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On the Electricity of Rain and Its Origin in Thunderstorms

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XV. *On the Electricity of Rain and its Origin in Thunderstorms.*

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Since Franklin first showed that thunder and lightning are caused by electrical discharges, there have been numerous theories to account for the production of electricity in thunderstorms, but none has been generally accepted by meteorologists. When attacking the problems of thunderstorm electricity, two methods naturally present themselves: we may either investigate the actual phenomena in the atmosphere, or try to repeat on a small scale in the laboratory the processes which may be supposed to take place during thunderstorms. During 1907–8 an investigation was undertaken on both these lines at the Meteorological Office of the Government of India in Simla. A systematic record was obtained by automatic instruments of the electricity brought down by the rain during practically the whole of one rainy season, and laboratory experiments were made to find the origin of the electricity of thunderstorms. The work has resulted in the formation of a new theory, which appears to account in a satisfactory manner for the electrical effects observed during thunderstorms.

The following paper is divided into three parts:—Part I deals with the measurements of the electricity of the rain, Part II with the laboratory experiments, and Part III contains the new theory based on the results detailed in the previous parts.

Part I.—*Measurements of the Electricity of the Rain.*

The electricity brought down by rain had previously been measured by Elster and Geitel* in Wolfenbüttel, by Gerdien† in Göttingen, and Weiss‡ in Vienna. The apparatus used in Simla differed from the form used by each of these in several particulars, chiefly in that it was entirely self-registering and was kept constantly in action during the whole of the rainy season, whether precipitation was expected or not.

The final form of the Simla apparatus is diagrammatically shown in fig. 1. A corrugated iron hut, 8 feet square, was erected on a suitable site in the grounds

* Elster and Geitel, 'Wien. Ber.,' vol. 99, Abth. II. a, p. 421, 1890; 'Terr. Magn.,' vol. 4, p. 15, 1899.

† Gerdien, 'Phys. Zeit.,' vol. 4, p. 837, 1903.

‡ Weiss, 'Wien. Ber.,' vol. 115, Abth. II. a, p. 1285, 1906.

of the residence of the author. Through a hole in the centre of the roof the rain fell into an insulated receiver AA which was connected to a self-registering electrometer.

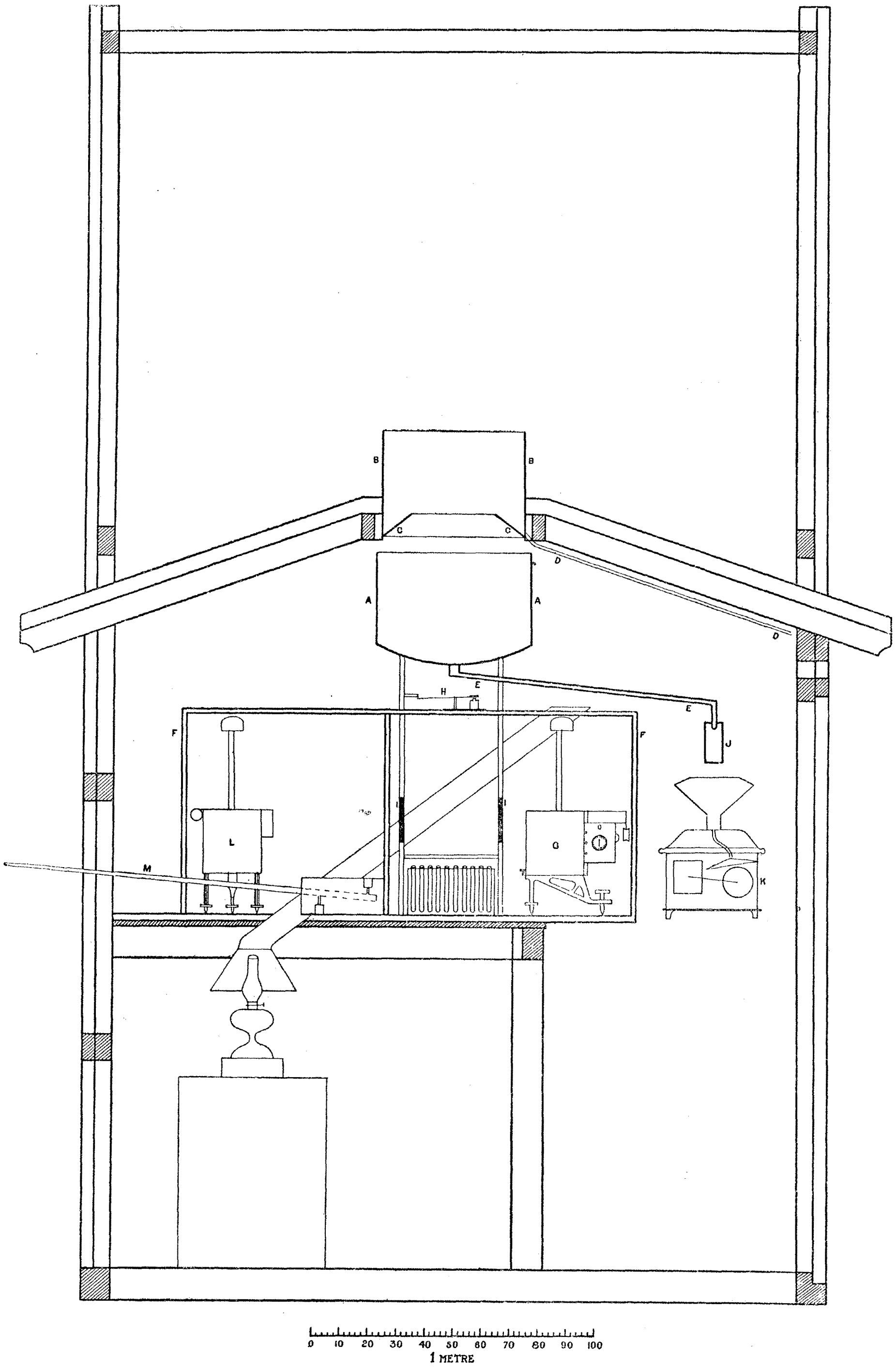

FIG. 1.

In order to prevent the rain which fell on to the roof near the hole from splashing into the receiver, a galvanised iron cylinder BB was fitted to the hole with its top

20 cm. above the level of the roof and its lower end just within the hut. To prevent the rain-water which struck the sides of this cylinder from running into the receiver, a conical rim CC was soldered inside the bottom of the cylinder and the water was drained away through the pipe D. This rim reduced the effective opening through which the rain fell to a diameter of 29 cm.

The receiver AA, which was placed immediately below the bottom of the cylinder, was a galvanised iron vessel 50·5 cm. in diameter and 31 cm. deep, having a slightly rounded bottom so that the water which fell into it ran off through the pipe EE. The receiver was supported on three legs, which passed freely through three holes in the top of the case FF, each being insulated on a sulphur-coated ebonite rod I fitting into a firm tripod fixed on to the bottom of the case.

The potential of the receiver was recorded automatically every two minutes by means of a Benndorf* self-registering electrometer G of the usual pattern, registering in the following way :—To the needle of a quadrant electrometer a long aluminium boom is attached and swings freely over a strip of paper 12 cm. wide, which is slowly moved forwards by means of a clock. Every two minutes the clock closes an electric circuit which actuates a magnet and causes a bar to press the end of the boom sharply into contact with the paper through a typewriter ink ribbon. In this way the paper receives a series of dots each representing the position of the boom, *i.e.* the deflection of the needle, at the instant the circuit was closed. In order to mark the time a second circuit is closed each hour, and a magnetic is thus excited which causes two dots to be imprinted, one on each side of the paper exactly in a line with the end of the boom; thus the line joining these dots is at right angles to the length of the paper, and would pass through a dot made at the same time by the boom. This device will be referred to later as the "hour marker." As shown in the figure, the Benndorf electrometer was placed within the case FF.

When the receiver was connected to the Benndorf electrometer and it received no charge, a series of dots was printed on the paper in a straight line, but when a charge was imparted to the receiver the needle of the electrometer was deflected and with it the boom, so that the dot made at the end of the next two minutes' interval indicated the amount of the deflection. If the instrument were then left to itself and received no further charge, the record would show a series of dots in a curved line inclined to the zero line. The inclination of this line was a measure of the rate of leak from the charged system.

For the purposes of measuring the charge brought down by the rain, an earthing device H was brought into use. This consisted of a light earth-connected wire which, by means of an electromagnet, could be brought into contact with the receiver and connect it to earth. This magnet was excited by the current which caused the registration of the electrometer, so that at the instant that the potential of the receiver was registered the latter was also connected to earth. In this way

* BENNDORF, 'Phys. Zeit.,' vol. 7, p. 98, 1906.

each dot on the paper indicated the charge which the receiver had obtained from the rain in two minutes. This earthing magnet could be disconnected when it was desired to test the insulation of the system by the method described above.

The amount of rainfall was recorded in the following way :—The end of the metal pipe EE which drained the water from the receiver ended within a vertical cylinder J. From the end of the pipe the water fell in large drops, and since the drops detached themselves from the pipe well within the cylinder they carried away no electricity. The drops then fell into the funnel of the rain-gauge K. This was of the ordinary tipping bucket pattern, recording on a drum which revolved in 24 hours. One slight alteration was however made. Instead of allowing the pen to be always touching the paper, it was only brought into contact with it for a moment at the end of each two minutes' interval, this being effected by means of an electromagnet actuated by the current, which excited every two minutes the magnets already referred to. As every dot on the rain-gauge trace corresponded with a dot on the electricity trace, it was possible to correlate the two records and find how much rain corresponded with each deflection of the electrometer. In order to make this correlation quite certain the electrical circuit which actuated the "hour marker" of the Benndorf electrometer was disconnected from the clock and arranged so that the circuit was automatically closed for an instant each time the bucket tipped. Thus every time the bucket tipped a dot was printed on each side of the electrometer trace, and if the rain was only light, so that the bucket tipped only once in about two minutes, the number of tips could be counted from the dots. If, however, the rainfall was rapid these dots were not separated but formed a line; the rainfall was then measured for each two minutes' interval from the rain-gauge trace.

This method of measuring the rainfall had one serious drawback. The rain was only registered when the bucket tipped, and as this only took place when 0·014 cm. of rain had fallen, the registration was not satisfactory with light rain. The registration was also not satisfactory at the beginning of a shower, for in this case the first tip did not take place until after considerably more than 0·014 cm. of rain had fallen, owing to a certain amount of water being used up in wetting the receiver and the pipe through which the water passed from receiver to gauge. Nevertheless, after the first tip and when the rain was not very light the method worked admirably and gave practically no trouble in use. In fig. 1, for the sake of clearness, the rain-gauge is shown out of place. In use it was behind the case FF, in which position the tube EE was much shorter than it has been necessary to show it in the diagram.

The corrugated walls of the hut were carried, as shown in the figure, to a height of about two metres above the roof of the hut. This was done in order to protect entirely the mouth of the receiving apparatus from the earth's electrical field, and to prevent the wind from sweeping across the mouth of the cylinder CC, which would have interfered with the entrance of the rain into the receiver.

During the course of the experiments two additions were made to the apparatus just described, which it had not been possible to get ready before the first few storms occurred.

A second Benndorf electrometer L was added to record the potential gradient. It is almost impossible to get a satisfactory method of recording the potential gradient during thunderstorms, because the changes in the gradient take place more rapidly than the instruments used can follow them, and the range over which the potential gradient varies is extreme. It was therefore considered sufficient to record only the predominant sign of the potential gradient during each two minutes' interval. This was done by putting an insulated bamboo rod MM, having an umbrella rib attached to its end, through a window into the open air, and connecting it to the second Benndorf electrometer.* It was also arranged that this simple collector should be connected to earth at the end of each two minutes. The same current which recorded on the first Benndorf electrometer was used for the second, and the records were thus simultaneously taken.

The second addition consisted of an arrangement to record the lightning discharges. A long wire was carried from the open air into the hut and connected to a coherer fitted with the usual decohering device. The current of the latter passed through the circuit of the "time marker" on the second Benndorf electrometer, so that each lightning discharge was recorded by dots on the edges of the paper which was receiving the record of the potential gradient. The coherer was purposely made somewhat insensitive in order not to record distant discharges, and on this account it often missed weak near discharges. The device, therefore, could not be said to count the number of discharges, but it gave a good idea as to whether the rainstorms were accompanied by many or few electrical discharges.

During the monsoon, for weeks together, the humidity of the air practically remained at 100 per cent., and thus everything, both indoors and outdoors, became very damp. Under such conditions, provision had to be made for keeping the insulation of the instruments in good condition. This was done by arranging that all insulators should be within the case FF, which was kept warm by continuously burning a lamp under the lower end of a pipe, 7 cm. in diameter, passing through the case in the manner shown in fig. 1. This precaution prevented all difficulty with the insulation of the instruments; but another difficulty connected with insulation could not be entirely avoided. This was caused by spiders spinning their webs from the insulated parts of the system to earth-connected objects. Since the collector of the potential gradient apparatus had to be exposed in the open air, it

* The rod carried a small tube containing radium at its end, but it is not believed that this materially assisted the equalisation of potential between the rod and the surrounding air, the ordinary "dissipation" at the end of the rod being sufficient for the purpose. The capacity of the rod being small, the quantity of electricity accumulated at the end of the rod did not—in the author's opinion—disturb sensibly the lines of force in the neighbourhood of the rod. [April 14, 1909.]

was very often subjected to this trouble, and many records of the potential gradient were lost in consequence. The only means which could be devised to diminish the difficulty was to take every opportunity of visiting the instruments and sweeping away the webs.

After the instruments had been set up, the question had to be decided how sensitive to make the electrometer. In view of the fact that the work was being undertaken mainly with a view to the investigation of thunderstorms, it seemed desirable that the sensitiveness should be so arranged that the deflection should never be greater in two minutes than would bring the boom of the electrometer to the edge of the paper on which the record was being made. This necessitated a somewhat low sensitiveness, and, as a consequence, the electricity of rain with very low charges could not be measured. There was the possibility of altering the sensitiveness of the instrument according to the kind of rain which was expected, but this was considered impracticable in view of the fact that the instrument could not be watched continually, but had to be left to itself to take the records entirely automatically. In reality, this difficulty was not serious. The conditions during thunderstorms are entirely different from those during gentle rain, and to investigate the two cases is really a matter of two distinct researches. The present research was concerned with highly charged rain, and so the fact that the instrument did not also record very small charges was not of any great consequence.

By good fortune, after the first one or two storms, a degree of sensitiveness was found which proved to be satisfactory during the rest of the rains. On only two or three occasions did the boom pass to the edge of the paper, and on each of these occasions the instrument was under observation, so that a rough estimate could be made as to what would have been the extent of the deflection from the time taken for the boom to reach the stop. This sensitiveness gave a deflection of 1 cm. for 40 volts, and, as a deflection of 0·2 mm. could be recognised with certainty, a potential of 1 volt could be measured. The capacity of the receiving system was determined to be 141 cm., and hence the smallest charge which could be measured with certainty was 0·47 electrostatic unit. The rain entered the receiver through an opening 29 cm. in diameter, so that when a charge of 7×10^{-4} electrostatic unit fell on each square centimetre of surface in two minutes it was sufficient to be recorded by the instrument.

In order to determine the charge brought down by each cubic centimetre of rain it was only necessary to divide the charge registered by the electrometer during any two minutes by the amount of rain recorded by the rain-gauge during the same interval of time. On account, however, of the limitation of the method of recording the rainfall already pointed out, it was not possible to find the value of the charge per cubic centimetre of rain from electrometer and rain-gauge records for every single two minutes' interval; but experience showed that it was exceptional not to be able to do so, and during the greater part of the rains this value was obtained.

The degree of accuracy to which this measurement could be made during heavy rain or highly charged light rain was 0·1 electrostatic unit per cubic centimetre of rain-water. A charge of 0·1 electrostatic unit of electricity on a cubic centimetre of rain was taken as the lowest charge with which the research was concerned. All charges less than this amount were written as *nil*.

Before discussing the results of the electrical measurements, it is desirable to give a short description of the character of the rain in Simla during the period when the measurements were made. The months of April and May are the hot months of the year. But although Simla is at an elevation of about 7000 feet above sea level, and the temperature does not therefore rise very high, yet the almost uninterrupted sunshine during these two months is very favourable to the formation of thunderstorms. In 1908, the first thunderstorm occurred on April 5, and afterwards storms of greater or less intensity occurred at intervals of seldom longer than a fortnight. The monsoon normally arrives in the Simla hills during the second half of June, and previous to its arrival the thunderstorms become more and more frequent, culminating in storms of some violence which accompany the actual arrival. In the year under review it was difficult to fix a definite day for the setting in of the monsoon, because of the gradual manner in which the changes occurred.

The greatest storm of the year occurred on July 1, and afterwards the thunderstorms became less frequent and the monsoon rainfall more steady and continuous. From this date the monsoon gave more or less heavy rain each day and continued until the beginning of September; as usual it ended with one or two sharp thunderstorms.

From the beginning of the thunderstorms in April to the end of the rains in September the part of the apparatus for measuring the rainfall and the electricity associated with it was in constant action, so that the electrical state of nearly every shower was recorded. The potential gradient and coherer records commenced on June 18 and the latter were entirely free from failure. The data used in the following discussion have been obtained from every storm during which any electricity was recorded, however light the rain, and also from those storms during which no electricity was measured, but rain fell at a greater rate than 0·007 cm. in each two minutes' interval. The latter limitation has been chosen because with a rainfall of this amount charged to 0·1 els. unit per cubic centimetre of rain the electrometer would have shown the smallest measurable deflection. Thus when the rainfall was heavier than this amount and no electricity was recorded it could be said with certainty that the rain was not charged to 0·1 els. unit per centimetre, while with lighter rainfall which showed no electricity the same conclusion could not be drawn; it was therefore considered best to neglect such lighter rainfall.

It has been found impracticable to divide the storms observed into thunderstorms and storms which were not thunderstorms. For three months rain fell nearly every day and it was quite impossible to take notes during the whole time that the rain was falling in view of the routine work of the department. Nor do the coherer records allow of such a division being made, for the coherer often recorded one or two discharges on days when no thunder was heard and little rain fell. Thus the difference between rain of this latter type which could not be called thunder rain and that associated with much thunder and lightning was simply a matter of degree and not of kind. For this reason the rainstorms have in the following analysis generally been treated irrespectively of whether the rain was accompanied by electrical discharges or not.

Want of space makes it impossible to give here the detailed results of the measurements. The figures are, however, to be published *in extenso* in part 8, vol. 20, of the 'India Meteorological Memoirs.'

Results.

The aggregate amount of rain which fell during the periods of rainfall investigated was 76·3 cm.

The electrometer trace registered charged rain during 1926 two minutes' intervals, during 1362 of which the electrometer recorded positive electricity, and during 564 negative electricity. The total quantity of positive electricity which fell on each square centimetre of surface was 22·3 electrostatic units and of negative electricity 7·6 units.

From this it is seen that 2·9 times as much positive as negative electricity fell during the rains and that the time during which positive rain fell was 2·4 times longer than that during which negative electricity fell. This result is of great importance in view of the generally accepted belief that much more negative than positive electricity is brought down by the rain, a belief on which several theories of atmospheric electricity have been based.

When charged rain is falling the effect is equivalent to a vertical current of electricity; with positively charged rain the current may be considered to be flowing from the atmosphere into the ground, and with negatively charged rain from the ground into the atmosphere. The values of the currents attained in this way are of considerable importance from the points of view of both atmospheric electricity and of terrestrial magnetism.

An analysis of the data for this purpose is given in Table I.

In this table, column 2 contains the number of times positive currents (*i.e.* currents caused by positively charged rain) were recorded with values between the limits shown in the first column, and similar data for negative currents are given in column 3.

Neglecting for a short time currents greater than 300×10^{-15} ampere we see that large currents are more seldom met with than smaller currents, this being true for both positive and negative currents. The most important fact, however, is that as the currents become larger the frequency with which positive currents occur tends

TABLE I.

Current in 10^{-15} amp. per sq. cm.	No. of two minutes' intervals during which the current was: Positive.	No. of two minutes' intervals during which the current was: Negative.	No. of positive intervals. / No. of negative intervals.
2– 50	1058	511	2·1
50–100	165	48	3·4
100–150	81	17	5·0
150–200	33	5	6·6
200–300	31	4	8·0
>300	15	18	—

to become much greater than the frequency with which negative currents occur. In other words, the greater the current the more likely is it to be carried by positively charged rain.

To these deductions the data for currents greater than 300×10^{-15} ampere appear to be exceptions. But as 15 of the 18 negative currents greater than 300×10^{-15} ampere were recorded in a single and very abnormal storm on May 13, the relation shown must be considered accidental. The values of the greatest currents are of particular interest and the following list is therefore given of all those having a greater value than 300×10^{-15} ampere.

TABLE II.

Positive currents: Amps. $\times 10^{-15}$.	Positive currents: Date.	Negative currents: Amps. $\times 10^{-15}$.	Negative currents: Date.
419	April 7	345	May 13
416	May 9	356	,, 13
830*	,, 9	400	,, 13
830*	,, 9	410	,, 13
406	,, 9	392	,, 13
400	,, 13	392	,, 13
990*	July 19	341	,, 13
990*	,, 19	341	,, 13
990*	,, 19	436	,, 13
690*	,, 19	392	,, 13
327	,, 19	366	,, 13
436	,, 19	362	,, 13
352	August 18	396	,, 13
386	September 13	352	,, 13
396	,, 13	392	,, 13
		331	July 29
		428	,, 29
		331	,, 29

* These values are estimated from the time it took the boom to reach the stop at the edge of the paper and are therefore only approximate.

A current of a given value may be made up in two ways: (1) by light rain carrying heavy charges; or (2) by heavy rain carrying light charges. Hence it will be interesting to investigate the charges brought down by a given quantity of water and then to see how these charges vary with the rate of rainfall.

TABLE III.

Charge per c.c. of rain, els. units.	No. of two minutes' intervals during which the charge was — Positive.	No. of two minutes' intervals during which the charge was — Negative.	No. of positive intervals. / No. of negative intervals.
<0·1	911		
0·1–1	837	305	2·7
1–2	148	56	2·6
2–3	52	25	2·1
3–4	39 ⎫	6 ⎫	6·5 ⎫
4–5	9 ⎬ 71	8 ⎬ 37	1·1 ⎬ 1·9
5–6	9 ⎪	3 ⎪	3·0 ⎪
>6	14 ⎭	20 ⎭	0·7 ⎭

Table III shows the number of two minutes' intervals during which rain having different charges was recorded. It will be seen that although these numbers do not indicate any marked change in the proportion of positively charged rain as the

TABLE IV.

Positive charge per c.c. of rain. — Els. units.	Positive charge per c.c. of rain. — Date.	Negative charge per c.c. of rain. — Els. units.	Negative charge per c.c. of rain. — Date.
+7·2	April 7	−6·6	April 12
6·3	,, 7	6·6	,, 12
6·1	,, 8	6·5	May 13
6·0	,, 13	6·5	,, 13
6·0	,, 13	17·7	,, 13
6·0	,, 26	17·7	,, 13
6·0	,, 26	10·1	,, 13
6·0	May 13	10·4	,, 13
6·2	,, 13	6·4	, 13
6·2	,, 13	19·8	,, 13
8·0	,, 13	19·8	,, 13
8·0	,, 13	8·6	,, 13
7·7	June 9	15·2	,, 13
7·7	,, 9	15·2	,, 13
		11·0	,, 13
		9·3	,, 13
		9·1	,, 13
		8·9	,, 13
		12·0	,, 13
		12·0	,, 13

charges become greater, they do indicate a slight tendency for the ratio of positive to negative electricity to become less as the charges increase; but it would not be safe to base any deductions on the slight variations indicated.

The effects of the storm of May 13 are again seen in the figures for highly charged negative rain; for of the 20 records of rain with higher negative charges than 6 els. units per cubic centimetre of water, 18 occurred during this one storm.

Table IV is a list of the charges which equalled or exceeded 6 els. units per cubic centimetre of water.

From this it will be seen that during the storm on May 13 the negative charge on the rain reached the large amount of nearly 20 els. units per cubic centimetre of water. With the exception of these the largest charges were positive charges of 8 els. units per cubic centimetre of water.

We can now turn to the question whether there is any relationship between the rate of the rainfall and the charge it carries:—

Table V.

Rate of rainfall, mm. of rain in two minutes.	Rain with no charge.	Rain with positive charge.		Rain with negative charge.		Ratio of number of positive to number of negative two minutes' intervals.
	No. of two minutes' intervals.	No. of two minutes' intervals.	Mean charge per c.c. of rain in els. units.	No. of two minutes' intervals.	Mean charge per c.c. of rain in els. units.	
<0·14	—	187	1·7	168	2·2	1·1
0·14	441	277	1·0	152	1·0	1·8
0·28	153	223	0·6	68	0·5	3·3
0·42	53	91	0·4	20	0·5	4·5
0·56	22	70	0·2	15	0·4	4·7
0·70	6	54	0·3	10	0·6	5·4
0·84	2	45	0·2	7	0·0	6·4
0·98	0	23	0·3	4	0·0	5·8
1·12	0	24	0·4	0		
1·26	0	14	0·4	0		
1·40	0	14	0·3	0		
1·54	0	10	0·3	0		
1·68	0	7	0·5	0		
1·82	0	4	0·3	0		
1·96	0	3	0·1	0		
2·10	0	5	0·2	0		
2·24	0	3	0·4	0		
>2·24	0	13	0·3	0		

In this table, columns 2, 3, and 5 give the number of two minutes' intervals during which rain, having the intensities shown in the first column, was recorded as bringing down no charge, a positive charge, and a negative charge respectively; while in columns 4 and 6 the corresponding mean charges per cubic centimetre are tabulated. Column 7 gives the ratio of the number of two minutes of positive rain to the number of two minutes of negative rain.

Two interesting results are shown in this table, the most important being that the ratio of the number of positively charged falls to negatively charged falls increases as the rainfall becomes more intense. In this respect it is important to notice that in no case in which the rainfall exceeded 1 mm. in two minutes was a negative charge associated with the rain. The second interesting result is that both with positively and negatively charged rain the highest charges are carried down by light rain, although with heavier rain than 0·028 cm. in two minutes the magnitude of the charge does not appear to depend on the intensity of the rain.

The general character of the rain in reference to its electrical state may now be discussed, starting with the rain which accompanied thunderstorms.

It has already been pointed out that a hard and fast line cannot be drawn between rain which falls during thunderstorms and rain not connected with thunderstorms. Still there can be no possible doubt that the rain connected with thunderstorms was more highly charged than rain with which were associated few lightning discharges or none at all. During some storms in July and August, which were not accompanied by electrical effects, rainfall exceeding 0·070 cm. in two minutes occurred without giving the slightest indication of any electrical charge, while on the other hand it sometimes happened that during thunderstorms the rain was too light to be registered on the rain-gauge, and yet charged up the receiver to a potential between 20 and 30 volts in two minutes. It is, however, important to point out that the most highly charged rain did not always accompany the storms with the greatest amount of thunder and lightning. Also, often during a thunderstorm the rain would continue after the thunder and lightning had ceased, and yet be as highly, if not more highly charged than during the violent electrical display.

As a preliminary to discussing the general characteristics of negatively charged rain, the remarkable storm of May 13, 1908, which has already been referred to, will be considered.

At about midday the weather appeared threatening and a violent thunderstorm worked up soon after 13 hours. The thunder was very loud and near, and the lightning vivid. At 13 hours 46 minutes the rain began to fall, but not very heavily. The heaviest rain occurred at about 14 hours 36 minutes, the average rainfall being then at the rate of 0·042 cm. in two minutes, and the greatest rate 0·070 cm. in the same time. At 14 hours 48 minutes the rate of rainfall became less, and from then until 17 hours 30 minutes steady rain continued at an almost constant rate of 0·014 cm. in two minutes. Unfortunately, during the storm it was impossible to follow the changes very closely owing to the demands of other work, and hence it is not known exactly at what time the thunder and lightning ceased; there are reasons, however, for believing that it did not continue long after 15 hours, and it is known for certain that it had ceased before 16 hours.* During the period at the commencement of the storm, when the rain was moderately heavy and the electrical discharges violent, the rain was positively charged, but from 15 hours 24 minutes to 17 hours 8 minutes, that is, during the steady rain without thunder and lightning, the rain carried down a negative charge which at times exceeded 19 els. units per centimetre of water, this being by far the greatest charge measured on any rain. This charge is so great that the electrical force on the raindrops within a field of half the intensity necessary to cause a lightning discharge would be equal to the force exerted by gravity on the raindrops, so that it would be quite possible for fields to occur which would actually cause such drops to rise against gravity.

The noteworthy features of this highly negatively charged rain were that it occurred after a violent thunderstorm, during which the rain had been positively charged, and that the rate at which it fell was not great, but uniform and steady. These characteristics of negatively charged rain which were so marked in this storm are more or less traceable throughout all the storms investigated.

It has already been pointed out that negatively charged rain does not occur when the rate of the rainfall becomes large, and from Table V, p. 389, it will be seen that the rainfall was less than 0·028 cm. in two minutes during 88 per cent. of the time that negatively charged rain fell, while for positively charged rain this proportion was only 64 per cent. Thus it would appear that negative electricity is, as a rule, brought down by light rain.

Negatively charged rain fell during all periods of the storms, and in some very rare cases the whole rain was negatively charged; but there appeared, from the data collected, to be a tendency for negative electricity to be associated with the latter half of a storm. In order to bring out the relationship, as many storms as possible have been divided into four equal parts as regards time, and the occurrences of positively and negatively charged rain in each quarter have been counted, with the following result :—

Table VI.

Quarter of the storm.	Percentage of time of rainfall during which the charge measured was negative.	
1st	30	33
2nd	35	
3rd	50	46
4th	43	

From this it is seen that although more positive than negative rain fell in all periods of the storms, the difference was least in the second half, or, in other words, the

* This storm occurred before the coherer had been installed.

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tendency was for negative electricity to be brought down by the rain more generally in the second than in the first half of the storms.

Other characteristics of negatively charged rain were noted in the course of the work, namely, that such rain nearly always fell from a lightly clouded sky, and fell at a very uniform rate, without the rapid changes in the rate of falling which accompanied the positively charged rain.

The chief characteristics of positively charged rain were that it was always associated with the heavy rainfall which accompanied the centre of a thunderstorm, and with nearly every case in which the rainfall suddenly increased in violence. Both light and heavy rain were more often charged positively than negatively, and on the average light rain was more highly charged than heavy rain.

The relationship between potential gradient and rain electricity will now be considered. The potential gradient record did not commence until July 18, and owing to spiders spinning their webs from the collector to the surrounding objects a good many days' records were lost. In spite of these facts many data were collected, and can be used to show the relationship between the signs of the electricity of the rain and the potential gradient. Defining the sign of the fine weather potential gradient as positive, it may be taken as a general rule that negative potential gradient only occurs during periods of disturbed weather. It is a well-known fact that during thunderstorms the potential gradient undergoes violent and rapid changes, and these changes must in some way be associated with the same electrical effect that causes the thunder and lightning. Thus one might expect that a close relationship would exist between the sign of the potential gradient and the sign of the rain electricity, but this consideration was not borne out by the measurements.

From the records of the three instruments, potential gradient electrometer, rain electricity electrometer, and rain-gauge, it has been possible to pick out 1950 two minutes' intervals during which rain fell and the potential gradient was measured. From these data the following table has been constructed :—

TABLE VII.

	No. of two minutes' intervals during which the potential was		Percentage occurrence of negative potential gradient.
	Positive.	Negative.	
Rain uncharged	245	668	72
Rain charged positively	267	437	62
Rain charged negatively	117	216	65

From this it will be seen :

(1) That during rain, whether charged or uncharged, the potential gradient was more often negative than positive.

(2) That there was no relationship between the sign of the potential gradient and the sign of the rain electricity.

(3) That the excess of negative potential gradient over positive potential gradient was somewhat less when the rain was charged than when it was uncharged, the percentages of negative potential gradient in the two cases being 63 and 72 respectively.

Before summing up the results of this work, it is desirable to point out the sources of error which might be held to influence the results :—

(1) A certain number of raindrops are bound to fall on the rim at the top of the cylinder B (see fig. 1, p. 380), and part at least of each drop will probably splash into the receiver A. If, now, this rim has high charges induced on it by the influence of the earth's field, the drops which break on it will take away some of the induced charge and give it up to the receiver when they fall into it.

This difficulty was guarded against by carrying up the walls of the shed to a height of about 1·5 metres above the level of the top of the cylinder B, thus reducing the earth's field in the neighbourhood of B as much as possible. But the best proof that the results were not affected by this source of error is to be found in Table VII, which shows that the sign of the rain electricity was independent of the sign of the potential gradient, which it would not have been if the water which entered the receiver had obtained its main charge from the rim.

(2) The possibility of the "Lenard effect" being a source of error has also to be considered. LENARD showed that when a drop of pure water falls on a surface and splashes, a separation of electricity takes place, the water retains a positive charge, and the air takes a negative charge. If steps are taken to remove the charged air from the water by a blast of air, the positive charge on the water can be measured; but if the splashing takes place at the bottom of a fairly deep vessel, not artificially ventilated, there is no appreciable separation of electricity. It was for this reason that the receiver A was made 31 cm. deep. With such a vessel the Lenard effect could not play any appreciable part.

But, again, the results themselves are the best test, for they show positive charges which could not be given to water by a single splashing under the most favourable conditions in a laboratory. LENARD* found that when a stream of water, in small drops of 2 mm. diameter, impinged on a metal plate with a velocity of 18 metres a second, and great care was taken to obtain complete separation of the electricity by artificial ventilation, each drop developed $0{\cdot}2 \times 10^{-12}$ coulomb of electricity. From this we find that a cubic centimetre of water developed 0·15 els. unit of electricity. It therefore appears unlikely that with raindrops falling on to the bottom of the receiver A, and without any ventilation to separate the electricity, anything like such a large charge as 0·1 els. unit per cubic centimetre of water could be given to the rain by the Lenard effect. Now a charge of 0·1 els. unit per cubic centimetre of

* *Loc. cit.*, p. 626.

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water has been taken as the limit of the accuracy of the electrical measurements in this work, hence it may be concluded that the results are not materially affected by the Lenard effect.

The more important results of this work may now be summed up as follows:—

(1) During 71 per cent. of the time that charged rain fell the charge was positive.

(2) 75 per cent. of the electricity brought down by the rain was positive.

(3) Light rain was more highly charged than heavy rain.

(4) All rainfall which occurred at a greater rate than a millimetre in two minutes was positively charged.

(5) The proportion of negative electricity brought down by the rain was slightly greater in the second than in the first half of the storms.

(6) The potential gradient was more often negative than positive during rain.

(7) No relationship between the sign of the potential gradient and the sign of the electricity of the rain could be detected.

Part II.—*Laboratory Experiments.*

While the measurements of the rain electricity described in the previous part of this paper were being made, a second investigation was undertaken in the laboratory of the Simla Meteorological Office, with the object of finding the physical process by which electrical separation takes place during thunderstorms. The scheme of the research was to imitate as far as possible in the laboratory each process which takes place in a thunderstorm and to note any electrical effects.

A large number of experiments was made with vortex rings composed of air in different physical states to see if any electrical separation accompanies the friction and mixing of masses of air having different temperatures and humidities; the freezing and thawing of water were examined and a number of other experiments made, but all with negative results. A series of experiments was then undertaken which was based on the following considerations.

Lenard* has shown that if air ascends with a greater velocity than 8 metres a second no water can fall through the current, for if the drops are below a certain size they are carried upwards with the air, while if they are above that size they are unstable and quickly break up into smaller drops, which are then carried upwards. Now, as will be seen later, it is exceedingly probable that during thunderstorms ascending currents much greater than 8 metres a second come into play, and these must therefore hold a considerable quantity of water in suspension. This water will be constantly going through the process of growing from small drops to large drops, only to be broken up into small drops again. If, therefore, the breaking of large drops into small drops is accompanied by a separation of electricity, thunderstorm electricity might owe its origin to such an effect.

* Lenard, 'Met. Zeit.,' vol. 39, p. 249, 1904.

In 1892 Professor LENARD* published his well-known work on the electrification of water by splashing, and in that work he had made experiments on the question here raised, but had come to the following conclusion, which he printed in italics: "Thus mere breaking up of the water is just as ineffective as the falling of streams of water through the air; it was only the impact of separate drops upon a flat obstacle which produced an electrical effect."†

The experiments on which this conclusion was based did not appear conclusive, and it was considered necessary to make further experiments before accepting it as final.

The first experiments made led to negative results, but it was soon found that this was probably due to the impurity of the water drawn from the Simla mains, for even the Lenard effect could not be obtained with it. The experiments were then repeated with distilled water, and it was at once found that the mere breaking up of large drops into spray on an air jet gave to the water a considerable positive charge.

There is no need to describe in detail the experiments by which this result was first obtained, for better methods, capable of giving quantitative results, were developed later, and a description of the final experiments will at once be given.

A metal tray T (see fig. 2), 30 cm. square and 15 cm. deep, was supported on three amber insulators I, while through the bottom of the tray, exactly in the middle, a vertical piece of glass tube was passed which was drawn out to a nozzle 2 mm. in diameter at its upper end. Underneath the tray this glass tube was connected by means of a short piece of rubber tube to another glass tube S, which had been coated inside and out with sulphur. The latter formed a very highly insulating tube, by means of which the nozzle in the tray could be connected to the air reservoir R and air passed through it without any fear of the charge collected on the tray being conducted away. The reservoir was supplied with air by means of the foot bellows B, and the pressure inside could be kept fairly constant by observing the water manometer M.

At a distance of about 70 cm. above the nozzle a glass funnel F was fixed, connected to a glass tube ending within a metal cylinder C. The glass tube was filled with wires by which the flow of water out of the funnel could be regulated until large drops fell from the end of the tube at the rate of about 80 a minute. The cylinder C was insulated from the funnel, and could be either connected to earth or to batteries, according as to whether it was desired to have the falling drops electrically neutral or charged.

By adjusting the position of the funnel it could be arranged that each drop fell

* 'Wied. Annal.,' vol. 46, pp. 584–636, 1892.

† Blosses Zerstieben des Wassers ist also ebenso unwirksam wie das Hindurchfahren von Strahlen durch die Luft; nur Auftreffen getrennter Tropfen auf ein flaches Hinderniss gab stets electrische Wirkung.

upon the jet of air escaping from the nozzle, where it was split up into numerous small drops through the sudden stoppage of its downward motion. When this adjustment was well made the drops broke up in a symmetrical crown about 4 cm. above the nozzle, and the greater part of the small drops so produced fell directly into the tray. In order to prevent small spray from being blown over the sides of the tray, a roof in the form of a hollow truncated pyramid, having a hole 5 cm. square at the top, was fitted over it. The drops fell through the hole in the roof and were broken up on the air jet, but only a very little of the spray escaped with the stream of air.

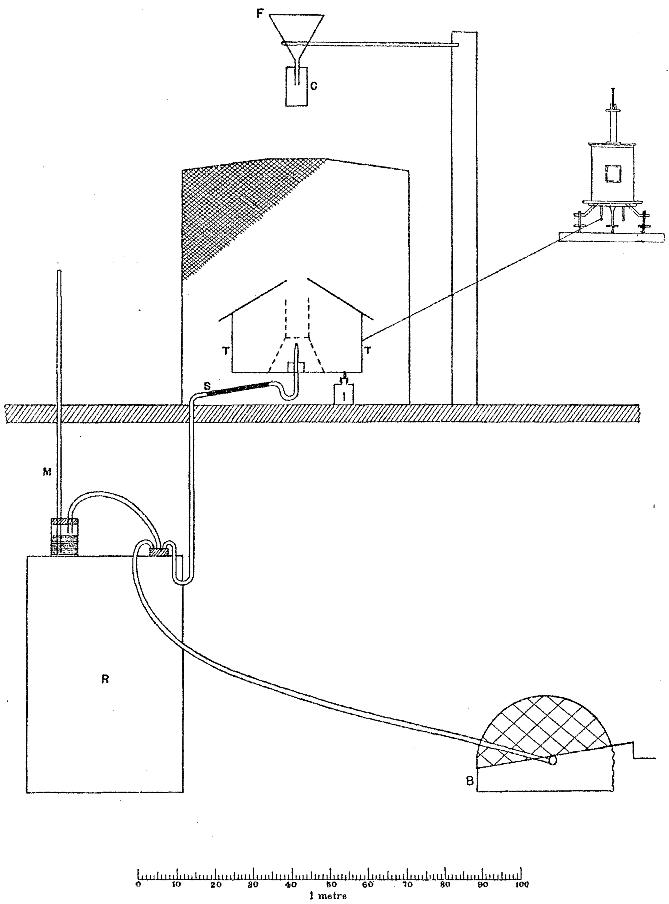

FIG. 2.

A fine wire-gauze cage was placed over the tray to protect it from extraneous electrical fields, and a Dolezalek electrometer was used for measuring the potential of the tray.

The method of making an experiment was as follows. The funnel was filled with distilled water and a cock opened to let the water flow in large drops from the orifice within the metal cylinder. The bellows were then worked until the manometer showed a pressure of about $\frac{1}{2}$ metre of water and the position of the funnel above the nozzle was adjusted until the drops were symmetrically broken up on the air jet. The box was then connected to earth and a reading taken of the zero of the electrometer; after a convenient interval the earth connection was broken and the drops counted as they fell. Readings were taken of the electrometer after each 100 drops had fallen until 500 had been counted, when the flow of water was stopped. The following shows the result of a typical experiment in which distilled water was used :—

TABLE VIII.

No. of drops	0	100	200	300	400	500
Deflection	20·0	19·5	18·8	18·2	17·5	16·9

Total deflection = 3·1 cm. = 7·2 volts. Capacity of system = 87 cm.
Hence charge per drop = $4{\cdot}2 \times 10^{-3}$ els. unit.

Before going any further it will be as well to consider how much of the charge, thus measured, could reasonably be ascribed to the breaking up of the drops on the jet of air.

Three possible sources of error have to be considered :—

(*a*) That the charging might be due to the blast of air alone.
(*b*) That the drops might be electrified before being broken up.
(*c*) That the effect might be due to the Lenard effect coming into play when the drops fell into the tray after being broken up on the air jet; or in other words, that the separation of electricity might not take place when the drops broke on the jet, but when they splashed on the water in the bottom of the tray.

(*a*) That the blast caused no charging could easily be tested by keeping it in action without the drops falling. Frequent experiments were made and showed no trace of charging.

(*b*) The electrification of the drops was tested by placing a small cylindrical box over the air nozzle (as shown by the dotted outline in the figure) to catch the drops as they fell. A small hole was made in the side of this box about 2 cm. from the bottom, so that a layer of water 2 cm. deep was always in the bottom, and into this the drops fell. The Lenard effect would come into play when the drops splashed on the water in the box, but as all the electricity separated remained within the tray and its lid, this effect could cause no charging of the system. If, however, the drops had fallen with a charge on them it would have been detected by a deflection of the electrometer. No such effect could be observed.

(*c*) In order to prevent the Lenard effect from coming into play when the drops fell into the tray after breaking up on the air jet, use was made of the fact discovered by LENARD that the splashing of salt water produces the opposite charge to that given by the splashing of distilled water. A layer of salt water 2 cm. deep was therefore placed in the bottom of the tray and into this the drops fell after breaking up on the jet. The following test was then made: The funnel was slightly moved to the side so that the drops of distilled water fell directly with their full velocity on to the salt water on the bottom of the tray, and the blast was also set in action in order to remove the air containing any charge separated from the water on splashing, and so to produce the largest Lenard effect possible.

The result was as follows :—

TABLE IX.

No. of drops	0	100	200	300	400	500
Deflection	20·0	20·1	20·2	20·2	20·3	20·4
Total deflection = 0·4 cm. = −0·9 volt.						

This shows that the Lenard effect due to splashing on the bottom of the tray produced a slight negative charge, and so it may be concluded that the positive charge found in the experiments in which the drops were broken on the air jet was not due to splashing on the bottom of the tray.

It would therefore appear justifiable to assume that the whole of the charge measured in the apparatus under discussion was due to the breaking up of the drops on the air jet.

The following table gives the results of six experiments :—

TABLE X.

Distilled water. Volume of each drop = 0·24 c.c.	
No. of drops broken.	Mean charge produced by a drop breaking on the air jet.
	els. unit.
500	$5 \cdot 0 \times 10^{-3}$
500	$4 \cdot 2 \times 10^{-3}$
400	$5 \cdot 8 \times 10^{-3}$
400	$5 \cdot 1 \times 10^{-3}$
400	$5 \cdot 8 \times 10^{-3}$
400	$5 \cdot 8 \times 10^{-3}$
Total . 2600	Mean . $5 \cdot 2 \times 10^{-3}$

This result is of the same order of magnitude as that found by LENARD for single large drops breaking on a metal obstacle, the charge produced by each drop in these experiments being even larger than that found by LENARD in his experiments.

Experiments were next undertaken to investigate the extent to which the process is affected by any charge already on the drops, for it is quite conceivable that charged drops might behave quite differently from uncharged drops. For these tests the apparatus already described was adapted. It was only necessary to connect the cylinder C to a battery, so that each drop which fell from the funnel had a definite charge induced on it, and carried it away with it on its fall. The charge carried by each drop was found by catching the drops in the small box shown dotted in fig. 2. The box was then removed, and the charged drops broken up on the air jet. The difference between the total charges measured, with the same number of drops in each case, indicated the extent of charging due to the breaking up on the air jet.

The following gives a typical experiment, in which distilled water was used and each drop carried a positive charge :—

TABLE XI.

Drops caught in little box.						
No. of drops	0	100	200	300	400	500
Deflection	20·0	17·3	14·3	11·4	8·5	5·7
Total deflection = 14·3 cm. = +33·5 volts. ∴ Charge per drop = $19·5 \times 10^{-3}$ els. unit.						

The small box was then removed, and the drops broken on the air jet.

TABLE XII.

Drops broken on air jet.						
No. of drops	0	100	200	300	400	500
Deflection	20·0	16·5	13·0	9·4	5·9	2·5
Total deflection = 17·5 cm. = 41·0 volts. ∴ Charge per drop = $23·9 \times 10^{-3}$ els. unit.						

From these two experiments we find that drops originally positively charged to $19·5 \times 10^{-3}$ els. unit have had this charge increased to $23·9 \times 10^{-3}$ els. unit when broken up on the air jet, the increase being $4·4 \times 10^{-3}$ els. unit per drop.

There is, however, in this result a slight error, due to the fact that when the drops break up on the air jet a certain number of the fine drops produced are carried upwards with the air stream and so escape out of the measuring system. This loss was measured by the use of Simla tap water, which, as has already been remarked, was found to be quite incapable of producing a charge, either by splashing or breaking up on the jet. An experiment was made with tap water charged in the same way as in the experiment just considered, and it was found that after breaking on the jet the drops had lost part of the charge originally on them, both when the charge was positive and when it was negative. The mean value of the loss was found to be 5 per cent. of the charge on the drops.

With drops originally uncharged a 5 per cent. loss was of no particular account, the experiments were not accurate to this amount; but with highly charged drops a loss of 5 per cent. of the original charge was appreciable and had to be taken into account.

The following table gives the results of all the experiments made with charged distilled water :—

TABLE XIII.

Distilled water.		
No. of drops broken.	Mean charge on drop before breaking.	Mean charge due to breaking. (Corrected.)
	10^{-3} els. unit.	10^{-3} els. unit.
1000	+19·6	+5·6 } 6·4
1200	+59·1	+7·2 }
1000	−19·5	+4·9 } 4·7
1200	−58·0	+4·5 }
4400		
	Mean	+5·6

From this table it will be seen that charged drops obtain a positive charge by being broken up on the air jet, and that the magnitude of the charge is approximately the same whether the drops are charged positively or negatively. Great accuracy cannot be expected in these experiments with charged drops, because the electrometer has to be made very insensitive in order to allow of the large charges brought down by the drops being measured, and the final result is obtained from the slight variation in these large charges caused by the splashing. It is, however, interesting to notice that the mean of all the experiments with charged drops gives a mean charge due to the breaking up on the air jet almost equal to that found for uncharged water.

In Table XIV the results of all the experiments are summed up :—

TABLE XIV.

Initial charge on drop.	Electricity added to a drop in consequence of the breaking on the air jet.	
10^{-3} els. unit.	10^{-3} els. unit.	
0	+5·2	
+19·6	+5·6	5·3
−19·5	+4·9	
+59·1	+7·2	5·8
−58·0	+4·5	
	Mean . . +5·5	

As all the drops in these experiments contained approximately 0·24 c.c. of water, the charge given to the water is equivalent to a volume charge of 23×10^{-3} electrostatic unit per cubic centimetre of water.

After making these experiments it was felt that objection might be raised to applying the results thus obtained to the breaking up of raindrops in the atmosphere, because no such violent scattering of the drops could take place in the atmosphere as that obtained when falling drops impinge on a concentrated jet of air. A further experiment was therefore devised to produce the breaking up of the drops in a more natural way than the one already described.

The apparatus used is sketched in fig. 3. BB was a vessel made out of tinned iron, 65 cm. in diameter and 45 cm. high. In the middle of the bottom was a hole 7 cm. in diameter, surrounded by a conical rim 7 cm. deep; thus a layer of water 7 cm. deep could be put into the vessel without running out through the hole. Through this rim passed two small tubes, 0·8 cm. in diameter, which were fitted with a simple arrangement for opening and closing them to allow of the passage of the water at will. Soldered underneath the main vessel was a smaller one of the shape shown in the figure, and around the upper rim a third vessel AA was fixed on insulators so that it could be either connected to or insulated from the main vessel B, according to the experiment to be made. The whole was supported on insulators in such a position that the hole in the centre was directly over but not touching a large pipe through which a blast of air could be sent by means of the rotatory fan F.

When the fan was in action and the tubes open, water passed out through the latter in a solid stream into the middle of the air current, by which it was at once carried upwards and broken into spray. As the greater part of water carried upwards fell back into the main reservoir of water, it could be used over and over again. With this arrangement quite large charges were obtained by the vessel B in a comparatively short time. For example, the vessel B was connected to A and the water allowed to run. The whole system was then found to become charged at the rate of 20 volts per minute when a rapid blast of air was produced by the fan. This rate of charging would have been increased if a large amount of fine spray had not been carried from the apparatus by the air current. From the data that the system had a capacity of approximately 180 cm. and the water ran out of the tubes at the rate of 1200 c.c. a minute it will be seen that the charge given to the water was approximately 10×10^{-3} electrostatic unit per cubic centimetre, *i.e.* a charge of the same order of magnitude as that produced when individual drops were broken up violently on a concentrated air jet.

As the majority of the drops in this experiment after being carried upwards fell back on to a pure water surface, the experiment was not entirely free from the Lenard effect. In order to get over this difficulty the large vessel A fitted round the upper rim of B was insulated from it. This vessel caught a certain amount of the fine spray thrown up by the blast, and as the drops were exceedingly small and were only just beginning to fall when they were caught, they struck the sides of the vessel A without sufficient momentum to cause splashing; it was therefore concluded that very little separation due to the Lenard effect could take place at the impact. The vessel B was then connected to earth, and A to a Wilson electroscope, and the water and blast set into action. When the electroscope measured a definite potential the blast and water were stopped, and the quantity of water caught in the vessel A was run off and measured.

The following shows the results obtained in a series of experiments in which rain-water was used and the system was allowed to charge itself up to 9 volts before measuring the water collected in A:—

	Amount of water caught in A.
1st experiment	300 c.c.
2nd ,, ...	280 ,,
3rd ,, ...	290 ,,
4th ,, ...	230 ,,
5th ,, ...	265 ,,
Mean	273 ,,

Capacity of system = 135 cm.

$$\therefore \text{ Charge on 273 c.c. of water} = \frac{135 \times 9}{300} \text{ els. units.}$$

$$\textit{i.e.} \text{ Charge per c.c. of water} = 15 \times 10^{-3} \quad ,,$$

Thus the charge per cubic centimetre of water is of the same order of magnitude as that found when single drops were violently broken up on the air jet, and is only slightly smaller in amount. From these experiments it would appear safe to conclude that when pure water is broken up from large to small drops in the air under ordinary conditions of temperature and pressure a separation of electricity takes place.

In all the experiments described hitherto the amount of separation has been measured by means of the charge retained on the water. Experiments were now undertaken to see if the charge carried away by the air could be measured.

The experiment was arranged as indicated in fig. 4. AA was a zinc cylinder 8·5 cm. in diameter and 60 cm. long. Its lower end fitted into a glass taken from a "hurricane lamp," which in turn fitted into another small cylinder as shown at B. Through the bottom of the lower cylinder a glass tube drawn out to an orifice about 2 mm. in diameter at its upper end projected into the middle of the glass, and through this orifice a jet of air was passed in a way similar to that described in the previous experiments (see fig. 2, p. 396).

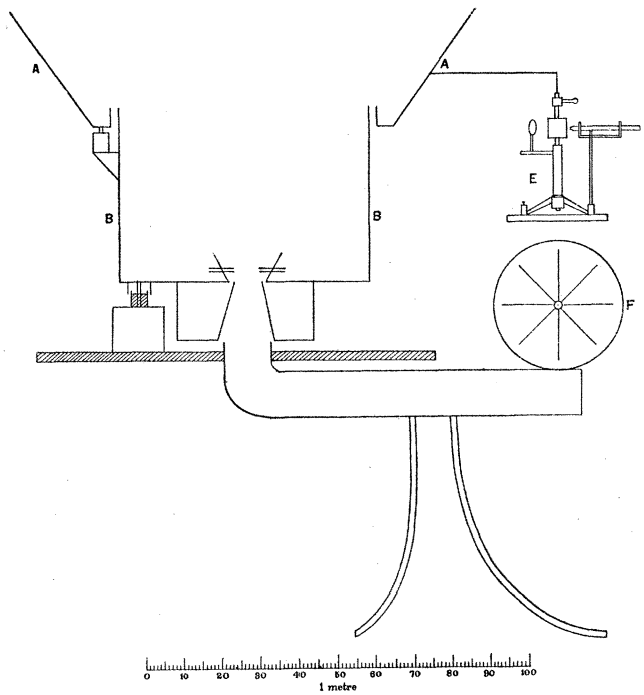

FIG. 3.

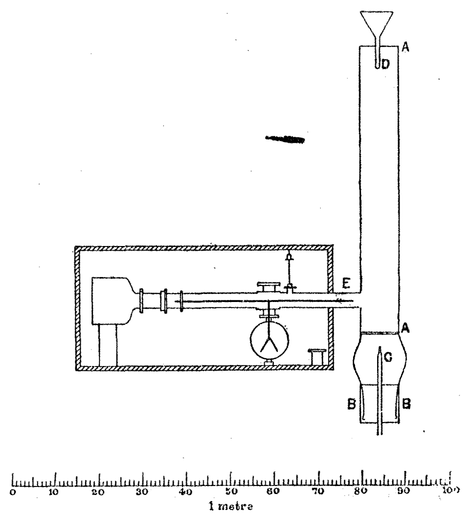

FIG. 4.

From a tube D at the top of the cylinder AA drops of water fell on to the jet of air and were broken up into small drops by the impact. In order to test the air of the jet on which the drops were broken for an electrical charge, an Ebert apparatus was connected to the cylinder AA through a short tube E fixed about 5 cm. above the place where the drops were broken. When the fan of the Ebert apparatus was in action it drew air through holes in the top of the cylinder AA which swept the air of the jet with it through the Ebert apparatus. The experiments were made as follows :—

The central cylinder of the Ebert apparatus was charged to a potential which could be read by the divergency of the leaves of the attached electroscope. The air of the jet was then put into action, and a reading of the electroscope taken. The fan was then allowed to draw air through the instrument for 10 minutes, when a second reading of the electroscope gave the loss of electricity due to the natural ionisation of the air in that period. Drops were then allowed to fall from the tube D on to the jet, and two more readings of the electroscope were taken with intervals of 10 minutes between them, and the number of drops which had fallen in that time was noted. The difference of the results of the two experiments gave the amount of electricity imparted to the air by the breaking of a known number of drops, and from this the amount due to the breaking of a single drop was calculated. Similar experiments were made with the central cylinder of the Ebert apparatus charged both positively and negatively. The results are shown in the following table :—

TABLE XV.

Distilled water.						
Sign of charge of air.	Loss of volts in 10 minutes with air jet without drops.	Loss of volts in 10 minutes with drops being broken on air jet.	Loss of volts due to the breaking of the drops.	No. of drops broken in 10 minutes.	Loss of volts due to breaking of one drop.	Mean of two experiments.
Negative . .	1·1	30·3	29·2	394	0·074	0·071
Negative . .	1·9	27·9	26·0	384	0·065	
Positive . .	2·0	12·3	10·3	385	0·027	0·024
Positive . .	2·7	10·8	8·1	411	0·020	

Now, as the capacity of the Ebert apparatus was 14 els. units—

The mean negative ionisation caused by the breaking of one drop . . . . $= \frac{0·071 \times 14}{300} = 0·0033$ els. unit.

The mean positive ionisation caused by the breaking of one drop . . . . $= \frac{0·024 \times 14}{300} = 0·0011$ els. unit.

Excess of negative ionisation caused by the breaking of one drop . . . . $= 0·0033 - 0·0011 = 0·0022$ els. unit.

The results of these experiments are interesting, in that they show—

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

(2) That three times as many negative ions as positive ions are released.

The difference between the negative and positive charges produced should correspond to the charge remaining in the water. Now, it has been shown above that $5·5 \times 10^{-3}$ els. unit of positive electricity is retained by the water of each drop after breaking, and this amount agrees as well as could be expected with the $2·2 \times 10^{-3}$ els. unit per drop found in the air; the difference is no doubt due to the fact that many of the

* This experiment does not indicate the nature of the ions produced: for instance, the positive ions might be exceedingly fine water drops. Still it shows that something of the nature of ordinary ionisation takes place and that the ions exist long enough to be separated by the Ebert instrument.

tions given to the air at the splashing of the water are not drawn into the Eber instrument, but give up their charges to the sides of the apparatus.

The results of these experiments may be summed up in the following sentence :—

When water drops are broken up in the atmosphere a separation of electricity takes place, the water becomes positively charged, and the air negatively charged; and further, the amount of separation is independent of any charge previously on the drop.

PART III.—*Theoretical Conclusions.*

The consideration of the electricity of thunderstorms, which was the starting point for the experiments just described, will now be resumed. It has been pointed out that if the breaking of the raindrops in the air were accompanied by a separation of electricity, this property might be the cause of the electrical effects observed during thunderstorms, and it now remains to ascertain the extent to which this suggestion can be developed into a satisfactory explanation of the phenomena of thunderstorms.

In order that the explanation may be satisfactory it is necessary to show—

(1) that there is a considerable breaking up of raindrops during a thunderstorm.

(2) That the quantity of electricity which could be developed in this way is sufficient to account for the electrical effects observed.

(3) That the general meteorological conditions which usually accompany thunderstorms agree with the explanation.

Turning now to the first of these requirements, it will be shown that in all probability the rainfall of thunderstorms is accompanied by considerable breaking up of large into small drops. This can best be done by considering Prof. LENARD'S article on "Rain,"* already referred to.

Prof. LENARD made a number of experiments to determine the final velocity attained by drops of water of different sizes when falling through air. His experimental method was to create a vertical current of air and find the velocity of the current which was just able to support drops of a given size. The following table gives the results obtained :—

Diameter of the drops.	Velocity of the air which supported the drops = the final velocity of the drops in still air.	
	Observed.	Calculated.
mm.	Metres per second.	Metres per second.
1·28	4·8	5·65
3·49	7·37	9·3
4·50	8·05	10·6
5·47	7·98	11·7
6·36	7·80	12·6

* LENARD, 'Met. Zeit.,' vol. 21, pp. 249–262, 1904.

About this table Prof. LENARD says:—"One sees from it that the velocity quickly reaches a limiting value as the size of the drops increases (very nearly equal to 8 metres a second), above which it does not increase; it even decreases a little as the drops grow still greater."

He then showed that this apparent anomaly is due to the drops becoming deformed, so that instead of retaining the shape of spheres they become flattened out, thus presenting an increased resistance to the air through which they fall. In consequence of this deformation large drops rapidly break up in the air into smaller drops, and LENARD found that drops of 4 mm. diameter were stable under all conditions, but that drops 5·5 mm. and above in diameter could not exist for more than a few seconds after attaining their final velocity relative to the air.

This fact plays an important part when drops of water are falling through ascending currents. According to the table given above, all drops of water of a smaller diameter than 4·5 mm. will be carried upwards by a current of 8 metres a second, while all drops of a larger diameter than this will be held in suspension, neither rising nor falling. But the latter are unstable, and after floating for a few seconds in the current break up into small drops which are carried upwards. Thus no water could possibly fall through an ascending current of air having a velocity of 8 metres a second or more.

That thunderstorms are accompanied by strong ascending currents is admitted by all meteorologists, but I know of no actual measurements of the ascending currents within a thundercloud; still the question can be discussed from indirect evidence.

There is no essential difference in kind between a tornado, a hailstorm, and an ordinary thunderstorm, all of which are accompanied by electrical discharges.

Now in the first two of these we know definitely that ascending currents of excessive velocity do occur. The many authenticated cases in which heavy structures and implements have been raised to considerable heights during tornadoes give absolute proof of ascending currents comparable with the greatest horizontal winds known. Now a horizontal velocity of 8 metres a second (29 kilometres, or 18 miles an hour) is defined as a moderate breeze, and wind velocities of 40 metres a second (approximately 100 miles an hour) have been measured during tornadoes; thus we see that ascending currents having velocities many times greater than 8 metres a second must occur during tornadoes.

In the formation of hailstones we have equally certain evidence of strong ascending currents. A hailstone cannot grow appreciably above the size which would be sufficient to cause it to fall to the ground through the ascending currents below it, so that the size of a hailstone gives a rough measure of the upward velocity of the air current in which it was formed. Now hailstones have been met with having all sizes between those of peas and those of melons. A hailstone as big as a pea would require a vertical velocity of at least 10 metres a second to hold it in suspension;

thus the ascending currents which produce stones as large as oranges and melons must be enormous.

It would therefore appear that those disturbances in the atmosphere which are accompanied by the greatest amount of electrical discharge are also accompanied by violent ascending currents, much larger in all cases than the 8 metres a second necessary to hold water in suspension, and so it cannot be considered to be an unwarrantable assumption that in all thunderstorms a velocity of 8 metres a second occurs.

A strong vertical current in the atmosphere must have a form something like that of an hour-glass, having a comparatively large cross-section at the bottom where horizontal currents are feeding into it, and spreading out at the top to allow of the escape of the air after ascension. For simplicity in the following discussion we will imagine an ascending current to consist of three parts: (*a*) a base in which the cross-section is large and the vertical velocities are small; (*b*) a column of ascending air of which the cross-section is comparatively small and the vertical velocities are large and more or less constant throughout; (*c*) a cap or crown in which the air rapidly spreads out in all directions so that the vertical velocities are very small a short distance above the head of the column. If the air in the base is saturated, then as it rises through the column it will have its temperature reduced at the rate of approximately $0^\circ\cdot 5$ C. for each 100 metres of ascent, and there will be considerable condensation of water, which will form drops and tend to fall. If, however, the vertical velocity within the column is 8 metres a second or over no water can fall, but it will all be carried upwards until it reaches the top of the column, where the vertical velocities diminish. Here the water will accumulate in the form of drops which will continually be going through the cycle of growing to 5·5 mm. in diameter and then being broken up into a number of small drops, each of which will grow again. A rough approximation of the rate at which the water accumulates can be formed by assuming certain simple conditions. Thus let us assume that the height of the column is 2000 metres, so that the air which enters the base will be cooled 10° C. during the ascent, and let the initial temperature be 15° C. Then by the time the air reaches the top approximately 6 grammes of water will have been precipitated within each cubic metre of air, and if all this accumulates at the top of the column,* 6×8, or 48, grammes of water will have collected over every square metre of the column in one second, that is, in 10 minutes the water accumulated would be equivalent to a layer of water 2·9 cm. deep, or if the water is in the form of drops there would be at the end of 10 minutes 36 drops, each of the maximum size of 5·5 cm. diameter, over every square centimetre of the cross-section. Thus if the

* This of course is only assumed for purposes of a rough approximation; it is not intended to assert that all the water carried up by the current would accumulate at the top of the column, but as the accumulation which would result from rain falling from above has been neglected, the calculation will give some idea of the magnitudes with which we are concerned.

ascending current had a velocity of only 8 metres a second enough water would be deposited for a considerable breaking up of drops.

Turning now to the second point which the theory has to consider, a rough estimate will be made of the amount of electricity which could be separated under such conditions. For this purpose it will be necessary, in order to simplify the reasoning, to make several somewhat artificial assumptions. It will be assumed that the ascending current extends over a fairly large area, so that vertical distances may be considered as small in comparison with horizontal ones; that the separation of electricity takes place uniformly over a horizontal plane; and that all the positive electricity remains in the water near the place of separation, while all the negative is carried vertically upwards in the air stream. We will first consider how many drops must be broken in order to set up the potential gradient of 30,000 volts per centimetre which is necessary for a lightning discharge. This field is set up between two parallel plates having a surface density of 8 els. units per square centimetre. Thus sufficient drops must break over each square centimetre to provide 8 els. units before a discharge can take place, and as the breaking of each drop provides 5×10^{-3} els. unit, this will occur when $\frac{8}{5 \times 10^{-3}}$, or 1600, drops have broken.

Thus if 1 drop breaks over each square centimetre every second, a discharge can take place after 27 minutes; or, if 27 drops break, after 1 minute. Now it has already been shown that under certain conditions which are not at all improbable, 36 drops of water, each large enough to be broken up, will have accumulated in the course of 10 minutes over each square centimetre of the ascending current; hence, it does not seem at all improbable that with even moderate values of the ascending current sufficient breaking of drops could take place to give the rapid electrical discharges observed in thunderstorms. In this connection it is important to realise that each electrical discharge in a thunderstorm only neutralises the electricity over a small area of the region in which separation takes place. Thus suppose that the ascending current is 4 kilometres in diameter, and that each discharge neutralises the charge over 1 square kilometre of area, then it would take 12 discharges to neutralise the whole electricity over the whole surface. Under these conditions, if the potential gradient were being created at the rate of 30,000 volts per centimetre every minute, the lightning discharges would occur on the average every 5 seconds.

It may also be considered how many times a given mass of water would have to be broken up in order to give to the rain which falls from the cloud the charges of electricity which are actually measured. The case of rain positively charged will be considered first. From Table III, p. 388, it will be seen that the positive charge carried down by the rain is of the order of magnitude of 1 els. unit per cubic centimetre of water. The laboratory experiments showed that water which has splashed once has a charge of the order of magnitude of 10×10^{-3} els. unit per cubic centimetre. Thus the water on the average would have to splash something like

100 times to give the charges measured. There is no reason for considering that this would be impossible with violent and widespread ascending currents.

The air which passes through the accumulation of water at the head of the ascending current carries with it the negative electricity separated during the splashing. This electricity is rapidly absorbed by the cloud particles through which the air streams in its upward course, and it is very probable that large negative charges could in consequence be accumulated in the cloud. Thus the cloud over the ascending current will consist of negatively charged water particles, and these will coalesce to form rain having a negative charge. There is no means of estimating what negative charge might be expected, but there is no reason for considering that it should be smaller than the positive charge brought down by the water which has been broken up several times at the head of the ascending current. Thus it would appear that the process could provide both the positively and negatively charged rain actually observed.

The quantitative estimate which has just been made has been based on values which cannot be considered as being anything more than the roughest approximations. It shows, however, that it is not necessary to assume ascending currents of more than 8 metres a second to supply enough electricity for a considerable amount of lightning discharge, and that given reasonably rapid ascending currents, sufficient separation of electricity could take place to account for the most violent thunderstorms.

The preceding discussion will now be summed up in an account of the probable mechanism of a thunderstorm.

When extensive ascending currents occur in air which is not exceedingly dry, the formation of cumulus clouds with possible precipitation will naturally follow. As the ascending currents become more and more rapid large amounts of water will be held in suspension, until finally, when they attain a greater velocity than 8 metres a second, all water will be retained. As a consequence there will be considerable breaking up of drops in the air accompanied by a separation of electricity, by which the water becomes positively charged and the air negatively charged.

The electrical effects react on the rate of splashing. Uncharged drops combine only with difficulty, and rebound from one another as though they were solid. Charged drops, on the contrary, combine with facility to form single large drops.* Thus as the water becomes more and more highly charged the drops will the more rapidly grow to the size necessary for them to be broken again, and as a consequence the greater will be the splashing and the greater the rate of electrical separation.

An ascending current must at some place in its ascent spread out horizontally and so have its vertical velocity reduced. At the part of the current where the velocity falls below 8 metres a second a large accumulation of water will in all probability take place, and this will be the seat of the greatest amount of separation of

* Rayleigh, 'Roy. Soc. Proc.,' vol. 28, p. 406, 1879.

electricity. Now where the vertical current spreads out horizontally the stream lines of the air have horizontal components. For the present purpose it does not matter whether we consider that the vertical current spreads out uniformly on all sides or is deflected in a certain direction. In either case the water accumulated at the head of the current will be gradually moved horizontally until it reaches the edge of the rapid vertical current, and there it will be able to escape by falling; but as it will necessarily take some time for any given mass of water to travel from the centre to the outside of the ascending current, there will be time for considerable breaking up before the drops actually fall. Thus the water carried up by the ascending current will fall as positively charged heavy rain over one or other of the edges of the ascending current. This is of course considering the case in its simplest terms. As a matter of fact, the ascending current will vary in velocity, will have its gusts and lulls just as a horizontal wind has. Such variations, however, will be of great help in causing splashing, for LENARD* found that "the sudden contact of already deformed drops with a quicker air stream is very favourable to the breaking of the drops." Another consequence of the gusts and lulls in the ascending currents will be the raising and lowering of the region in which the water is held in suspension, and with this will follow rapid changes in the electrical field which may possibly help to produce electrical discharges.

The water which has become positively charged on the ascending current and then fallen as rain will be the heavy rain which occurs in the centre of the thunderstorm: the 'Platzregen" of the German authors. In view of this consideration, it will be interesting to look at the results of actual measurements of rain electricity, to see if the heavy rain which falls in the centre of a thunderstorm is positively charged. There are four sets of measurements of rain electricity which can be used for the purpose, viz., those of ELSTER and GEITEL'S first series of experiments, published in the 'Wiener Berichte'; their second series, published in 'Terrestrial Magnetism and Atmospheric Electricity'; those of WEISS, published in the 'Wiener Berichte'; and finally those in this paper.

These will be taken in the reverse order, and the Simla measurements considered first. It has already been pointed out in the first part of this paper (p. 390), that in every one of the 97 cases in which the rainfall equalled or exceeded 0·112 cm. in two minutes the rain was positively charged.

WEISS† does not record any case of a thunderstorm, nor do rainfalls so large as those just described occur in his observations; but nevertheless he made observations during two rain squalls ("Regenboe," Tables 12 and 14), and he states that in the former "Platzregen" fell; from his tables it will be seen that this excessive rain was positively charged (Nos. 182–184 of Table 12). In the second "Regenboe" the rain was positively charged throughout.

* *Loc. cit.*, p. 256.

† WEISS, 'Wien. Ber.,' vol. 115, p. 1285, 1906.

ELSTER and GEITEL'S* observations, recorded in 'Terrestrial Magnetism and Atmospheric Electricity,' give the same result. In the article referred to no tables are given, but 17 figures show the results of the observations. In four of these figures (figs. 2, 7, 10, and 17) we find "Platzregen" recorded, and in each case high positive charges accompany the heavy rain.

The only exceptions to this general rule are to be found in ELSTER and GEITEL'S† first paper on the electricity of rain, published in the 'Wiener Berichte' for 1890, in which we find that the "Platzregen" is more often accompanied by negative than positive electricity. In view of all the other observations, which show without exception the positive charge of "Platzregen," it is difficult to explain this discrepancy; but, accepting it in full, it may still be said that the evidence in favour of the view that the excessive rain within a thunderstorm is positively charged is overwhelming.

Advancing a step further, it will be necessary to consider what happens to the negative electricity which is separated when a drop breaks up. It is very probable that this charge is given to the air in the form of free negative ions, and it appears certain that these will, on formation, be carried upwards with the full velocity of the ascending air; they will then quickly leave behind the drops of water which retain the positive electricity.

But the negative charge cannot exist long as free ions, for the latter will be rapidly absorbed by the cloud particles with which the air is filled. In this way the cloud particles may become exceedingly highly electrified. Now within a highly electrified cloud there must be rapid combination of the water drops, and from it considerable rain will fall: this rain will be negatively charged, and, under suitable conditions, both the charge on the rain and the rate of rainfall could be large. But it is important to notice that the negatively charged rain has an entirely different origin from that of the positively charged rain, and therefore the character of the rainfall might be expected to be different in the two cases. It has already been shown that the positively charged rain is likely to occur in heavy downpours in consequence of its intimate connection with the ascending currents, but as the negatively charged rain is formed in the large cloud masses, which are more or less uniformly charged and extend over and around the ascending currents, the negatively charged rain is likely to have a much more uniform rate of fall, and also to occur in the intervals between the bursts of the positively charged rain.

The observations bear out these considerations in a remarkable way. In storm after storm it was found that negatively charged rain fell in the lulls after a heavy downpour of positively charged rain. Negatively charged rain never occurred in heavy downpour, but was very often associated with steady rain from a lightly clouded sky. Also negative electricity was measured but rarely, and in large quantities

* ELSTER and GEITEL, 'Terr. Mag. and Atm. Elect.,' vol. 4, pp. 13–32, 1899.

† ELSTER and GEITEL, 'Wien. Ber.,' vol. 99, p. 421, 1890.

never, in the regions of the storms in which violent and frequent lightning discharges occurred.

It will sometimes happen that the negatively charged cloud will be carried by the upper winds to some distance from the place where the separation of electricity was effected and will then give rain. In such cases, rain charged with negative electricity would be likely to occur. The frequency with which negative electricity was observed by ELSTER and GEITEL with rain associated with distant thunderstorms might be explained in this way.

If the ascending current keeps a considerable amount of the highly charged water in suspension, and the negative electricity is held in the cloud above, it is very probable that the main lightning discharges would take place from the accumulated water at the head of the ascending current to the charged cloud above. This would explain the observation that most lightning discharges pass within the thundercloud from base to summit.

Falls of hail are frequently associated with thunderstorms, and hailstones—as has already been pointed out—can only form if they are supported during formation by strong ascending currents. Further, the structure of a hailstone indicates that it is often carried up and down past the zero isothermal. Now, a current of air sufficiently strong just to support a hailstone as big as a pea would be more than sufficient to carry up the water it condenses within itself; hence, hailstones would always have a greater downward velocity relative to the ascending current than the water in the current, and there would be a large amount of splashing between the two. There would be, consequently, a much greater amount of separation of electricity than would have taken place without the hailstones, and this might very well account for the great violence of the electrical discharges in hail-storms.

The observations made by Mr. CLAYDEN* on the formation of thunderclouds seem to me to be in entire agreement with the general disposition of air currents required for the theory here proposed.

The present discussion is confined to the electrical phenomena of thunderstorms, as I have not yet collected data which are sufficient to allow me to decide whether in steady rain such as accompanies ordinary depression, positive or negative electricity predominates. It is quite conceivable that the charge brought down under such conditions is due to causes entirely different from those which produce the excessive electrical separation in thunderstorms. For similar reasons the electrical phenomena connected with snowstorms have not been considered. Until all these effects have been studied it is not possible to discuss the bearing of my observations on the general problem of atmospheric electricity.

The investigation of vertical air currents during a thunderstorm would have an

* *Loc. cit.*, pp. 109, 110.

important bearing on the questions discussed in this paper. A simple method might be based on a comparison of the rates of ascent of balloons during normal weather and during thunderstorms. The retardation due to the water attaching itself to the balloon would have to be estimated, but in spite of the uncertainty arising from this cause, valuable information would probably be obtained by a systematic series of observations.

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