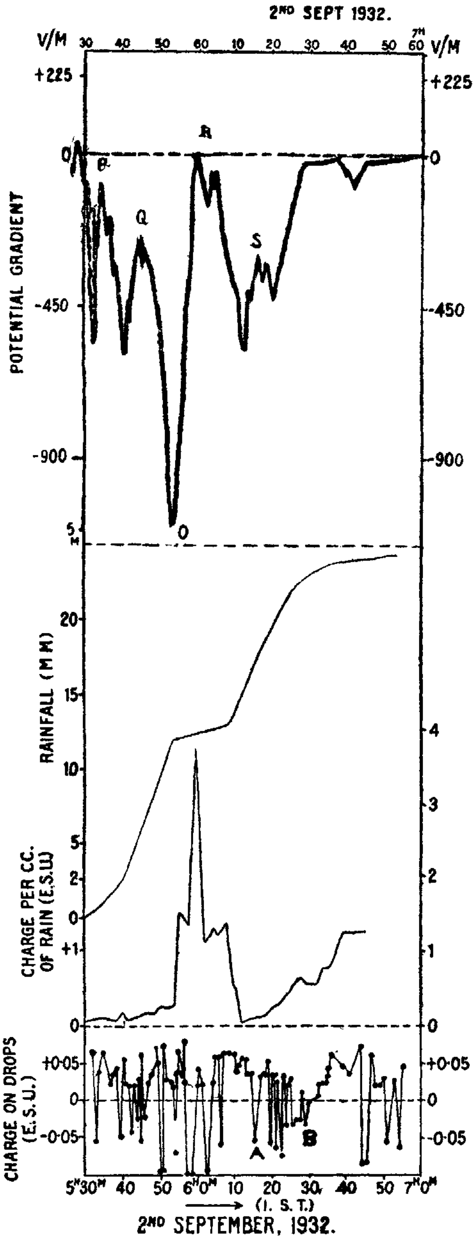

Fig. 6.

indicated by the peak *O*, was reached, when the intensity of rain decreased, and consequently positive charge was not being removed as rapidly as before. The decrease in rain was apparently associated with a regeneration of positive charge in the cloud, and consequently the gradient tended to revert to positive, but soon afterwards the intensity of rain increased, a very rapid removal of positive charge commenced and consequently the field became negative again. The reversion towards positive, indicated by the peak *S*, is associated with an increase in the rate of removal of negative charge. We see indeed from the portion marked *AB* in the drop record, that during the period the negative charge was being removed at greater rate than before.

(b) Non-thunder-storm rain associated with feeble negative gradient.

The records obtained on the 10th July, 1932, (fig. 7) illustrate the case of weak positive gradient followed by a weak negative gradient attained during a shower.

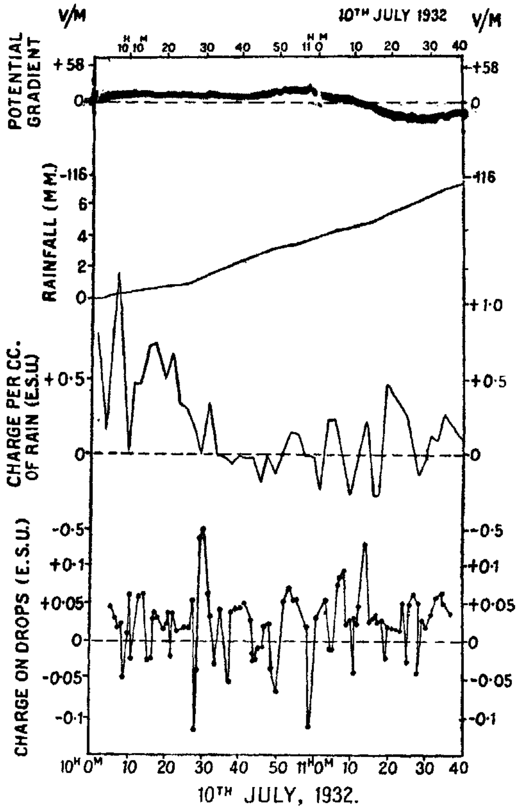

FIG. 7.

The intensity of the gradient near the ground surface seems to be dependent largely on the state of separation of positive and negative charges in the cloud. The intensity of separation of charges would appear to depend on the vertical air motion in the cloud, the greater the vertical motion, the greater is the separation. On the 23rd June, 1932, (fig. 5), the cloud was distinctly of cumulo-nimbus type and suggested considerable vertical motion and so also that on the 2nd Sept., 1932, (fig. 6). On the 10th July, 1932, (fig. 7), on the other hand, the sky was overcast with moving nimbus cloud, in which the horizontal motion was more conspicuous than the vertical motion. The low potential gradient under the cloud would thus appear to be due to very little separation of positive and negative charges in it.

The reduction of the positive gradient and its becoming negative towards the end is due to more positive charge being removed from the cloud than negative.

An illustration of a slightly different type of feeble negative gradient is furnished by the records obtained on the 15th July, 1932, (fig. 8). On this day also the sky was completely overcast with nimbus clouds and there was a strong horizontal wind. The drops reached the receiver in a very slanting direction. The positive and negative drops were more or less mixed up in the cloud and did not apparently become concentrated in the different parts of the cloud. Drops of both signs fell from the cloud. The reduction of the potential gradient to negative (marked *P* in the record) was due to a more rapid removal of the positive charge than negative at the time. The subsequent increase in the intensity of rain was associated with the removal of more negative drops than positive; the field, therefore, reverted to positive.

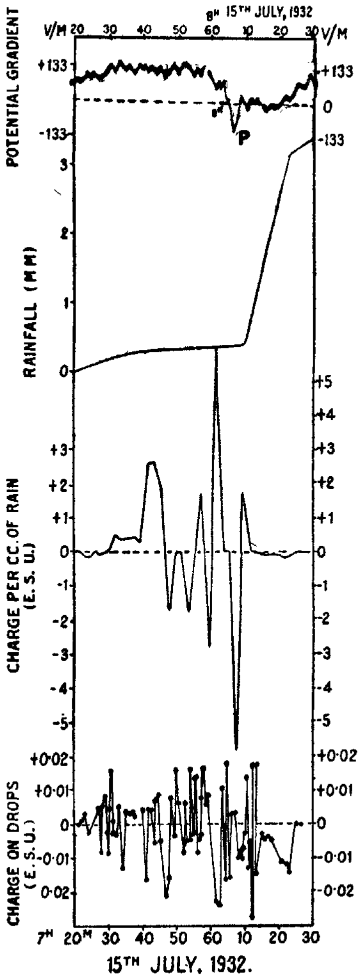

FIG. 8.

(c) *Non-thunder-storm rain associated with an increase in the positive gradient.*

An example of the increase in the positive potential gradient is furnished by the records obtained on the 22nd July, 1932, (fig. 9). The increase occurred during

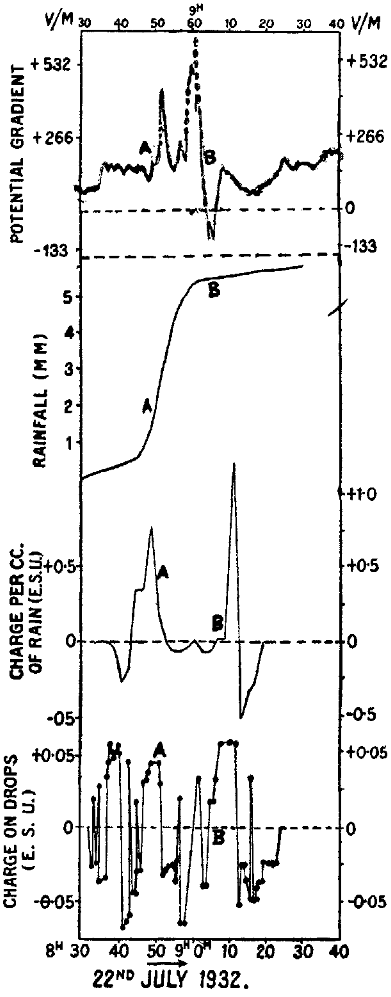

FIG. 9.

the period (marked *AB* on the records) when the intensity of rain was maximum. The charge record shows that this increase was due to a greater removal of negative charge from the cloud than positive. This was followed by a greater removal of positive charge; consequently the field became negative for a short while. The field reverted again to positive soon after, as rain began to remove more negative charge than positive.

The records obtained on the 30th and 31st July, 1932 (fig. 10), illustrate a case in which, except on one occasion (marked *A* on the record), the gradient never reached a negative value, and in general it showed a slightly higher value than the normal positive. This generally higher value appears to be due to the number of negative drops removed by rain being on the whole greater than the number of positive drops.

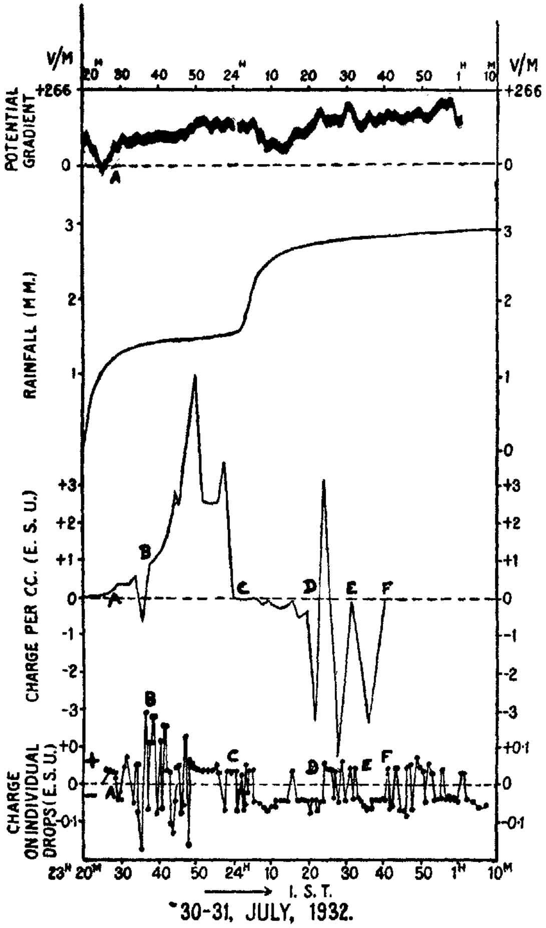

FIG. 10.

The drop record shows 72 negative drops against 62 positive drops. The comparatively low gradient throughout is obviously due to the charges not having separated much from each other; and the fluctuation in the field at any stage can be attributed to a greater or less removal of positive or negative drops. The negative peak, for instance, is seen to have been preceded by an excess removal of positive drops and followed by an excess removal of negative drops.

6. ANALYSIS OF CHARGE OF RAIN-DROPS.

We now proceed to make an analysis of the charge of rain-drops. The most important point to consider is whether the average charge per drop is consistent with the average charge per c.c. obtained with Simpson recorder. For the purpose of comparison we can take, as suggested by observations, the average radius of a rain-drop to be about 0·13 cm. and therefore about 100 drops to make 1 c.c. of rain. In making the comparison we must consider only those portions of the

TABLE V.

Charge on single drops.

Date.	Period.	Positive.				Negative.			
	H. M. H. M.	Actual charge per drop by drop-recorder. (e.s.u.)	Charge per drop by Simpson receiver. (e.s.u.)	Ratio.	Amount of rainfall collected by the receiver in the interval. (c.c.)	Actual charge per drop by drop-recorder. (e.s.u.)	Actual charge per drop by Simpson recorder. (e.s.u.)	Ratio.	Amount of rainfall collected by the receiver in the interval. (c.c.)
23rd June, 1932	18 50 to 19 00	0·023	0·021	1·1	2·5	..	..	..	..
23rd June, 1932	19 00 to 19 10	..	..	..	..	0·031	0·023	1·3	1·4
31st July, 1932	00 32 to 00 42	..	..	..	..	0·043	0·030	1·4	0·25
30th July, 1932	23 48 to 23 58	0·038	0·036	1·06	0·45	..	..	..	..
31st July, 1932	00 16 to 00 24	..	..	..	..	0·041	0·030	1·4	0·25
22nd July, 1932	08 44 to 08 52	0·039	0·039	1·00	2·90	..	..	..	..
29th Aug., 1932	18 50 to 19 00	..	..	..	..	0·050	0·032	1·6	2·03
29th Aug., 1932	18 22 to 18 26	0·030	0·024	1·3	0·66	..	..	..	..
			Mean	1·11			Mean	1·4	

TABLE VI.

Date.	Simpson recorder showing predominantly positive charge.			Date.	Simpson recorder showing predominantly negative charge.		
	Period. H. M. H. M.	No. of positive drops.	No. of negative drops.		Period. H. M. H. M.	No. of positive drops.	No. of negative drops.
10th July, 1932 ..	10 06 to 10 30	21	10	5th July, 1932 ..	22 18 to 22 30	6	25
10th July, 1932 ..	12 22 to 12 32	8	4	15th July, 1932 ..	08 00 to 08 24	7	20
15th July, 1932 ..	07 32 to 07 46	10	5	23rd June, 1932 ..	19 00 to 19 12	3	10
30th July, 1932 ..	23 26 to 23 46	18	12	25th July, 1932 ..	09 16 to 09 26	4	9
29th Aug., 1932 ..	18 20 to 18 38	14	6	25th July, 1932 ..	09 34 to 09 46	5	8
2nd Sept., 1932 ..	05 30 to 05 50	15	6	31st July, 1932 ..	00 08 to 00 20	1	12
2nd Sept., 1932 ..	05 50 to 06 10	14	7	29th Aug., 1932 ..	17 44 to 18 04	8	17
2nd Sept., 1932 ..	06 10 to 06 30	16	10	29th Aug., 1932 ..	18 42 to 19 04	5	26
2nd Sept., 1932 ..	06 30 to 06 44	9	3	4th Sept., 1932 ..	23 00 to 23 24	11	23
4th Sept., 1932 ..	21 22 to 21 38	14	8				

TABLE VII.

Non-thunder-storm Rain.

Relationship between the volume of a drop and its charge.

Date.	Period. H. M. to H. M.	No. of drops. Positive.	No. of drops. Negative.	Average volume per drop. (c.c.)	Average charge per positive drop. (e.s.u.)	Average charge per negative drop. (e.s.u.)
31st July, 1932 ..	08 05 to 08 10	2	4	$3{\cdot}5\times10^{-2}$	0·067	0·098
25th July, 1932 ..	14 50 to 14 55	2	3	$3{\cdot}0\times10^{-2}$	0·033	0·042
15th July, 1932 ..	08 50 to 09 00	6	6	$2{\cdot}9\times10^{-2}$	0·037	0·026
25th July, 1932 ..	16 20 to 16 32	7	2	$2{\cdot}6\times10^{-2}$	0·032	0·036
15th July, 1932 ..	07 51 to 08 02	7	10	$2{\cdot}5\times10^{-2}$	0·042	0·048
25th July, 1932 ..	18 10 to 18 20	8	2	$2{\cdot}5\times10^{-2}$	0·130	0·001
25th July, 1932 ..	14 40 to 14 50	7	5	$2{\cdot}2\times10^{-2}$	0·031	0·031
25th July, 1932 ..	16 44 to 16 50	4	1	$2{\cdot}1\times10^{-2}$	0·036	0·031
15th July, 1932 ..	08 45 to 08 48	3	5	$2{\cdot}1\times10^{-2}$	0·054	0·066
31st July, 1932 ..	08 10 to 08 20	6	11	$2{\cdot}0\times10^{-2}$	0·169	0·105
15th July, 1932 ..	08 02 to 08 10	4	8	$1{\cdot}9\times10^{-2}$	0·093	0·153
15th July, 1932 ..	08 10 to 08 20	3	9	$1{\cdot}9\times10^{-2}$	0·162	0·094
15th July, 1932 ..	07 40 to 07 50	6	6	$1{\cdot}7\times10^{-2}$	0·078	0·129
31st July, 1932 ..	08 40 to 08 50	4	9	$1{\cdot}6\times10^{-2}$	0·157	0·158
31st July, 1932 ..	08 50 to 08 53	4	1	$1{\cdot}4\times10^{-2}$	0·118	0·214
31st July, 1932 ..	08 33 to 08 40	8	2	$1{\cdot}3\times10^{-2}$	0·097	0·095

Simpson records which show predominantly positive or predominantly negative charge; correspondingly the drop records must show a preponderance of positively charged drops or negatively charged drops. For, as both positively and negatively charged drops are present in the rain, the calculated average charge per c.c. from Simpson records must always be less than the average charge per c.c., if the drops which made the 1 c.c. of rain were either all positively or all negatively charged. It is only when we consider the portions which show high positive or negative charge that we can expect to get the nearest approach to charge per drop as actually recorded. The results of comparison for a few typical cases are given in Table V.

Since only selected portions of records have been used in preparing the above table, the results can only be regarded as qualitative.

It will be seen from the table that the charge of drops of rain as deduced from the Simpson records is always less than the average charge of drops given by the drop-recorder.

The relative proportion of positive and negative drops during periods when the Simpson recorder shows predominantly positive or predominantly negative charge can be seen from the figures given in Table VI.

TABLE VIII.

Non-thunder-storm Rain.

Date.	Period.	Rain-fall in mm.	Ratio of positive to negative drops.	Average charge per drop (from drop-recorder).		Average charge per c.c. (from Simpson recorder).	
	H. M. H. M.			Positive. (e.s.u.)	Negative. (e.s.u.)	Positive. (e.s.u.)	Negative. (e.s.u.)
23rd June, 1932 ..	19 30 to 19 40	9·0	0 : 5	..	0·034	0·005	0·250
2nd Sept., 1932 ..	05 40 to 05 50	7·2	8 : 5	0·041	0·039	0·018	..
2nd Sept., 1932 ..	06 10 to 06 20	7·1	10 : 3	0·044	0·056	0·010	..
23rd June, 1932 ..	19 20 to 19 30	4·2	3 : 7	0·030	0·048	0·079	0·038
2nd Sept., 1932 ..	05 50 to 06 00	3·8	7 : 4	0·044	0·086	0·172	..
22nd July, 1932 ..	09 00 to 09 10	3·0	3 : 6	0·027	0·041	0·006	0·004
2nd Sept., 1932 ..	05 30 to 05 40	2·9	6 : 2	0·044	0·054	0·007	..
2nd Sept., 1932 ..	06 20 to 06 30	2·5	7 : 7	0·027	0·041	0·043	..
15th July, 1932 ..	08 10 to 08 20	2·3	3 : 9	0·162	0·096	0·180	0·008
22nd July, 1932 ..	09 10 to 09 20	1·4	5 : 5	0·048	0·032	0·044	0·041
10th July, 1932 ..	10 30 to 10 40	1·2	6 : 2	0·055	0·035	0·034	0·008
2nd Sept., 1932 ..	06 30 to 06 40	1·0	6 : 0	0·038	..	0·091	..
10th July, 1932 ..	10 40 to 10 50	1·0	5 : 1	0·050	0·058	..	0·011
10th July, 1932 ..	11 20 to 11 30	0·9	8 : 2	0·045	0·059	0·031	0·009
2nd Sept., 1932 ..	06 00 to 06 10	0·8	7 : 2	0·052	0·078	0·20	..
22nd July, 1932 ..	08 50 to 09 00	0·7	6 : 7	0·058	0·026	0·047	..
10th July, 1932 ..	11 10 to 11 20	0·6	8 : 1	0·030	0·047	0·036	0·029
10th July, 1932 ..	10 20 to 10 30	0·5	7 : 4	0·051	0·054	0·045	..
23rd June, 1932 ..	19 10 to 19 20	0·5	3 : 5	0·033	0·045	0·049	0·206
30th July, 1932 ..	23 40 to 23 50	0·4	10 : 8	0·131	0·077	0·361	..
10th July, 1932 ..	10 00 to 10 10	0·4	4 : 1	0·039	0·047	0·081	..
2nd Sept., 1932 ..	06 40 to 06 50	0·3	6 : 2	0·042	0·084	0·125	..
15th July, 1932 ..	07 20 to 07 30	0·3	4 : 3	0·052	0·055	..	0·017
15th July, 1932 ..	07 30 to 07 40	0·3	7 : 6	0·061	0·068	0·043	..
10th July, 1932 ..	10 10 to 10 20	0·3	9 : 5	0·044	0·030	0·060	..
23rd June, 1932 ..	19 00 to 19 10	0·3	2 : 10	0·039	0·037	..	0·269

TABLE IX.

Thunder-storm Rain.

Date.	Period.	Rain-fall in mm.	Ratio of positive to negative drops.	Average charge per drop (from drop-recorder).		Average charge per c.c. (from Simpson recorder).	
				Posi-tive. (e.s.u.)	Nega-tive. (e.s.u.)	Posi-tive. (e.s.u.)	Nega-tive. (e.s.u.)
5th July, 1932 ..	21 20 to 21 30	16·8	8 : 12	0·063	0·053	..	0·120
5th July, 1932 ..	21 30 to 21 40	15·8	0 : 9	..	0·037	0·116	0·053
4th Sept., 1932 ..	21 20 to 21 30	9·7	10 : 5	0·055	0·058	0·013	..
4th Sept., 1932 ..	21 30 to 21 40	8·6	7 : 6	0·046	0·057	0·012	..
4th Sept., 1932 ..	21 40 to 21 50	8·6	8 : 5	0·027	0·062	0·023	..
4th Sept., 1932 ..	21 10 to 21 20	8·6	13 : 3	0·035	0·044	0·028	..
5th July, 1932 ..	22 20 to 22 30	4·6	6 : 19	0·041	0·069	..	0·078
4th Sept., 1932 ..	22 00 to 22 10	3·3	4 : 5	0·067	0·115	0·061	0·029
4th Sept., 1932 ..	22 10 to 22 20	2·4	7 : 2	0·063	0·084	0·074	0·039
4th Sept., 1932 ..	22 20 to 22 30	2·2	11 : 3	0·047	0·056	0·013	..
5th July, 1932 ..	22 00 to 22 10	1·7	10 : 16	0·031	0·047	..	0·042
4th Sept., 1932 ..	22 30 to 22 40	1·5	9 : 5	0·053	0·042	0·013	..
5th July, 1932 ..	22 10 to 22 20	1·4	6 : 21	0·076	0·041	0·050	0·075
5th July, 1932 ..	22 30 to 22 40	1·4	6 : 20	0·044	0·073	..	0·054
4th Sept., 1932 ..	21 50 to 22 00	1·3	6 : 9	0·028	0·040	0·047	..
4th Sept., 1932 ..	23 10 to 23 20	1·1	5 : 7	0·064	0·091	..	0·082
4th Sept., 1932 ..	22 40 to 22 50	1·0	5 : 6	0·099	0·082	0·032	0·059
4th Sept., 1932 ..	22 50 to 23 00	1·0	5 : 7	0·041	0·086	..	0·049
4th Sept., 1932 ..	23 00 to 23 10	0·9	3 : 12	0·059	0·052	..	0·080
5th July, 1932 ..	18 10 to 18 20	0·9	7 : 11	0·133	0·141	0·017	0·018
29th Aug., 1932 ..	17 30 to 17 40	0·9	7 : 10	0·032	0·038	..	..
5th July, 1932 ..	18 20 to 18 30	0·6	9 : 15	0·107	0·155	0·016	0·011
29th Aug., 1932 ..	17 40 to 17 50	0·5	3 : 10	0·040	0·045	0·109	0·090
5th July, 1932 ..	16 40 to 16 50	0·4	7 : 4	0·039	0·029	0·201	..
29th Aug., 1932 ..	18 50 to 19 00	0·4	2 : 12	0·033	0·050	..	0·272
5th July, 1932 ..	16 50 to 17 00	0·3	5 : 7	0·032	0·025	0·005	0·143
29th Aug., 1932 ..	18 20 to 18 30	0·3	9 : 4	0·026	0·027	0·180	0·256
29th Aug., 1932 ..	19 00 to 19 10	0·2	6 : 12	0·035	0·061	..	0·188
5th July, 1932 ..	22 40 to 22 50	0·2	8 : 13	0·076	0·079	0·384	0·305
29th Aug., 1932 ..	18 00 to 18 10	0·2	9 : 7	0·022	0·026	0·275	0·155
29th Aug., 1932 ..	19 20 to 19 30	0·2	10 : 7	0·028	0·015	0·024	0·035
29th Aug., 1932 ..	18 10 to 18 20	0·2	6 : 2	0·036	0·033	0·531	0·104

It will be seen from Table VI that when the rain has a predominantly positive charge, the number of positive drops is in considerable excess of the number of negative drops, being two or three times the latter, and when the rain has a predominantly negative charge, the disparity in some cases is still greater. It is important to note that scarcely the rain consists of drops which are all positively charged or all negatively charged.

The question whether the charge of a drop varies according to its size is rather difficult to settle.

Since the state of electrification of different clouds are different, the conditions under which the drops get electrified in different clouds are also different. Therefore, the charges of drops from one cloud are not strictly comparable with charges of drops from another cloud. Nonetheless, if the data be arranged in the order of sizes of the drops, we may be able to say whether in general the smaller sizes carry more or less charges than bigger sizes. Table VII gives a statistical analysis of the data.

In preparing Table VII certain periods have been taken in each of which the sizes of drops were more or less the same. The reason for doing this is that in practice it has been found very difficult to identify an individual drop whose size was noted by eye on the manometer with the corresponding displacement on the charge record, owing to the errors involved in noting down the time of successive drops, which was taken to the nearest half a minute. Moreover, when the drops were of very small size, the displacement on the manometer produced by an individual drop was very small, and consequently, on such occasions, the displacement produced by three or four successive drops was measured and the mean size of a drop determined.

It will be seen from Table VII that generally speaking the smaller drops have larger charge.

In order to find out whether the charge of a drop varies with the intensity of the rain, we have given in Table VIII the amount of rainfall recorded in intervals of 10 minutes and also the average charge per drop, positive and negative, during each of these intervals for non-thunder-storm rain. It will be seen that the charge per drop does not undergo any marked increase or decrease with decrease in the intensity of rain.

It is found that even though rainfall remains the same during consecutive intervals of 10 minutes the average charge per drop, positive or negative, undergoes wide variation. We see from the last two columns obtained from Simpson records, that as the rainfall becomes lighter and lighter there is a general tendency of charge per c.c. of rain to increase. We must, however, remember that as rain becomes lighter, the drops generally become smaller in size. Consequently in the same c.c. of rain, there will be more drops when the rain is light than when it is heavy. The general increase of charge per c.c. of rain as shown by the Simpson record would thus appear to be in no way inconsistent with the charge indicated by individual drops. Although the charge per drop shows generally no marked increase with decrease in the intensity of rain yet because the drops become smaller and smaller in size when the rain becomes lighter and lighter there is an intrinsic increase of charge when compared with some standard size of drops.

Similar features are shown by Table IX in respect of thunderstorm rain.

7. THEORY OF CHARGE ON RAIN-DROPS.

Simpson's 'breaking-drop' theory of the origin of electricity of rain is based on his experimental result showing that—

(1) breaking of drops of water is accompanied by the production of both positive and negative ions,

(2) three times as many negative ions as positive ions are released, thus leaving the drops charged positively.

TABLE X.

Date.	Period.	No. of drops.		Average volume per drop.	Average radius in mm.	Average charge per positive drop in e.s.u.	Average charge per negative drop in e.s.u.	Maximum charge by Rayleigh's formula in e.s.u.	Ratio positive.	Ratio negative.
	H. M. H. M.	Positive.	Negative.							
31st July, 1932 ..	08 06 to 08 10	2	4	$3{\cdot}5\times10^{-2}$	2·01	0·067	0·098	5·24	0·013	0·018
25th July, 1932 ..	14 50 to 14 55	2	3	$3{\cdot}0\times10^{-2}$	1·91	0·033	0·042	4·90	0·007	0·008
15th July, 1932 ..	08 50 to 09 00	6	6	$2{\cdot}9\times10^{-2}$	1·90	0·037	0·026	4·87	0·008	0·005
25th July, 1932 ..	16 20 to 16 32	7	2	$2{\cdot}6\times10^{-2}$	1·81	0·032	0·036	4·53	0·007	0·007
15th July, 1932 ..	07 51 to 08 02	7	10	$2{\cdot}5\times10^{-2}$	1·80	0·042	0·048	4·49	0·010	0·011
25th July, 1932 ..	18 10 to 18 20	8	2	$2{\cdot}5\times10^{-2}$	1·80	0·130	0·091	4·49	0·029	0·020
25th July, 1932 ..	14 40 to 14 50	7	5	$2{\cdot}2\times10^{-2}$	1·71	0·031	0·031	4·13	0·008	0·008
25th July, 1932 ..	16 44 to 16 50	4	1	$2{\cdot}1\times10^{-2}$	1·70	0·036	0·031	4·13	0·009	0·008
15th July, 1932 ..	08 45 to 08 48	3	5	$2{\cdot}1\times10^{-2}$	1·70	0·054	0·066	4·13	0·013	0·016
31st July, 1932 ..	08 10 to 08 20	6	11	$2{\cdot}0\times10^{-2}$	1·68	0·169	0·105	4·05	0·027	0·026
15th July, 1932 ..	08 02 to 08 10	4	8	$1{\cdot}9\times10^{-2}$	1·65	0·093	0·153	3·95	0·023	0·039
15th July, 1932 ..	08 10 to 08 20	3	9	$1{\cdot}9\times10^{-2}$	1·65	0·162	0·094	3·95	0·041	0·024
15th July, 1932 ..	07 40 to 07 50	6	6	$1{\cdot}7\times10^{-2}$	1·59	0·078	0·129	3·73	0·021	0·035
31st July, 1932 ..	08 40 to 08 50	4	9	$1{\cdot}6\times10^{-2}$	1·55	0·157	0·158	3·59	0·044	0·044

From the stage of cloud particles (of average diameter 7×10^{-4} cm.) to the stage of rain-drops (of average diameter 7×10^{-2} cm.), there is an increase of 10^6 times (or a million fold increase) in the volume of each particle. It is now generally agreed that only a small part of this increase can be due to condensation and the rest must be due to coalescence of particles.

While these experiments explain generation of charge on rain drops in those cases where this process of breaking is operative, we get no explanation as to why a drop which has been formed by coalescence of a large number of cloud particles, without breaking during coagulation, should be electrically charged. Simpson's breaking-drop theory, therefore, gives no insight into the general process of acquirement of charge by cloud particles.

Since in the initial stage, just when condensation has occurred in the cloud level, the particles of cloud suspended in the air may be regarded as colloids, the best method of approaching the problem is obviously to use the very large amount of knowledge that has been obtained in recent years in regard to the charge of colloidal particles.

Before we proceed to discuss this matter, it is important to remark that Lord Rayleigh (1882) has shown 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. It is seen from this formula that the maximum charge possible on a drop of radius 0·1 cm. is 1·8 e.s.u. and on drop of radius $\frac{1}{3}$ cm. 9·6 e.s.u.

It will be seen from Table X that the ratio of the actual charge to the maximum possible charge varies from $\frac{1}{100}$ to $\frac{1}{25}$. We also see that the ratio shows a general increase with decrease in the size of the drops. When we analyse the charges in the rain-drops as determined by the experiments described in this thesis and compare them with those on oil drops as found by Millikan in his classical experiments, we get indirect evidence that the origin of charge on rain-drops is more fundamental than is postulated by Simpson's theory.

The average radius of Millikan drop is 2×10^{-4} cm. Millikan found that the number of ions in a drop varies from 1 to 130, the common value being about 10. Assuming that a rain-drop of radius 10^{-1} cm. has grown by coagulation of Millikan drops, its charge will be

$$0{\cdot}06\ N \text{ e.s.u.}$$

where N represents the number of ions in a Millikan drop. Taking N to be 10, we find the charge to be equal to 0·6 e.s.u. Actually, however, the charge on a drop is $\frac{1}{10}$ of this amount or less. The charge could have been 0·6 e.s.u. if all the drops that coalesced carried charges of the same sign. But since they would not necessarily be of the same sign, the charge should be expected to be less than 0·6 e.s.u.

We proceed now to find whether on the assumption that the cloud particles are all initially colloidal particles, the observed charge on the rain-drops will be accounted for. That the growth of rain-drops can occur by coalescence of minute particles of water, all electrically charged, is confirmed by Lord Rayleigh's experiments (1878-79).

Now, the experiments on the cataphoresis phenomena show that the majority of the colloidal particles are negatively charged when they are suspended in water. This is in agreement with the rule that when two substances are electrified by friction the substance with the higher dielectric constant takes on a positive charge (Lewis, *A System of Physical Chemistry*, Vol. I, p. 334, 1924). The same law would indicate that the majority of water particles suspended in air should be positively charged in the same way as air bubbles in water should be negatively charged and this is what has actually been found by Alty (1924, 1926).

The charge E on a colloidal water particle suspended in air will be given by the well-known formula

$$E = V \frac{R^2}{D} K$$

where V is the potential difference between the water particle and the air in contact with it, K is the dielectric constant of air, D the thickness of the Helmholtz electrical double-layer, which is supposed to be small compared with R the radius of the particle.

Taking

$$V = \frac{0{\cdot}031}{300} \text{ e.s.u.}$$

$$R = 0{\cdot}001 \text{ cm.}$$

$$D = 5 \times 10^{-8} \text{ cm.}$$

$$K = 1 \text{ for air}$$

$$E = \frac{0{\cdot}031}{300} \times \frac{(10)^{-6}}{5 \times 10^{-8}}$$

$$= 2 \times 10^{-3} \text{ e.s.u.}$$

In connection with cataphoresis it is necessary to realise that the movement of the colloidal particle in an electric field is only made possible by the fact that there is a certain slip or 'give between the two coatings of the double electrical layer'. If the charges were fixed the particles as a whole would have no effective charge and would therefore remain motionless in the electric field. The final stage in cataphoresis must be, therefore, a polarisation of the colloid-medium system, followed by a transfer of charge on the layer made up of the molecules of the medium, to other contiguous molecules.

Another point of view is that the charge is due to the unequal adsorption of the ions of electrolytes by colloidal particles. Those ions which are adsorped in larger quantity owing to their higher adsorption potential, form the charging ions (aufladende ionen according to Pauli), their partners remaining in larger amount in the intermicellar liquid as compensative ions (Gegenionen of Pauli). The excess of one kind of ions on the surface determines the sign of the charge and its density.

In the early stage after condensation has taken place on nuclei and a cloud has formed, the growth of drops may be expected to take place under the laws which govern the coagulation of colloidal particles. It is known that on addition of a very small quantity of electrolytes (ions) to suspensions, emulsions or colloids the corresponding substances are thrown out of solution. The operation seems to be of a physical nature. Hardy-Schulze's law makes the important generalisation that ions carrying a sign opposite to that carried by the colloid are the most active precipitants, and at the same time the higher the valency of the ions (i.e. the greater the number of unit charges upon it) the greater is its precipitating action. In the atmosphere, gaseous ions are present in such large numbers that it is not difficult to imagine their precipitating action on colloidal cloud particles.

Experiments with a Wilson Condensation Chamber under ordinary temperature (15° C. to 30° C.) and expansion ratios 1·05 to 1·3 shows that as soon as the cloud has formed, the particles have diameters varying from 4 μ to 10 μ. The colloidal water particles suspended in air is therefore of slightly larger diameter than the colloidal particles suspended in water. On the other hand, coronae measurements indicate that in cloud suspended in air, the particles have diameters varying from 2 μ to 12 μ, while the diameters of fog droplets is on the average 5 μ.

This process of coagulation by oppositely charged ions will undoubtedly be accompanied by a reduction in charge of the drop that would be obtained by simple addition law. A rain-drop of a radius 0·1 cm. which has grown by coagulation of particles of radius 0·001 cm. will contain 10^6 such particles.

Since each particle has a charge of 2×10^{-3} e.s.u. the total charge on the rain-drop, if all the particles which formed it had charges of the same sign, will be 2×10^3 e.s.u. Actually, however, we find that the charge on a rain-drop is considerably smaller than this amount. The decrease during coagulation is obviously due to loss of charge in various ways, one of which is the coagulation of oppositely charged drops and the other is the loss of charge due to encounter with oppositely charged ions.

It has been pointed out by Robonitch and Kergin (1935) that adsorption of ions of opposite sign to the colloidal particle is one of the main factors in diminishing the stability of the colloid and causing its coagulation. When ions of higher valency, of larger specific adsorption potential, than the initial compensating ions are adsorped, they enter the inner part of the outer component of the double-layer. This diminishes the number (density) of electric charges on the boundary between the liquid moving with the particle and the rest of the liquid and consequently the electro-kinetic or ζ-potential on this surface. The latter being more or less accurate quantitative measure of repulsive forces between particles, these forces decrease too, and the stability of the system breaks down.

With regard to the kinetics of the charging process, Panthenier and Moreau Hanot (1936), have shown that when the particle is so large that the effects due to diffusion of the ions towards the particle, and to mirror forces, can be neglected, the kinetics of the charging of a spherical dielectric particle can be expressed by the following equation (assuming that each ion striking the surface of the part gives up its charge):

$$Q = \left(1+2\frac{K-1}{K+2}\right) Ea^2 \left(\frac{\pi u n \epsilon t}{1+\pi u n \epsilon t}\right),$$

where Q is the charge acquired by the particle in the time t, a the radius, k the dielectric constant of the particle, E the strength of the external electric field, n the number of ions per c.c., u their mobility, and ϵ the electronic charge.

In the work of J. P. Gott, the ionic atmosphere was produced by means of X-rays, water drops of 4·4 mm. diameter were used, and the initial rate of charging was determined. The experiments of Fuchs, Petrjanoff and Rotzieg (1936) with oil drops gave results which are given in Fig. 11.

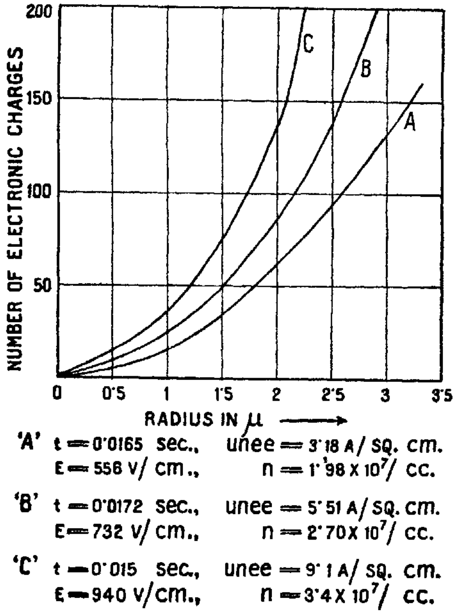

FIG. 11.

This shows that as the field strength increases there is a rapid increase in the rate of charging.

8. CONCLUSION.

The general agreement of charge on a rain-drop obtained by the above-mentioned consideration with that actually observed would suggest that the process is operative in the atmosphere on a large scale. Besides the growth of charge by coagulation of colloidal particles, the capture of ions by formed water drops in a pre-existing electrical field in the way described by Gott will lead to a general increase of charge up to a certain limit and whenever the vertical motion is of such an order as to break the drops, the charge will be further augmented by the Simpson process.

A method of coagulation due to the relative rates of fall of cloud particles of different sizes, which has been worked out by Findeisen, Langmuir and others, must be in operation on a large scale in a developing cloud. Findeisen's analysis (1937, 1938, 1939) shows that drops of size 2×10^{-2} cm. would fall from a cloud of about 200 m. thick, 8×10^{-2} cm. from a cloud 1,000 m. thick and 14×10^{-2} cm. from a cloud 2,000 m. thick. Langmuir (1948) has worked out how accretion takes place by collision, taking due account of aerodynamic flow. Since coagulation is the main process by which cloud particles grow into rain-drops, it is no wonder that in a raining cloud, there is a mixture of both positively and negatively charged drops.

9. SUMMARY.

During the years 1930–32, an apparatus was maintained in continuous action in the Colaba Observatory, Bombay, for recording the electric charge on individual drops of rain. A drop of rain in order to have access into the insulated receiver has first to pass through a fixed but adjustable cylindrical opening of average diameter 1·4 cm. and then through a second opening of diameter 2·4 cm. at the periphery of a rotating disc. Both openings are provided with trap arrangements so that a drop striking the sides is caught and led away. The period of rotation of the disc is so adjusted that with moderate intensity of rain a second drop may not enter into the receiver until the charge of the first has been recorded and the system earthed by an automatic device. A glass manometer of very fine bore is attached to the receiver and keeps a record of the size and number of drops.

For recording the charge given to the receiver by a drop of rain, a Wilson tilt electroscope is used very nearly at its maximum sensitiveness, and the movement of the gold-leaf is photographed by allowing light from a point source to pass through a minute slit and a short focus lens and fall transversely as a narrow beam of about half the breadth of the leaf over a fine pin-hole made at its lower end, which is twisted at right angles to its plane. The transmitted light through the hole gives a magnified image of its displacement on a quickly moving photographic paper. All necessary precautions were taken to avoid the influence of the field of the earth and any artificial field on the drops.

This method of recording is of particular interest in view of the fact that the Wilson tilt electroscope has not to our knowledge been used in the past as a recording instrument. Simultaneously with the above apparatus, a Simpson apparatus giving the charge of rain collected every two minutes was kept in action. In 1934, observations were repeated at Poona with an independent arrangement in which a Lindeman electrometer was used. Potential gradient was also continuously recorded using a ionium collector.

An analysis of the records shows that both positively and negatively charged drops are present in the rain received from any part of the cloud. When the rain received during any interval is positively or negatively charged as a whole, there is an excess of positively or negatively charged drops. The mean charge of positive drops is 0·021 e.s.u. in non-thunder-storm rain and 0·051 in thunder-storm rain, the mean charge of negative drops is 0·023 e.s.u. in non-thunder-storm rain and 0·057 e.s.u. in thunder-storm rain.

A detailed analysis of the observations lend support to the view that initially the cloud particles develop charge in exactly the same way as colloidal particles or particles floating in a medium and capturing ions. The breaking of drops by the Simpson process or the striking of one particle against another tends to augment the charge after they have grown to a certain size.

When the cloud extends to heights considerably above the freezing level so that the cloud particles get frozen into ice-particles, the striking of the ice-particles against each other will make them negatively charged.

The experiments were continued at Poona in 1935 and 1936, in which a Lindeman electrometer was used instead of the Wilson tilt electroscope. As each drop entered the receiver, the charge recorded was read through the microscope.

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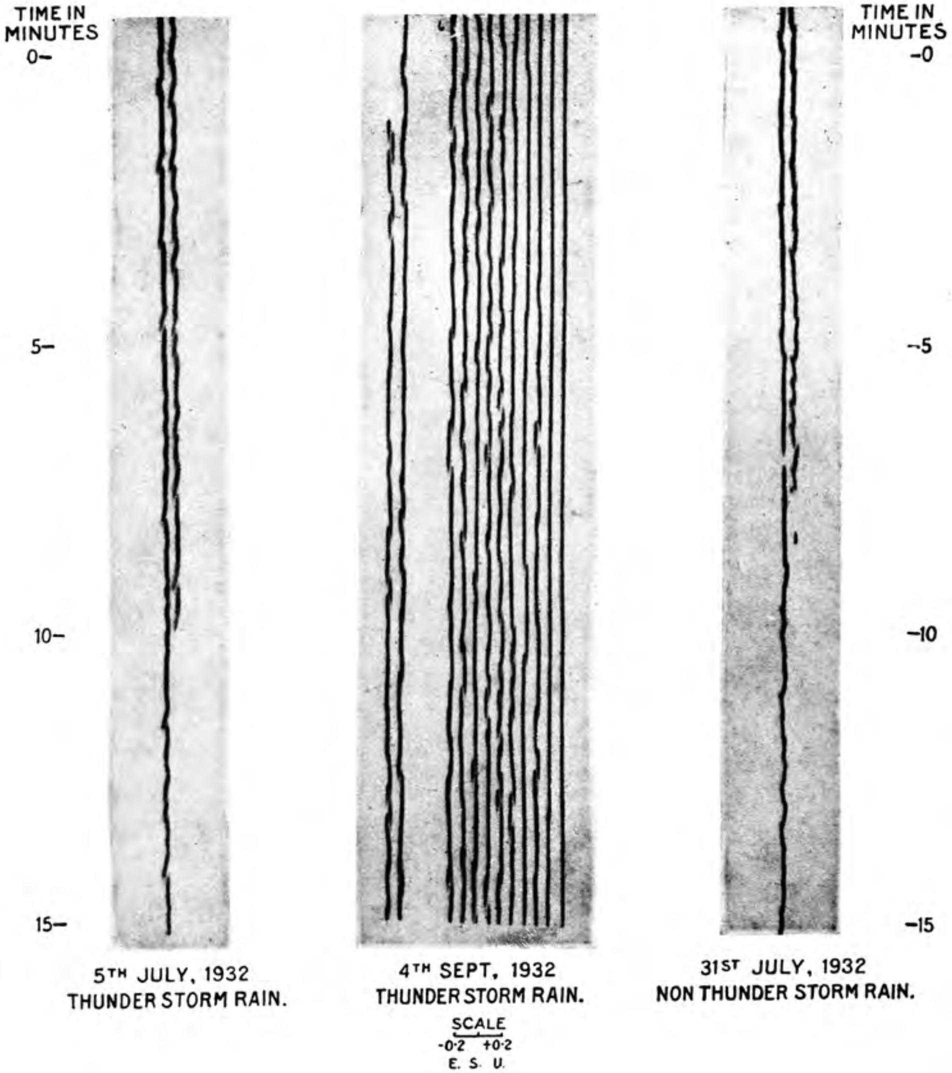

5TH JULY, 1932
THUNDER STORM RAIN.

4TH SEPT, 1932
THUNDER STORM RAIN.

31ST JULY, 1932
NON THUNDER STORM RAIN.

Portion of a record of the charges of Thunder-storm rain-drops.