The electric charge on rain and the "breaking drop" theory of its origin

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THE ELECTRIC CHARGE ON RAIN
AND THE " BREAKING DROP " THEORY OF ITS ORIGIN

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INTRODUCTION.

INTRODUCTION.

The present essay, giving a detailed account of only a small branch of the subject of Atmospheric Electricity, has been written after a general study of the whole subject. The sources used in this general survey are given in the bibliography; detailed references are quoted in the text.

Most of the work here described has been done during the Twentieth Century, but it will not be out of place, perhaps, to give at this juncture a brief historical account of the development of the subject.

Historically our knowledge of Atmospheric Electricity can be divided into three well-marked periods. (i)

The first of these periods opens with the suggestion made by a number of philosphers between 1735 and 1750, that the phenomenon of lightning is nothing more than an exhibition on a large scale of the sparks which were then being drawn from the primitive electrical machines of the time.(ii). An Englishman, Stephen Gray, seems to have been the first to make this suggestion in 1735, but it was Franklin (iii), who forced the idea on the attention of men of science. Dalibard,(iv), by his experiments at Marly-la-Ville in France, in May 1752, and Franklin in the same year, were the first to show by actual experiment that electricity can be drawn from the clouds during thunderstorms.

(i) Compare.. A.B.Chauveau.. " Électricité Atmosphérique " Vol. 1.
(ii) S. Gray.. Letter to Mortimer, March 1735.
l'Abbe Nollet... " Leçons de Physique " Vol 4, p 314.
Hales.."Considérations sur la cause physique des tremblements de terre ".
Barberet.. " Dissertation sur le rapport qui se trouve entre le phénomène du tonnerre et ceux de l'électricité" 1750. ~~1750~~
(iii) Franklin.. Letters to Collinson, member of Royal Society.
(iv) Dalibard Letter to l'Académie des Sciences, May 13, 1752.

Beginning in this successful way, the period extended for a hundred years, during which it was shown that the atmosphere is electrified not only during thunderstorms but also during fine weather, even when there is not a cloud in the sky. It was in the same year (1752), that Lemonnier (i) observed the electrification of the atmosphere in fine weather, and his observations were verified and carried further by the work of Beccaria, de Saussure and others. Numerous experiments were made, chiefly by exposure of insulated conductors to the atmosphere and observance of their electrical state by means of crude electroscopes, generally of the pith-ball type. It was found that the electrification of the air undergoes a regular daily and yearly variation, and that the state of the weather plays a predominating part in determining the electrical state of the atmosphere. The results were, however, very vague and as the observations were almost entirely qualitative, it was impossible to formulate any clear ideas or even to describe the results in any coherent way.

During the latter half of this period, that is, during the first half of the nineteenth century, little progress was made and observations gave place to speculative theory. Erman (ii) suggested in 1803 the idea of a negatively charged earth in order to explain the then known phenomena. This was further developed about forty years later by Peltier (iii), but the state of electrical theory at the time was such that the importance of this idea was not realised. During this same period also, Pouillet (iv) tried to develop a theory originally due to Volta (v), which suggested that the electrification of the air was due to a separation of electricity

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(i) Lemonnier..="Observations sur l'électricité de l'Air".
Mémoires de l'Acad.d.Sc. 1752, p 233.
(ii) Erman... Journal de Physique, 59, pp95 to 105, (1804)
(iii) Peltier... Ann.de Ch. et Phys. 3, vol 4, p 129, (1842).
(iv) Pouillet.. " " " " " 2, " 35, p 401, (1827)
(v) Volta... = " Lettres sur la météorologie électrique
(Op de V. 1 part 2)

on the evaporation of water over the earth's surface. This theory has since been proved untenable.

The decline of interest in Atmospheric Electricity coincided with the period in which the foundations of the modern mathematical theory of electricity were being laid on the classical work of Coulomb and Faraday. Amongst the pioneers of this new study of electricity was William Thomson, afterwards Lord Kelvin.

Thomson's interest in Atmospheric Electricity appears to have been aroused by his mathematical study of electrostatics. On May 18, 1860, he gave a Friday evening discourse at the Royal Institution on " Atmospheric Electricity ", and with that lecture the second period of the history of Atmospheric Electricity opens. Thomson showed what the previous observations signified when expressed in terms of electrical charge on the ground and in the air. But, more important still, he introduced the idea of the electrical potential of a point in the air and showed how it could be measured and even recorded. For this purpose he invented his celebrated water-dropper, and the development of his three electrometers, the quadrant, the absolute, and the portable was largely due to his interest in the measurement of Atmospheric Electricity. Electrical potential gradient in the atmosphere now became recognised as an important meteorological factor, a factor with a physical meaning and one which could be recorded continuously. In 1861 the first self-recording electrometer was installed under Thomson's direction at Kew, and this started the longest series of measurements of Atmospheric Electricity in existance.

Thomson showed (as had previously been pointed out by Erman and Peltier) that the direction of the fine weather field shows that the earth carries a negative charge and the upper layers of the air, a positive one. The state of affairs close to a flat portion of the earth can thus be expressed in three ways :-

(a) the earth carries a negative charge of surface density σ per unit area;

(b) there is a vertical field of strength $F = 4\pi\sigma$, just above the ground;

(c) between two horizontal planes close to the ground there is a potential difference of $dV = V_{h+dh} - V_h = -F\,dh = -4\pi\sigma\,dh$, where $h+dh$ and h are the heights of the planes.

The quantity dV/dh is called the potential gradient and is positive, since σ is found to be negative. For the same reason, the field is directed downwards, and this downward direction direction is by convention adopted as the positive direction for electric fields in the atmosphere. In these definitions it is assumed that the portion of the ground considered is flat and far removed from projections, such as trees and buildings, which would disturb the distribution of charge and concentrate the lines of force at certain points.

The average value of the fine-weather potential gradient is about 100 volts per metre; the corresponding value for the average charge density is 2.7×10^{-4} electrostatic units per square centimetre, or 0.0009 coulomb per square kilometre. The total fine-weather charge on the earth is of the order of 500000 coulombs.

For the next forty years after the impulse given by Thomson (1), work on atmospheric electricity consisted almost entirely of measurements of the potential gradient in all parts of the world, from north polar to south polar regions and from sea level to the tops of the highest mountains. The whole of this work was dominated by Thomson's mathematical theory and by Thomson's methods. It was carried out by eminent scientists in all parts of the world, amongst whom we may mention Exner, Elster and Geitel, and Benndorf in Germany; and Brillouin and Lenard in France.

During this period also, some observations were made on an entirely

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(1) W. Thomson.... Reprints of papers on electrostatics.

different aspect of the problem ..... electrical conduction in the atmosphere. Coulomb had shown in 1785 that a metallic conductor, placed in air, gradually lost its charge in a manner to be ascribed not only to faulty insulation, but also to some extent, to the conduction of electricity away from the body into the air. Few workers however took up the investigation of this " dissipation of charge ", and the false idea that damp air conducts electricity better than dry air persisted for a whole century, in spite of the researches of Matteucci(i) and Warburg(ii).

In 1877, Linns(iii) showed that the loss of charge was greatest during fine weather, i.e. when the air was dry; he found also, that the loss in a given time varied in a regular manner with the season of the year.

In the light of what was then known of the conduction of electricity through gases, no satisfactory explanation of the dissipation of electrical charges was forthcoming.

We may say, then, that during this period, although our knowledge of the electrical field of the earth's atmosphere was greatly extended, little advance was made in our knowledge of the causes of the electrification. At the end of the nineteenth century the study of atmospheric electricity was again at a low ebb.

This period of lethargy was broken and the third period introduced by the discovery, during 1900 and 1901, of radioactivity and of the existence of ions in the atmosphere. These discoveries led to renewed interest in atmospheric electricity, and to the most rapid period of growth in our knowledge of the electricity of the atmosphere since the study commenced in the middle of the eighteenth century.

It was learnt that the conductivity of all gases might be increased artificially to an enormous extent by the action of Rontgen and

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(i) Matteucci... Ann.Chim.Phys.(3),27,p133(1849); 28, p385 (1850).
(ii) Warburg.. Pogg.Ann. 145, p 578, (1850).
(iii) Linns ... Meteorol.Zeitschr. 4, p 345(1887)
Elektrot. " 11, p 506(1890)

Bequerel rays, and from this fact emerged the theory of ionic conduction in gases. In the light of this theory, gases, just as electrolytes, contain positively and negatively charged particles, (e.g. atoms, molecules or molecular groups), which move under the influence of an electric field in a direction determined by the sign of their charge; these particles are called gas ions. The application of the theory of gas ions to the facts of electrical conduction in atmospheric air is due to the work of Elster and Geitel(1) in Germany, and C. T. R. Wilson in England, who succeeded in offering a satisfactory explanation of the processes responsible for the dissipation of electric charge.

In general, in air at atmospheric pressure, two main classes of ions may be distinguished; the small or mobile ions having a mobility of 1 to 2 cm/sec/volt/cm. in dust free air, and the large or slow ions with mobilities 0.01 to 0.0005 cm/sec/volt/cm. The number of these ions per cc. of air varies considerably. Over land areas the large ions considerably outnumber the small ones, while over the oceans this state of affairs is reversed.

A simple relation holds between the conductivity of the air ~~and~~ and the numbers per cc. and the mobilities of the ions responsible for conduction. Consider a point in the atmosphere at which the electric field intensity is F and the specific conductivity, the reciprocal of the specific resistance, is λ . The conduction current, i , through unit area drawn perpendicular to the field is then equal to $F\lambda$, for F is numerically equal to the potential difference, and $1/\lambda$ is the resistance between the ends of a unit cube of the air. In this equation we assume that conditions are such that Ohm's Law can be applied to the air. Since the current is carried by positive and negative streams of ions moving in opposite directions, we may write $i = F(\lambda_+ + \lambda_-)$, where λ_+ and λ_- are called the polar conductivities.

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(1) Elster and Geitel... Phys.Zeits. 1, pp 11 - 245. (1899)

In the ordinary fine-weather field positive ions are driven towards the earth and negative ions away from it; the motion of these ions constitutes a downwardly directed conduction current the value of which is given in the equation above.

There is, however, a fine-weather current of a different nature which plays a part in the transfer of electricity by the atmosphere. If the air should contain, at any point, an excess of ions of one sign,(a space charge), movement due to wind or ordinary turbulence will give rise to a mechanical transference of electric charge. Thus if v is the upward vertical component of the velocity of the air and ρ the space-charge per cc., the upward convection current due to this cause will be $v\rho$ per square centimetre. The real current density in fine weather is thus the resultant of the downward conduction and the upward convection currents, and is given by

$$I = i - v\rho$$

The mean value of this total fine-weather current is not far from 2×10^{-16} amperes per square centimetre or 2 microamperes per square kilometre, so that the total current flowing in this way between the upper atmosphere and the whole earth is about 1,000 amperes.

We may regard the negatively charged earth and the positively charged upper layers of the atmosphere as forming two plates of a condenser with the lower air as the dielectric. Although the conductivity of the air between the plates is small, the applied potential difference is great enough to make the leakage of charge through it very considerable. The average value of the charge per unit area of the earth's surface is 9×10^{-14} coulombs per square centimetre, and that of the fine-weather conduction current is 2×10^{-16} amperes per square centimetre. Left to itself a condenser of this kind would be discharged by internal leakage in a time of the order of ten minutes.

But, in spite of the continuous operation of this leakage, the earth's charge remains practically constant. The fact that the electric field persists, proves that some compensating processes exist, and that, on the whole, the electric field is being regenerated as fast as it is being destroyed. Unless we assume an actual creation of negative electricity or destruction of positive electricity within the earth(1), the total air-earth current over the whole surface of the earth must on the average be zero, i.e. the downward flow of positive electricity from the air to the earth, which takes place under the action of the normal electric field of fine weather, is exactly balanced (if we take the average over any considerable time) by currents, not necessarily conduction currents, in the opposite direction.

The most important of such currents which may possibly be effective are (a) convection currents of charged air, (b) convection currents carried by negatively charged rain or other precipitation, (c) upward conduction currents in regions where the potential gradient is negative, and (d) currents carried by corpuscular radiations.

It is with the possibility (b) that we are here concerned.

It had been suspected for a long time - without very clear experimental proof owing to the difficulties of measurement - that rain, whether of thunderstorm origin or not, was generally charged. Under the influence of the ideas of Peltier and Exner, who supposed the water-vapour emanating from the surface of the earth to be negatively charged like the surface of the earth itself; there naturally arose the idea of considering rain as the vehicle of the return of the negative charge dissipated from the earth, and therefore as the principal agent in the regeneration of the earth's charge. On this theory the electric charge brought down by rain should, on the whole, be negative.

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(1) G.C.Simpson... Monthly Weather Review, 44, p 115, (1916).

With this point of view in mind, the first experimental determination of the electric charge on rain was undertaken by Elster and Geitel, at Wolfenbüttel, in 1888.

As we shall show in what follows, observations at various places in Europe, and in India, have disproved Peltier's idea that rain on the whole brings down a negative charge to the earth. Consequently, the value of the suggestion contained in (b) above, is now very much discounted.

Following upon actual determinations of the electrification of rain, there naturally arose the question of the origin of the electrification observed.

There have been several theories to account for this electrification, one of which is discussed in detail here. This aspect of the problem has given measurements of the electric charge on rain a new importance, as it leads to the question of the mechanism of thunderstorms; which, in its turn, brings us back, in the light of recent research, to the fundamental problem of the maintenance of the earth's negative charge.

In the following pages the experimental determination of the electric charge on rain is discussed in full, and then the " Breaking-Drop " theory of its origin, with the evidence upon which it is based.

It may be said that this theory has many things in its favour, but that there has, of late, been much evidence brought forward against it. In the conclusion therefore, we discuss briefly the alternative theories in the light of the most modern research, and sum up the present position.

THE EXPERIMENTAL DETERMINATION OF THE ELECTRIC CHARGE ON RAIN.

1. A. EARLY EXPERIMENTS.

Elster and Geitel.

The first experiments undertaken with a view to measuring the electricity of rain were performed by the two German physicists Elster and Geitel (1), at Wolfenbuttel, Brunswick, in 1888.

In essentials their apparatus consisted of a well insulated zinc vessel connected to a quadrant electrometer. The vessel was exposed to the rain for times varying from 5 seconds to 2 minutes (depending on the intensity of the effect); the opening was then closed and the electrometer deflection noted. From the Capacity of the system and the Potential observed (allowing for insulation losses), the quantity of electricity brought down could be calculated.

Elster and Geitel realised clearly the precautions necessary in making the experiments. Apart from the necessity for effective insulation of the vessel and the electrometer, there were two other possible sources of error. The whole of the receiving and recording apparatus had to be protected from the influence of the earth's field, and to ensure this the apparatus was surrounded by an earthed metal cage about 2metres high. Also, owing to the existence of fairly high potential-gradients of variable sign under shower conditions, it was possible that drops splashing from surfaces exposed to the earth's field could bring relatively large charges of variable sign into the receiver. To guard against this the receiving vessel was placed inside another metal vessel, the edge of which was 2 or 3 decimetres

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Elster and Geitel.... Met. Zeits. 5, p 75, (1888) ....(1)
" " " (Wien. Ber. 94, p 241, (1890)
later work..... (Terr. Mag. 4, p 15, (1899).

above the upper edge of the former.

Elster and Geitel's observations were on rain and snow during 1888 and 1889 but were not very extensive, and could afford but uncertain indication of the effects of the total rain during ~~the~~ a whole year. They were almost exclusively concerned with the sign of the charge brought down and furnished evidence of the relative frequency of the rain with positive and negative charges. The measurements gave little indication of the magnitudes of the charges, and, in addition, they did not include any observations on the quantities of water concerned.

For both rain and snow the occurrence of negative charges was ~~f~~ found to be more frequent, and from their observations Elster and Geitel concluded that there was a real predominance of negative charge brought down by rain.

At the beginning and end of each observation of charge the potential gradient was recorded, and an attempt was made to find some connection between the variations in sign of the rain and the variations in potential gradient. The results showed, in general, that the occurrence of negative rain was associated with an increase in the normal field, and the occurrence of positive rain with a diminishing field which in some cases actually became negative. This effect was explained as being due to local changes in the surface density of the earth's charge, resulting from the charges carried by the rain.

Gerdien.

In 1901 the Royal Society of Sciences at Gottingen decided to authorise investigations of rainfall electricity to be carried out. Preliminaries were begun in January 1902 with the erection of a special observation hut on the site of the new Geophysical Institute which was then being built, and soon afterwards the work was commenced by Gerdien.

The first observations were carried out in essentials according to the method of Elster and Geitel, but " it soon appeared that it is certainly impossible for a single observer to follow simultaneously the quickly varying course of rainfall electricity and potential gradient and then to turn his attention in an adequate degree to meteorological phenomena". For these reasons and because, in addition, he wished to measure the mass of rainfall, Gerdien devised a photographic method of registration of the three quantities.

In his published papers (1), Gerdien gives an account of the methods he used to secure the simultaneous registration of the potential gradient, the charge brought down by the rain and the mass of the rain, but, unfortunately, in none of these does he give any actual observations of these quantities. After describing carefully how he measured the charge by connecting the receiving vessel to the needle of the electrometer and allowing it to leak away to earth through a known high resistance; how he used a household balance with a decimal scale to provide a means of measuring the mass of the rain; how he arranged for a clock to mark out each minute on the photographic record, Gerdien merely gives a general account of his results confirming, more or less, those of the two earlier investigators.

He differentiates between three types of rainfall with reference to their electric peculiarities ... (a) Landregen... ordinary steady rain, (b) Boenregen... squall rain, and (c) Gewitterregen..... thunderstorm rain.

The " Land-rain " he found was generally accompanied by a negative potential gradient which in some cases increased to 1,000 to

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(1) Gerdien.. Registrierung der Niederschlags-Elektrizitat im Gottingen Geophysikalischen Institut..Separat Abdruck aus den Sitzungsberichten der math.-phys. Klasse der Kgl.Bayer Akademie der Wissenschaften. Bd. 33, Vol 2, 1903.
~~and~~ and .... Phys. Zeit. 4, p 837, 1903.

2,000 volts per metre. The sign of the charge carried by the rain varied, but in general the negative predominated. In some cases the rain brought down no charge but on the whole, the charge brought down was equivalent to a current of something less than 10^{-14} amperes per square centimetre.

With the "squall rain", on the other hand, he found that the sign of the potential gradient and of the charge on the rain suffered rapid variation. The potential gradient rose to values from 4,000 to 6,000 volts per metre and the current density was roughly 10^{-13} amperes per square centimetre. Again the sign of the charge on the rain was more often ~~positive~~ negative than positive.

As one might naturally expect both the field and the current density were large during thunderstorm rain - the former reaching values of 10,000 volts per metre and the latter of 10^{-12} amperes per square centimetre. For these storms Gerdien noted the rapid destruction and recovery of the field, and once more he found the negative charge predominating.

The rough values above are the only figures that Gerdien gives in his papers, and nothing at all is said of the charge per cubic centimetre of rain which, presumably, he could have found from his measurements of the mass of the rain.

Like the experiments of Elster and Geitel those of Gerdien only lasted for a short period (not precisely stated), and they indicated a marked preponderance of negative rain. He gave an explanation of the results based on the experiments of C.T.R. Wilson, (1), on the condensation of water vapour on ions during the adiabatic expansion of a volume of air supersaturated with moisture.

For the purpose of this explanation, Gerdien supposes the atmosphere to have been swept previously by rain and to contain

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(1) C. T. R. Wilson.... Phil. Trans. 1897.

nothing but ions of both signs, and considers an ascending current of air similar to those which produce the cumulus clouds of summer. The cooling of the enormous mass of air is adiabatic owing to the difficulty of exchanges of heat taking place. As there is no dust, condensation cannot take place until fourfold supersaturation is attained, and when this is the case, the water vapour condenses on the negative ions.

While the negative drops grow and remain on the ascending current, the positive ions continue to be carried upwards. Owing to the accumulation of negative drops, an electric field begins to be created, capable of attracting the positive ions in a sense opposite to the ascending current. According to the known mobilities of the ions and of the velocities of the ascending currents, it seems reasonable to suppose that the positive ions are carried upwards to such a height that sixfold supersaturation is attained; in which case the water vapour condenses upon them and they lose their mobilities as ions.

If then these two supersaturations are produced in the course of the same shower, one ought to find the rain initially charged negatively. As it is probable that the expansion of the mass of air produces fourfold supersaturation more often than sixfold, one ought to find at the surface of the earth a preponderance of negative rains.

Unfortunately for this theory, it is not proved that a mass of atmospheric air can be supersaturated. (1)

Weiss.

In January 1906, a new series of researches was begun by E. Weiss at Vienna, and although they only lasted for four months they are worthy of notice because of the method employed and the results obtained.

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(1) Baldit.. Ann.Soc.Met. de France, 59, April 1911.

It was with regard to eliminating sources of inaccuracy that the method of Weiss differed particularly from those so far described. He believed that with the Elster and Geitel system it was not impossible that drops should fall from the protecting cover into the actual receiving vessel. Instead of the vessel he took an insulated brush, exposed it in the open to the rain for a specified length of time, and afterwards connected the brush with the electrometer at a place protected from the earth's field. With the measurements of shower electricity thus carried out, he joined observations on the variation of the potential gradient (as did the majority of investigators), as well as on the number and size of the raindrops.

The mean intensity of the rain during an exposure of the brush was found by a method devised by Defant, whereby the rain was received for several seconds on a filter paper lightly dusted with eosin and alum. The drops of water left red stains, and from the number and diameter of these it was possible, with the aid of tables prepared by Defant, to estimate the corresponding quantity of rain.

Weiss' results (i) differed entirely from those of the earlier investigators, in that he found that there was an excess of positive charge brought down by the rain. He gave also the order of magnitude of the charge per cubic centimetre of water as 1 e.s.u. per cc.

The procedure in these experiments suffered from the disadvantage that the charge on the brush arose not only from showers but also from the vertical conduction current. With strong fields a charge could be indicated by the electrometer, even in the absence of rain. Moreover it has been shown that there is the possibility of a " point-effect ", whereby the brush can work with a compensatory effect like a very weak radioactive " collector " and so gradually take on the potential of its surroundings.

(i) Weiss... Wien. Ber. 115, p 1285, 1906.

Kohlrausch (i), realised some of these drawbacks, and repeated the experiments in Puerto Rico, in 1909. He protected the brush from the earth's field by placing it in a box, the punctured roof of which was covered with coco-nut matting. His results in the main agreed with those of Weiss.

None of Weiss' observations were on thunderstorm rain, and for some time they were not accepted, especially as they contradicted the work of such famous physicists as Elster and Geitel on the one hand, and Gerdien on the other, whose results were favourable to a simple explanation of the persistence of the earth's negative charge. For some time, therefore, the question remained in abeyance, until it was taken up again by Kahler at Potsdam, in 1908. (ii)

Kahler

The work of this investigator was begun at the Observatory, Potsdam, early in 1908 and continued for the whole of that year. The method of registration followed that of Elster and Geitel, and Gerdien.

The showers were allowed to fall into a zinc vessel, 30 cm. in diameter and 10 cm. high, set up under the roof (about 2 metres above the ground) of a corrugated iron hut erected in the Observatory field for observations on atmospheric electricity. The reception vessel was surrounded by a zinc cone, also with an aperture of 30 cm., which rose only a little above the roof of the hut. Round about this cone, on the roof, was erected a wire netting cage, open at the top, which was 120 cm. vertically and 85 cm. horizontally from the middle of the aperture. In this way the drops which touched the upper edge of the wire netting at an angle of less than 30 degrees, could not get into the cone and hence into the receiver.

(i) Kohlrausch... Wien. Ber. 118, Abh.2, p 25 - 69, 1909.
(ii) Kahler..... Pub. of Met. Institut. of Prussia, 213, 1909.
Le Radium, 7, p 338, 1910.

The receiving vessel was connected to the needle of a Benndorf electrometer which had been rendered more sensitive by bringing the two suspension threads close together. The electrometer was arranged to record its results by a series of dots on a piece of paper on which intervals of one minute could also be marked. In addition to the usual precautions, Kahler tried to ensure that the sensitivity of the electrometer needle remained constant during the experiments. He noted also the possibility of the " Lenard Effect " introducing spurious charges into the receiver, but he seemed to think that a correction for this effect was not necessary.

The results for the whole of the year 1908 showed a definite preponderance of positive charge on all types of rain. " The total surplus of rainfall electricity at Potsdam in 1908 was $+ 57 \times 10^{-11}$ Coulombs per square centimetre, corresponding to a current density of 1.7×10^{-13} amperes per square centimetre for the space of one hour(1)"

As far as the magnitudes of the current density were concerned the results agreed in the main with those of Gerdien. For ordinary rain Kahler obtained the values 10^{-16} to 10^{-15} amp/sq.cm., rising on rare occasions to 10^{-14} amp/sq.cm. For squalls and thunderstorms the corresponding values were 10^{-14} to 10^{-13} amp/sq.cm.

In the case of thunderstorm rain, the actual value of the charge on the rain was found to vary between 5 and 10 e.s.u. per cc., rising on exceptional occasions to as much as 20 e.s.u. per cc.

Simultaneous measurements of the intensity of the rain showed that, on the whole, there was no definite connection between the quantity of charge brought down and the intensity of the rain. Also, between the potential gradient and the sign of the charge on the rain there existed no simple relation. Often the potential gradient was found to vary considerably in sign, while the sign of the charge on the rain remained constant.

One great merit of Kahler's work as compared with that of the

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(1) Kahler... loc. cit. 1909, p 16.

earlier observers is that his observations lasted for a whole year whilst theirs were only for very short periods. His results may therefore be considered as favourable confirmation of the results of Weiss, relating to the question of the predominant sign of the charges brought down by rain.

1.

B. THE EXPERIMENTS OF G. C. SIMPSON.

It cannot be said that the observations so far described furnish very definite evidence on the question of the sign of the electric charge on rain. As we have seen the results are discordant, and, in addition, although all the workers described their experiments very carefully (but in no case gave a diagram of the apparatus used), it is difficult to assess the value of the observations; because, with the exception of Kahler, they do not give any of the figures or detailed information upon which they based their generalisations.

About the same time as Kahler was carrying out his experiments at Potsdam, G. C. Simpson, at Simla, in India, was engaged on the same problem. Simpson's experiments are among the most extensive that have ever been carried out in this branch of atmospheric electricity, and for that reason we describe them in detail here. (1).

Simpson's experimental arrangement is shown in Fig. 1.*

The apparatus, which was entirely self-registering and constantly in action whether there was any precipitation or not, was housed in a corrugated iron hut 8 feet square. Through a hole in the centre of the roof the rain fell into an insulated receiver AA, connected to a self-registering electrometer. To prevent the rain splashing into ~~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 inside the hut. To prevent 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 drained away through the pipe D. This rim reduced the effective opening through which the rain fell to a diameter of 29 cm.

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(1) G.C.Simpson... Phil. Trams. Roy. Soc. A, vol 209, pp 379-413. (1909)

* P. 135.

The receiver AA, immediately below the bottom of the cylinder, was a galvanised iron vessel 50.5 cm. in diameter and 31 cm. deep, with its bottom slightly rounded so that the water ran off through the pipe EE.

The potential of the receiver was recorded automatically every two minutes by the Benndorf self-registering electrometer G, registering as follows ..... To the needle of a quadrant electrometer a long Aluminium boom was attached and swung freely over a strip of paper 12 cm. wide, which was slowly moved forward by means of a clock. Every two minutes the clock closed a contact which actuated a magnet and caused a bar to press the end of the boom sharply into contact with the paper through a typewriter ribbon. In this way the paper received a number of dots each representing the position of the boom, i,e. the deflection of the needle, at each instant the circuit was closed. In order to mark the time a second circuit was closed each hour and a magnet was thus excited which caused two dots to be imprinted, one on each side of the paper exactly in line with the boom.

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 each two minute interval indicated the amount of deflection.

For the purpose of measuring the charge brought down by the rain an earthing device H, was used. This consisted of a light earth-connected wire by means of which 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 each dot on the paper indicated the charge which the receiver had obtained from the rain in 2 minutes.

The amount of the rainfall was recorded in the following way.... The end of the metal pipe EF, which drained the water from the receiver ended with 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 type, recording on a drum which revolved every 24 hours. The gauge was arranged so that it only recorded every 2 minutes, at the same time as the potential was recorded. Thus close correlation between the two records was obtained. There was one serious drawback to this method of measuring the rainfall. 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 not very satisfactory also at the beginning of a shower, for in this case, the first tip did not take place until considerably more than 0.014 cm of rain had fallen, owing to a certain amount of rain water being used up in wetting the receiver and the pipe through which the rain passed from the receiver to the gauge. After the first tip and when the rain was not very light the method worked very well.

In order to prevent the wind sweeping across the mouth of the cylinder PB, which would have interfered with the entrance of rain into the receiver, and to protect the mouth of the apparatus from the earth's electric field, the walls of the corrugated iron hut were carried about 2 metres above the roof.

A second Benndorf electrometer was arranged to record the potential gradient. As most of the experiments were carried out during thunderstorms, it was considered sufficient to record only the predominant sign of the potential gradient during each 2 minute interval, because of the difficulty of obtaining a satisfactory method of recording potential gradient under thunderstorm conditions. The bamboo rod MM, was used as a collector for this purpose.

A coherer device was arranged to give some indication as to whether the registrations were accompanied by many or few electrical discharges. The lamp shown in Fig. 1 was used to keep the apparatus dry.

The sensitivity of the electrometer was so arranged that when a charge of 7×10^{-4} e.s.u. fell on each square centimetre in 2 minutes, it was sufficient to be recorded. The accuracy of measurement of the charge per cc. of rain was 0.1 e.s.u. per cc., and all charges less than this were written as nil.

Simpson's observations lasted from April to September, 1908, and in his account of the experiments, he treats the rainstorms irrespective of whether they were accompanied by electrical discharges or not. In the following year he repeated the experiments under exactly the same conditions, and the results which we quote below are the average of the two series of measurements. These results we quote in full; they are taken from his second paper on the subject in the Proceedings of the Royal Society, 1910. (1)

TWO YEARS' DATA.

Table A.

Total quantity of rain investigated.....	172.1	cm.
Total quantity of + ve electricity which fell on each sq.cm. of surface...	44	e.s.u.
Total quantity of — ve electricity which fell on each sq.cm. of surface....	13.8	e.s.u.
Ratio of quantity of + ve electricity to quantity of — ve.....	3.2	

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(1) G. C. Simpson.... Proc. Roy. Soc. A, vol 83, pp 394-404 (1910)

Number of 2 minute intervals during which rain

+ vely charged..... 2994

— vely charged 1221

Ratio of number of intervals with + vely charged rain to number with — vely charged 2.5

Table B.

Current (i) 10^{-15} amp/sq.cm.	No. of 2 min. intervals during which current was		Ratio of number of + ve intervals to number of — ve.
	+	—	
2 - 50	2321	1033	2.2
50 - 100	363	114	3.2
100 - 150	149	35	4.3
150 - 200	55	8	6.9
200	90(84)	26(9)	3.5(9.4)(ii)

Note:- (i) When charged rain falls the effect is equivalent to a vertical electric current; with rain charged positively the current can be considered as going from the air to the earth, and with a negatively charged rain from the earth to the air.

(ii) The numbers in brackets are those obtained by omitting the results from an abnormal thunderstorm on May 13, 1908.

Table C.

Charge per cc. of rain. e.s.u.	Number of 2 min. intervals during which the charge was		Ratio of number of positive intervals to number of negative.
	+	—	
0.1 - 0.9	1953	686	2.8
1.0 - 1.9	252	122	2.1
2.0 - 2.9	108	53	2.0
3.0 - 3.9	60	27	1.6
4.0 - 4.9	24	15	
5.0 - 5.9	10	7	
6.0 & 6.0	15	21	

Table D.

Approx: rate of fall	Rain with no charge	Rain with +ve charge		Rain with −ve charge		Ratio of No. of +ve to No. of −ve 2 mins	Ratio of mean +ve charge/cc to mean −ve charge/cc
mm. in 2 mins.	No. of 2 mins.	No. of 2 mins	charge e.s.u. per cc.	No. of 2 mins	charge e.s.u. per cc.		
< 0.16	-	386	1.52	293	1.92	1.3	0.8
0.16	1112	818	0.74	420	0.87	1.9	0.8
0.38	300	509	0.40	159	0.41	3.2	1.0
0.60	44	231	0.21	50	0.33	4.6	0.6
0.82	4	126	0.19	13	0.15	9.7	1.3
1.04	0	104	0.24	10	0.11	10.4	2.2
1.26	0	63	0.26	7	0.13	9.0 } 14	2.0
1.48	1	63	0.26	2	0.10	31.5	2.6
1.70	0	27	0.28	1	0.10	27.0 } 20	2.8
> 1.70	0	74	0.21	4	0.05	18.5	4.2

Table E.

	Number of 2 minute intervals during which Potential Gradient was......		Percentage of occurrence of — ve. P. G.
	+ ve	— ve	
Rain uncharged	559	1298	70
Rain + ve.	871	1316	60
Rain — ve.	429	484	53
Total.....	1859	3098	

CONCLUSIONS.

(1) The electricity brought down by the rain was sometimes + ve and sometimes − ve. (Table A)

(2) The total quantity of + ve electricity brought down by the rain was 3.2 times greater than the total quantity of − ve electricity. (Table A)

(3) The period during which + vely charged rain fell was 2.5 times longer than the period during which − vely charged rain fell. (Table A)

(4) Treating charged rain as equivalent to a vertical current of electricity, the current densities were generally smaller than 4×10^{-15} amps/sq.cm.; but on a few occasions greater current densities were recorded(both + ve and − ve.) (Table B

(5) Negative currents occurred less frequently than positive currents, and the greater the current density the greater was the preponderance of positive currents. (Table B)

(6) The charge carried by the rain was generally less than 6 e.s.u. per cc. of water, but larger charges were occasionally recorded, and in one exceptional storm, on May 13, 1908, the negative charge exceeded 19 e.s.u. per cc. (Table C)

(7) As stated in (3) above, positive electricity was recorded more frequently than negative, but the excess was less marked the higher the charge on the rain. (Table C)

(8) With all rates of rainfall, positively charged rain occurred more often than negatively charged rain, and the relative frequency of positively charged rain increased rapidly with increased rate of rainfall. With rainfall of less than about 1 mm. in 2 minutes, positively charged rain occurred twice as often as negatively charged rain, while with greater intensities it occurred fourteen times as often. (Table D)

(9) When the rain was falling at a less rate than about 0.6 mm. in two minutes, the charge per cc. of water decreased as the intensity of the rain increased. (Table D.)

(10) With rainfall of greater intensity than about 0.6 mm. in two minutes; the positive charge carried per cc. of water was independent of the rate of rainfall, while the negative charge carried decreased as the rate of rainfall increased. (Table D)

(11) During periods of rainfall the potential gradient was more often negative than positive, but there were no clear indications of a relationship between the sign of the charge on the rain and the sign of the potential gradient.

(12) The data do not suggest that negative electricity occurs more frequently during any one particular period of a storm.

In his experiments Simpson definitely considered the possibility of the " Lenard Effect " introducing a source of error. Lenard showed (1) that when a drop of pure water fell on a surface and splashed, a separation of electricity took place, the water retaining a positive charge and the air taking 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 Simpson made the receiver A 31 cm. deep. With such a vessel the Lenard effect could not play any appreciable part.

Again, Simpson's results were a good test, for they showed positive charges which could not be given to water by a single splashing under the most favourable conditions in a laboratory.

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(1) Lenard... Wied. Annal. vol 46, pp 584 - 636, (1892)

Lenard found that when a stream of water, in small drops 2 mm in diameter, impinged on a metal plate with a velocity of 18 metres a second, (and great care was taken to obtain complete separation of electricity by artificial ventilation), each drop developed 0.2×10^{-12} coulomb of electricity; i.e. each cc. of water developed 0.15 e.s.u. It therefore appeared 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 charge as 0.1 e.s u. per cc. could be given to the rain by the Lenard effect. But Simpson took a charge of 0.1 e.s.u per cc. as the limit of accuracy of the electrical measurements, hence he concluded that the results were not materially affected by the Lenard effect.

We have described the experiments of Simpson in this detail because of their importance, and also because they will serve as a very useful basis on which to discuss the general implications of all the work that has been done on this subject.

In addition to being very definite on the question of the predominating sign of the electric charge on rain, Simpson's results showed that, " there can be no possible doubt that the rain connected with thunderstorms was more highly charged than rains with which were associated few lightning discharges or none at all." (1)

We must bear in mind in what follows that for the most part Simpson's observations were confined to rain of the thunderstorm type.

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(1) G. C. Simpson... loc. cit. 1909, p 390.

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C. THE EXPERIMENTS OF SCHINDELHAUER AND BALDIT.

The results obtained by Simpson in India seemed to arouse great interest in Europe, for there naturally arose the question as to whether the same general results would hold good for rains in more temperate latitudes, where thunderstorm conditions did not occur so frequently. Several physicists took up the problem on the Continent, among whom we may mention particularly Schindelhauer, at Potsdam, and Baldit, at Puy-en-Velay, in France.

Schindelhauer.

Schindelhauer's experiments (1) were begun under the direction of Kahler and the method used was essentially the same as that used by Kahler himself in the earlier observations of 1908. This work was much more complete than the previous series, as the observations were made on the rains of 1909, 1910 and 1911. It confirmed in a general way the results of Kahler and also the essential differences, as observed by Kahler, between the electrification of the rains at Potsdam and those at Simla.

We quote the more important of Schindelhauer's conclusions below:-

(1) 45% of the 1719 mm. of rain received was charged.

(2) Positive rains were more frequent than negative, in the ratio 2.2...... this agrees well with Simpson's value 2.5.

(3) The ratio of the quantity of positive electricity to the quantity of negative was 1.4... much less than Simpson's 3.2.

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(1) F. Schindelhauer.... Abh. d. K. Pr. Met. Inst. No. 263, 1913.

(4) The excess of positive electricity for the three years is only 4.93 e.s.u./ sq.cm..... this is much less than Kahler's value and is only one-sixth of Simpson's, for an equivalent quantity of rain.

(5) There was a variation in the electrification of the rain with the season of the year.

i. Proportion of rain charged, a minimum in Spring(38%), and fairly constant for the rest of the year.

ii. Relative frequency of positive rain a maximum in Winter (3.3)

iii. Ratio of quantities of positive and negative electricity varies also, minimum in Spring, and maximum in Winter.
e.g. Spring 1.01; Summer 1.16; Autumn 1.62; Winter 2.42.

iv. The mean charge per cc. of rain was least in Summer and Autumn, and greatest in Winter.

.... This seasonal variation had not been observed before.

(6) For the different types of rain...

i. Ordinary rains..	Current density 1 to 5×10^{-15} amp/sq.cm.Positive. Charge per cc. small, about 0.4 e.s.u./cc.
ii. Squall rains...	Strong current density, generally negative. Charge per cc.... 2 to 3 e.s.u./cc.
iii. Thunderstorm rain....	Strong current density, amounts of positive and negative approximately equal in magnitude and duration. Mean charge per cc... 2 to 3 e.s.u./cc.

(7) The charge per cc. of rain increased when the intensity of the rain decreased, the largest charges being generally carried by rains of feeble intensity.

(8) For the same intensity of precipitation, the negative charge per cc. was always larger than the positive charge, but the diffenence decreased as the intensity of the rain increased.

Qualitatively at least, these results seem to agree with those of Simpson in showing, but less strongly, an excess of positive charge brought down by the rain. Schindelhauer, however, was of the opinion that on the whole the net amount of electricity brought down by rain was zero,(i), a conclusion based, presumably, on (6) above.

Baldit.

Baldit's observations on the electricity of rain at Puy in the Summer and Autumn of 1910,(ii), by means of a direct reading electrometer, confirmed the principal results of Simpson and Kahler. He noticed in the course of these observations that both the sign and the magnitude of the charge on the rain varied rapidly, even during the course of a very short interval. He was thus led to criticise Simpson's method of registration from this point of view, and came to the conclusion that the latter's " Two-minute intervals " were too long. At the suggestion of A. B. Chauveau(iii) he therefore began a new series of measurements in 1911, in which the " time-interval " was reduced to 15 seconds. The second series of measurements (iv) lasted from May 16 to December 22, 1911.

The final arrangement of the apparatus is shown in fig 2.*

The electrometer used was a specially designed Gerdien electrometer, the needle of which, very light and well damped, followed exactly, as far as Baldit could tell, the least variation

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(i) Schindelhauer... Phys. Zeit. (1913), p 1292.
(ii) A. Baldit... " Observations sur l'électricité de la pluie pendant l'été 1910 au Puy-en-Velay". Ann.de la Soc. Met. de France 59th year April-May, 1911
(iii) A.B.Chauveau...Le radium, vol 8, April 1911.
(iv) Baldit.." Nouvelles observations sur les charges électriques de la pluie en 1911"...Le Radium,vol 9, March 1912.

* P. 135

in the electric charge of the rain. The needle was suspended by a metallic torsion-fibre connected to a strong copper rod which passed through an amber cylinder, and was connected to the receptacle in which the rain was received. A small light, placed 18 cm. from the electrometer, allowed the reading of the divisions of a graduated scale reflected by the moving mirror of the electrometer.

In the diagram the parts of the apparatus indicated are...

E.. electrometer. f... metallic torsion-fibre.

D... socket serving to fix the rain receiver V.

A movable cover C, turning on a vertical axis, and worked from the inside of the hut, served to stop the arrival of the rain during a measurement.

The method of observation was as follows:- The cover being in place and the receiver earthed, the equilibrium position of the needle was noted; the cover was then removed and the deflection of the needle observed every 15 seconds. When the deflection became too large, the apparatus was earthed by a special key and the observations recommended. Throughout his experiments Baldit made rigorous tests of the insulation and the rate of leakage of charge.

The actual charge carried by the rain was calculated from the observations in the following way...

If

ΔV	was the variation in volts of the potential of the apparatus in an interval of time t seconds, under the influence of the electric charges carried by the rain.
δv	the number of volts representing the natural leak of the apparatus in the same time t.
C	the capacity of the apparatus in e.s.u.
M	the height of the water in centimetres which represented the fall of rain in one second
S	the surface limited by the "rain-meter", in square cms.

Then the electric charge carried by the rain in 1 second, per square centimetre of the earth's surface (supposed horizontal), was given by

$$i = \frac{(\Delta V + \delta v)\, C}{300 \cdot t \cdot S} \quad \text{in electrostatic units.}$$

The electric charge per cc. of the rain was found by dividing this last expression by M .

The registration of the rain was made by a separate " rain-meter " placed beside the electrometer hut, with its rim at the same height above the ground as the rim of the receiving apparatus.

Baldit was satisfied that the " Lenard Effect " would not introduce an error within the limits of accuracy of his apparatus.

For the purposes of comparison we have arranged Baldit's results in tables corresponding as nearly as possible to those of Simpson.(i)

Table A.

Total quantity of + ve electricity which fell on each sq.cm. of surface...	7.52 e.s.u.
Total quantity of — ve electricity which fell on each sq.cm. of surface...	5.51 e.s.u.
Ratio of quantity of + ve electricity to quantity of — ve.......	1.36.
No. of 15 second intervals during which rain....	
+ vely charged... ...	8400
— vely charged......	2936
Ratio of number of intervals with + vely charged rain to the number with — vely charged.......	2.86

Table B.

Current. 10^{-15} amp/sq.cm.	Number of 15 second intervals during which the current was		Ratio of number of + ve intervals to number of — ve.
	+	—	
0.1 - 10	6149	1143	5.4
10 - 100	1980	1526	1.3
100 - 200	146	201	0.7
200 - 300	64	50	1.3
300 - 400	33	10	3.3
400 - 500	16	4	4.0
> 500	12	4	3.0

(i) Compare Tables A, B and D, pages....23, 24, 25.

Table D.

Approx: rate of fall. mm. in 2 mins.	Number of 15 second intervals during which rain was...		Ratio of number of + ve intervals to number of — ve.
	+	—	
< 0.04	3436	1048	3.3
0.04 - 0.08	1968	536	3.7
0.08 - 0.12	1384	604	2.3
0.12 - 0.16	548	268	2.0
0.16 - 0.20	612	304	2.0
> 0.20	400	196	2.0

Qualitatively, Baldit's results agree very well with those of Simpson, for they show a very clear preponderance in favour of positive rains, both from the point of view of duration and of the absolute quantity of electricity which falls on each square centimetre of surface.

They show also that the strongest current densities, during heavy rains, are more frequently positive than negative.

Quantitatively, there are important differences which arise from the differences in climate; Simpson's position being chosen in view of the heavy rains of the Indian Monsoon, whereas, during the 58 days of rain studied at Puy-en-Velay in 1911, the rains were of an extremely light nature. From this point of view the experiments of Simpson and Baldit are complementary, rather than antagonistic. We must not forget, on the other hand, that Simpson's measurements lasted for three times as long, and were on a much greater quantity of rain than those of Baldit.

There is an interesting point on which the two sets of measurements agree.... the conditions under which the greatest charges per cc. of rain were recorded.

The strongest positive charge recorded by Simpson was during a storm on May 13, 1908, when, on two occasions, the value + 8.0 e.s.u. was attained. On the same day he noticed the strongest negative charge, − 17.7 e.s.u.

Baldit(i), in his account of the experiments of 1911, remarks, " Les plus fortes charges par centimètre cube de précipitation, pendant les pluies de faible intensité, sont souvent négatives. La plus forte charge a été − 43.6 e.s.u. au bord d'un orage, pendant une pluie dont l'intensité ne dépassait pas 0.003 mm. par minute ".

This ~~result~~ last observation verifies a result mentioned by Simpson(ii), that in general, light rains carry down the largest charges per cc.

It verifies also a result contained in Simpson's tables, but not made very clear by that author. If we refer again to Table D (p.25), we see that,for rains of intensity equal to, or less than, 0.38 mm. in two minutes, the mean charge per cc is clearly greater for the negative charges than for the positive charges; the ratio of the negative to the positive charges per cc. becoming greater as the intensity of the rain decreases. To make this more clear we may rewrite the relevant portion of Simpson's table as follows...

Approx: rate of fall. mm. in 2 mins.	Mean + ve charge per cc. e.s.u.	Mean − ve charge per cc. e.s.u.	Ratio of mean − ve charge per cc. to the mean + ve charge per cc.
0.16	1.52	1.98	1.300
0.16	0.74	0.87	1.176
0.38	0.40	0.41	1.025

In addition to the results cited above, Baldit noticed that lightning flashes were often accompanied by a momentary diminution

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(i) Baldit.. loc. cit. 1912. (ii) Simpson... loc. cit. 1909.

of the charges on the rain, or even by a passing change of sign. A more lasting change of sign sometimes accompanied peals of thunder.

In comparing his own results with those of Simpson, Baldit lays stress on the disadvantages of the latter's " two-minute intervals ". As he points out, Simpson's registrations were made by a Benndorf electrometer, the needle of which was automatically earthed every two minutes, after having marked a single point on a moving band of paper. This point corresponded to the potential that the apparatus had attained at the end of each two minutes. The electric current calculated on this indication would therefore be the mean current during two minutes, and it would necessarily be less than the different partial currents obtained during the fractions of the interval, for example during the eight periods of fifteen seconds. It would be equal only in the case of a uniform current maintained for two minutes, which state of affairs does not arise during storm rains. Moreover, taking into account also the change of sign which could take place during a two minute interval, the indications would again be different.

The following table taken at random from Baldit's results for storm rain illustrates the force of this criticism....

Time.	Current Density	Time	Current Density.
18 m. 30 s.	-21.1×10^{-15} amp/sq.cm.	19 m. 45 s.	-12.4×10^{-14} amp/sq.cm.
18 45	-13.4	20 00	-16.0
19 00	$+14.2$	20 15	-28.1
19 15	$+18.7$	20 30	-15.9
19 30	$+8.7 \times 10^{-14}$		

The mean current calculated between 18.30 and 20.30 from the above figures is -7.2×10^{-14} amp/sq.cm., a value much smaller than the smallest value of the current in the series. These few results show the value of Baldit's shorter time intervals, and they also indicate the possibility of relatively high charges on rain, a fact which may be of interest for the explanation of the general phenomenon.

We have here outlined Baldit's results in a general way on the same plan as those of Simpson. In his own paper on the subject(i), Baldit differentiates between the various types of rain. His " pluies-non-orageuses ", " orageuses ", and " pluies de grain " correspond to the three types mentioned previously.... Ordinary rains, thunderstorm rains and " squall " rains.

For these three types of rain, in the order given, he found that:-

(i) The relative frequency of positive rain was 5.3; 1.7; 1.1.

(ii) The ratio of the quantities of positive and negative rain was 4.3; 1.5; 1.2

(iii) The ratio of the quantities of positive and negative charge brought to the ground by the rain was 2.3; 1.2; 1.1.

Note. In a paper in the Philosophical Magazine (1915), Simpson(ii) mentions the work of Benndorf(iii) at Graz(1910) and of Berndt(iv) at Buenos-Ayres in 1912, but we have had no opportunity of studying the results of these observers. We go on therefore, in the next section of the essay, to discuss the work of McClelland and Nolan at Dublin, begun in 1911.

(i) Baldit... loc. cit. 1912.

(ii) Simpson... Phil. Mag., 30, p 1, 1915.

(iii) Benndorf... Zitzungsbericht der Münicher Akademie. Jahrg.1912 p 246.

(iv) Berndt..... Phys. Zeit. 13, pp 151 et seq., 1912.

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D. THE EXPERIMENTS OF McCLELLAND AND NOLAN.

Work on this problem was begun at Dublin in March, 1911. The first series of experiments(i) lasted until June of that year, and then a second set of observations was undertaken (ii), lasting from October 1911 until May 1912. More recently work on the same subject was carried out at Dublin by McClelland and Gilmour(iii), in 1920.

In these three series of experiments the apparatus used and the general method were the same; we will therefore describe the apparatus and the method of experiment, and then go on to discuss the results of the different sets of observations.

The apparatus used is shown diagrammatically in Fig. 3.*

The rain was caught in a shallow conical vessel AB, 81.5 cms. in diameter. This was mounted inside a cubical wooden box, measuring about 108 cms. each way, and fitted with a zinc top CD, sloped so as to throw off the rain which fell on it. In this zinc top there was a circular opening EF, 79 cms. in diameter, through which the rain fell into the receiving vessel. The zinc top was surmounted by a strong zinc cylinder GH, 91 cms. high and 91 cms. in diameter; all the zinc fittings and the wooden box were connected to earth. In this way the receiver was protected from the earth's electrostatic field. The receiver was connected by an insulated wire passing through an earthed metallic tube to a Dolezalek electrometer in a building about four metres away. Attached to the receiving vessel, and in electrical

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(i) McClelland & Nolan..Proc.Roy.Ir.Acad. A, No. 5,pp 81-91,Vol.29, (1912).

(ii) " " " " " " " A,vol 30, No. 4, pp 61-71 (1912)

(iii) " " Gilmour. " " " " A, vol 35, No. 2,pp 13-29, (1920).

* P. 136.

connection with it, was a tipping bucket K, into which the rain flowed directly. This was adjusted to tip when 30 ccs. of rain had fallen into it. The water discharged at each tip of the bucket was caught in a pan underneath, and, flowing out through a pipe, was caught in a little vessel V, supported by a spring, and caused it to make contact with mercury and thus complete a circuit. The closing of this circuit caused a bell to ring close to the observer, and the arrival of each 30 ccs. of rain was signalled. The little vessel was perforated, so that after the rush of water ceased, the strength of the spring restored it to its first position, and the contact was broken.

The charge brought down by the rain was measured by observing the increase of potential of the receiving vessel.

In all three sets of experiments, the observers considered that as far as possible, they had eliminated all the sources of error mentioned in connection with previous work.

<u>First series of observations</u>   March -- June, 1911.

During the course of these observations very little rain fell, and no measurements at all were made on thunderstorm rain.

Accurate measurements were made on 5795 ccs. of rain, corresponding to a rainfall of 1.1 cm. Of this rain, 5113 ccs., or 88.2%, were positively electrified, and 682 ccs., or 11.8% negatively electrified. The 5113 ccs. of positive rain brought down 4154.2 e.s.u.; and the 682 ccs. of negative, 289.7 e.s.u.. Thus, of the total charge brought down by the rain, 93.5% was of positive sign.

As none of the rain was of thunderstorm origin, these results show that the excess of the positive over the negative charge on rain, is equally marked under normal conditions as during thunderstorms.

Another very striking result of these observations was that rain consisting of exceedingly small drops was always negatively charged.

McClelland and Nolan, in the published account of their work, considered their results with reference to three types of rain.

(a) Fine Rain Rain consisting of exceedingly small drops, so light as to be almost imperceptible, was classified as " fine rain ". As mentioned above, this rain was always negatively charged; but, as the quantity of water falling in this way, and the actual amount of electricity brought down, were very small, this type of rain had only a very unimportant effect on the percentage of negative electricity brought to the earth. It was found that the charge on this " fine rain ", remained relatively constant, having a mean value of 0.12 e.s.u./cc.

(b) Large Rain. In this group was classed rain consisting of relatively larger drops, and in this case the rain was generally heavy. Most of the rain of this type was positively charged, and on almost half of it, the mean charge per cc. was from 1 to 2 e.s.u./cc.. The highest charge recorded was 9.2 e.s.u./cc..

(c) Mixed Rain. This rain consisted of a mixture of types (a) and (b). With this type of rain frequent rapid changes in the sign of the charge on the rain were observed. The rain was, for the most part, positively charged, but the mean charge per cc. was much less than that found for " large rain ".

Second series of Observations. October 1911 -- May 1912.

These experiments were carried out in the same manner as those described above. The percentage of positive rain was 82.6%, and of positive charge brought down 76.9%. With these exceptions, the results were in complete agreement with those obtained in 1911.

Third Series. January 1 -- August 31, 1919.

McClelland and Gilmour carried out this more recent work with exactly the same type of apparatus as used in the experiments of 1911 and 1912.

One particularly interesting feature of the experiments was that an attempt was made to measure the size of the drops, and to see if there was any connection between the size of a drop and the charge it carried.

These measurements were based on earlier work by Bentley(i) and Defant(ii). Bentley computed sizes by allowing raindrops to fall on flour spread on a tray, and measuring the flour pellets so formed. Defant had adopted a method devised by Weisner(iii), of receiving the drops on filter paper and allowing them to spread. After trial of both methods, McClelland and Gilmour followed that of Defant.

A mixture of one part of eosin to at least thirty of talc powder, was rubbed into the filter paper. A drop of water falling on such a paper left a permanent pink circular stain as far as it spread. The relation between the volume of the drop and the diameter of the stain was found by allowing drops of known volume to fall on a filter paper, and measuring the stain produced. At first it was thought that drops as small as raindrops could be got from glass tubing drawn to a very fine point, and dipped in paraffin wax to prevent the water from wetting the glass. On trial it was found that the vast majority of raindrops were smaller than the smallest drops obtained in this way. Spraying water was then tried, but the number of drops falling on a given portion of the area sprayed over was too variable.

The method finally adopted was as follows.... The water was allowed to drop at constant pressure from a glass tube drawn to a very fine point, which was dipped in paraffin wax. This tube was enclosed in an outer tube, open at the lower end, through which a steady blast of air was driven by a compression pump. The blast forced the drops from the end of the inner tube before they could grow large. The drops obtained in this way were found to be very uniform.

(i) Bentley.." Monthly Weather Review ",Oct. 1904
(ii) Defant.. Akad.Wiss.Wien.Sitz.Ber. May 1905.
(iii) Weisner... Wien Ber. 14., Abh. 1., 1895.

To measure them, 100 drops were counted as they fell into a weighed beaker; about 20 were then allowed to fall on the prepared filter paper; then another 100 were counted into the beaker, and the beaker was weighed again. The volume per drop was thus obtained. The strength of the blast was then altered, giving drops of a different size, and the experiment repeated. Drops varying from 0.04×10^{-3} ccs. to 2×10^{-3} ccs. were obtained in this way. Drops larger than this were obtained without the use of the blast, using tubes of different bore, and altering the pressure. The diameters of the stains were measured by a travelling microscope, and a curve, volume of drop against diameter of stain, plotted.

Raindrops taken from a large number of storms were examined.. The volume of the largest drops obtained was 5×10^{-3} ccs. Drops of this size - indeed drops of volume greater then 2.5×10^{-3} ccs. - were exceptional, the great majority being smaller than 1×10^{-3} ccs. The smallest drops examined were of volume 0.03×10^{-3} ccs., although drops smaller than this certainly fell.

Drops of all sizes were found - generally very much mixed. In the case of " fine rain ", the largest drop found was of volume $< 0.08 \times 10^{-3}$ ccs.

We may summarise the results of this series of observations as follows:-

1. Rain was never found uncharged.
2. Of the non-thunderstorm rain tested
   (a) 73.5% was positively charged.
   (b) 84% of the electricity brought down was positive.
   (c) The average positive charge per cc. was.... 0.21 e.s.u.
   " " negative " " " " .... 0.08 e.s.u.
   (d) The average vertical current due to positive rain was .... 1.6×10^{-15} amp/sq.cm.
   The average vertical current due to negative rain was ... 0.5×10^{-15} amp/sq.cm.

2.(e) Rain consisting of droplets smaller than 0.08×10^{-3} cc. was always negatively charged.

(f) No general relation was found between the charge and size of drops.

3. Thunderstorm rain. Only two storms examined.

(a) 54.2% of the rain was positively charged.

(b) 50.3% of the electricity brought down was positive.

(c) The rain was more highly charged than ordinary rain.

If we consider all these observations at Dublin together with those of Simpson and Baldit, we see that, on the main issue, they agree that there is undoubtedly a large excess of positive electricity brought down by rain. The results seem to show that this is the case whether the rain is of thunderstorm origin or not.

In detail the agreement is not so complete. Simpson and Baldit found the highest charges, positive or negative, in the case of light rain; but the work of McClelland, Nolan and Gilmour seems to show that the largest charges per cubic centimetre of water are generally associated with heavy rain.

Again, these latter found that extremely fine rain always carried a negative charge, but only a small charge; on the other hand, Simpson and Baldit found the fine rain always strongly charged, positively or negatively.

1.

E. RECENT WORK.

THE ELECTRICITY OF OTHER ATMOSPHERIC PRECIPITATIONS.

SUMMARY.

The only other research carried out on the electricity of rain, from the same point of view as the work already described, was, as far as we can trace, that carried out at Otago University, New Zealand, in 1922, by Miss Marwick.(1).

Miss Marwick used apparatus differing only slightly in dimensions from that used in the Dublin experiments. The method of experiment was precisely that described by McClelland and his fellow-workers.

The distribution of positive and negative charges on the different types of rain was found to be as follows:-

Type of rain.	Total amount measured.	Quantity with positive charge.
Thunderstorm rain	4500 cc.	4260 cc..... 94.6%.
Ordinary rain.	2190 cc.	1740 cc..... 79.5%.
Drizzling rain.	60 cc.	60 cc.....100%
Hail and rain.	1770 cc	450 cc..... 39.4%

The results, in general, agree with those of the Dublin workers, and seem to show that large drops are highly charged, and mostly positively; and that the finer type of rain is only feebly charged, chiefly negatively.

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(1) Thora C. Marwick... Q.J.Roy Met.Soc., Vol 56, No. 233, Jan.1930.

The following table gives the average charge per cc. of the various types of rain in these experiments.

Type of Rain.	Average charge... e.s.u./cc.	
	Positive.	Negative.
Thunderstorm	0.77	0.28
Non-Thunderstorm	0.47	0.66
Drizzling	0.044	-

It was thought possible that there might be some connection between the lowness of these values and those of the atmospheric potential, which were considerably below those recorded under similar conditions in the northern hemisphere.

It was noted during these experiments, that the highest charges were recorded at the beginning of a storm, or after the storm had subsided a little and was beginning again. This may have some connection with the common observation that the changes of atmospheric potential are usually more violent at the beginning of a storm, and frequently die down as the storm proceeds. In the course of this work, no other connection was found between the potential conditions and the charge on the rain.

THE EXPERIMENTS OF P. GSCHWEND.

In a paper(1) on the electricity of rain in 1912 Benndorf remarked, "... it does not seem to me impossible, in view of the present day measuring technique, to attempt the measurement of the charge of single drops; and to investigate whether any connection exists between the size of drops and the charge, whether certain charges occur more frequently than others, and similar questions". It was with this point of view in mind, that Gschwend began his

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(1) Benndorf... Sitz.Ber.K.B.Akad. d. Wiss.Muniker. p 402, 1912.

researches on the electricity of rain.

The experiments were carried out at the Physical Institute, at Freiburg, from January to December 1919.

In his account of the work (1), Gschwend begins by discussing, in a general way, the methods and results of previous observers. He criticises these from two points of view...
(a) the disadvantages of the relatively large " time-intervals " used in most cases, and (b) the vagueness introduced into the results by the use of too large a surface of reception for the measurement of the charges brought down. In support of these criticisms, he gives the following table...

Workers	Place	Time	Reception Surface. sq. cm.	Interval.
Elster & Geitel	Wolfenbuttel	1888-9	415	2 sec. - 2 min.
Gerdien	Gottingen	1902	200	Continuous Registr:
Weiss	Vienna	1906	133	30 sec. - 2 min.
Kohlrausch	Puerto Rico	1907-8	133	2 min.
Simpson	Simla	1908-9	660	2 min.
Kahler	Potsdam	1908	900	2 min.
Benndorf	Graz	1908-910	4940	2 min.
Baldit	Puy-en-Velay	1910-11	200	15 sec.
Schindelhauer	Potsdam	1911	707	2 min.
Berndt	Argentina	1911-12	100	5 min.
McClelland & Nolan	Dublin	1911-12	19600	Continuous Readings
Herath	Kiel	1912-13	25000	" Registr:

In addition to reducing both the time interval and the reception surface, Gschwend measured the sizes of the drops, by allowing them to fall on a prepared filter-paper, after the method used by McClelland and Gilmour.

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(1) P.Gschwend.. Beitage zum Jahresbericht der kantonalen Lehranstalt in Samen, pro 1921/22.

A sheet of this prepared paper was laid in a small receiving vessel, which was placed in direct connection with a sensitive electrometer. The receiving vessel was exposed to the rain for one moment by the opening of a screen, and it was often found possible to catch a single drop, or a single snowflake, with a measurable charge.

The essential parts of the measuring apparatus are shown in Fig.4.*

The first screen B i , was fastened to the roof of the observing hut, and rose above it on the gable side 5.4 cm. This screen afforded sufficient protection from the splashing of drops from the roof of the hut into the vessel. Another screen B ii , was erected at a distance of 17 cm. below the first; this screen had a diameter of only 3.85 cm., while the upper one had a diameter of 18 cm. The receiving vessel, which was placed on the case of the electrometer, had the same diameter as the lower screen, and was 2.4 cm. high. The electrometer used was an Elster-Geitel thread-electrometer.

A feature of Gschwend's work was the minute care with which he tried to eliminate errors. He actually set up artificial fields over the apparatus, of 3900 and 6000 volts per metre, and measured the effect on the electrometer readings. He came to the conclusion, from these tests, that the disturbing effect of the earth's field would only be of importance in the case of near lightning. The possibilities of errors due to the vertical conduction current of atmosphere, due to the splashing of drops from projecting surfaces, or due to the " Lenard effect ", he also tested with great care. The splashing required for the " Lenard effect " was rendered almost impossible by the presence of the filter-paper in the bottom of the vessel.

In the same observation hut, Gschwend set up apparatus for measuring the potential gradient, and the actual intensity of the rain.

* P. 136.

The procedure during the taking of one observation was as follows:- A piece of the prepared filter-paper was placed in the vessel, the vessel insulated, and the upper screen opened. Then the lower screen was opened for a moment, the reading of the electrometer quickly noted, and both screens immediately closed. After the vessel had been earthed again, the filter-paper was changed, numbered, and laid on one side. The electrometer reading was noted, and in addition, the chief meteorological factors, such as wind, intensity of rain, size of drop, kind of clouds, lightning and thunder. Such measurements, with all manipulations, lasted on an average two minutes, while the actual time of exposure, in heavy rain, was about one second.

We may summarise Gschwend's results as follows....

1. In all showers there generally fell, even within a minute, on a surface of 6 square centimetres, rainfall particles of both signs; so that a recorder with a minute contact could not possibly register the total electricity.
2. The charges per unit weight of water were greater than had previously been observed. In rainfalls...

   The mean positive charge per mg. of water was 2.7×10^{-3} e.s.u.

   The mean negative charge per mg. of water was 3.2×10^{-3} e.s.u.

The table below shows some typical results for nine raindrops, seven of which were of thunderstorm origin....

Weight of drop mg.	Charge e.s.u $\times 10^{-3}$	Potential Gradient volts per metre.	Kind of rain.
17.05	-6.19	> -415	Ordinary rain.
12.9	$+7.35$	-332	
11.0	$+5.6$	-	Shortly before hail.
14 or 15	$+100$	-	Thunderstorm.
15 or 14	-17.3	-	
19.0	-5.4	> -2450	Shortly after T.storm
10.6	$+34.05$	-531	
22.5	-41.0	-460	Thunderstorm.
10.9	$+27.6$	-100	

3. No simple connection between the size of the drops and their charge could be found, either for the average of total rainfalls, or for individual showers, or groups of showers. The results showed that...
    (a) In land rains, the small drops were almost exclusively positively charged, while among the larger, the negative sign occurred more often than was the case among the small drops; the negative drops were, on the average, larger.
    (b) In squalls and thunderstorms, the large and small drops were sometimes positive and sometimes negative, although, in thunderstorms the negative drops were, on the average, larger.
4. No simple connections were found between the size of the drops, their charge, and the potential gradient. In the case of ordinary rain, it was noticed that the sign of the simultaneous potential gradient was more often opposed to the sign of the drop, than in agreement with it.
5. In all types of rainfall, the larger drops carried the greater charges. The charge per milligramme decreased with growing drop size, in ordinary rain and thunderstorms.
6. The total measurements indicated, in the mean, a surplus of positive electricity brought to the ground.
   The ratio of the total positive charge to the total negative was 1.5.

With regard to the positive surplus, these results agree with those [redacted] of other observers. As we have noted above, the charges observed were much higher than those found by previous workers; of particular importance is the fact that the experiments show that the large drops associated with thunderstorms can carry high negative charges as well as positive. There is agreement with the conclusion of McClelland and Gilmour, that no simple connection exists between the size of a drop and its charge; but, on the other hand, these experiments do not show that very small drops are always charged negatively; indeed, the opposite seems to be the case.

There can be no doubt, that measurements of this type are very important, and necessary, from the point of view of explaining the origin of the electricity of rain.

THE ELECTRICITY OF OTHER FORMS OF ATMOSPHERIC PRECIPITATION.

Most of the observers whose work we have described in connection with the electricity of rain, tried, whenever possible, to discover the nature of the electricity of other forms of precipitation, such as snow, sleet, and hail. Although we are not immediately concerned with this problem here, it may, perhaps, be of some value to indicate briefly the general nature of the results obtained. (1).

It must be said at once that the results are very contradictory.

G. C. Simpson, at Simla, found that snow was definitely more often positively charged than negatively, in the ratio 3.6 to 1.; and that the current densities, and the charges per cc., were greater than in the case of rain. These results are supported by the observations of Weiss, Marwick and Gschwend. Gschwend's experiments on single snow-flakes, showed the high values of the charge per unit mass of snow which were possible, his mean values being, positive, 11.6×10^{-3} e.s.u. per mg., and negative, 8.1×10^{-3} e.s.u. per mg.

On the other hand, the results of Elster and Geitel, showed a definite preponderance of negative charge brought down by snow. The experiments of Kahler, Schindelhauer, and McClelland and Nolan supported this view.

With the exception of Schindelhauer, all observers agreed that hail and sleet brought down a preponderance of positive charge. The Dublin experiments showed that large hailstones were more often charged

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(1) The actual observations on this subject are contained in the papers quoted earlier, dealing with the work of these authors.

positively, and the small ones more often negatively.

SUMMARY.

It is a well known feature of measurements of a meteorological nature that, although they may agree on main issues, there is often a great deal of contradictory evidence in points of detail. This tendency is shown in the results of the experiments we have described here, and it is therefore difficult to summarise the findings of the various observers.

The following conclusions may be said to be well established, remembering always the qualification as to the variations in points of detail.

1. Atmospheric precipitations, whatever may be their form (rain, snow, sleet or hail), are frequently (if not always), electrically charged.
2. In the course of a single storm, these charges may undergo frequent, and often very rapid, changes in sign and also in magnitude.
3. The charge per cc. of water may vary between very large limits, up to 40 e.s.u., and in some cases it may even surpass this value. On the average the charges are of the order of 0.4 to 0.5 e.s.u. per cc. The highest charges are more often negative than positive.
4. Positive rains are more frequent than negative.
5. The quantity of water charged positively is greater than the quantity charged negatively.

6. The total quantity of positive electricity received by the earth is greater than the total quantity of negative electricity received.

7. The earth's field undergoes variations analogous to those of the charge on the rain, but the connection between the two variations is not very clear.

   During non-thunderstorm rain the normal potential gradient is nearly always reversed.

   During thunderstorm rain, the potential gradient undergoes very large and rapid changes, both in sign and magnitude, and on the whole the potential gradient is more often reversed than not.

8. Hail and Sleet bring down an excess of positive charge. The electric character of Snow remains uncertain, but it seems apparent that a given weight of snow may bring down a much larger charge than an equivalent amount of rain. During snowfall high positive and negative values of the potential gradient may be observed.

9. The existence of uncharged rain, or other form of precipitation, remains uncertain.

10. The experimental evidence summarised above shows conclusively that the electricity brought down by rain is not the agent of the regeneration of the earth's negative charge. Indeed, the effect of the charge carried by rain would seem to act in the opposite sense.

2.

LABORATORY EXPERIMENTS ON THE ELECTRIFICATION OF WATER DROPS

2.

A. Early experiments. The work of G. C. Simpson.

G. C. Simpson (i), at Simla, in 1908, began experiments with the ultimate object of discovering the physical process by which the electrical separation takes place in thunderstorms. He tried, therefore, to imitate, as far as possible in the laboratory, each process which takes place in a thunderstorm, and to observe any electrical effects.

A large number of experiments were made with vortex rings composed of air in different physical states, to see if any electrical separation accompanied 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 were made , but all with negative results. Simpson then began experiments to see if any electrical effects were produced by the disruption of water drops in air.

This last possibility was suggested by earlier work due to Lenard(ii).

Lenard had shown that if air ascends with a velocity greater 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 in thunderstorms, it is exceedingly probable that ascending currents with velocities much greater than 8 metres a second come into play,

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(i) G. C. Simpson.... loc. cit. 1909.
(ii) Lenard....... Met. Zeit. 39, p 249, 1904.

and these must therefore hold a considerable amount of water in suspension. This water will constantly be going through the process of growing from small drops to large drops, only to be broken up into small drops again. Simpson considered that here was a possible origin for thunderstorm electricity..... if the breaking of large drops into small drops was accompanied by a separation of electricity.

It had long been known that the water drop which broke up on a solid or liquid surface, was the seat of a separation of electric charge. Tralles, in 1785, had detected the release of negative electricity to the air surrounding a waterfall, and ascribed it to the breaking of drops; but the effect was first studied in detail by Lenard.

Lenard (i), found that when distilled water splashed on a metal surface, the water took up a positive charge,and the air a negative charge. With very dilute solutions of different substances, he found that the sign and the magnitude of the charge on the liquid depended on the dissolved substance, and the degree of concentration of the solution. In all cases the electrification ultimately approached zero as the strength of the solution increased, and for solutions of moderate strength the effect was inappreciable. Lenard, at the same time, made experiments to see if there was any electrification produced when the water was broken up in air. He came to the following conclusion, which, in his account of the work, he printed in italics (ii). " 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."

(i) Lenard... Wied. Annal. 46, pp 584 - 636, 1892.

(ii) " Blosses Zerstiebens des Wassers ist ebenso unwirksam wie das Hindurchfahren von Strahlen durch die Luft; nur Auftreffen getrennter Tropfen auf ein flaches Hinderniss gab stets electrische Wirkung ".

Experiments of the same nature were performed by Kahler (i) and Aselmann (ii) who detected negative ions in the surrounding air,but no charge on the water drops.

Simpson was not satisfied that these experiments were conclusive, and he therefore commenced a series of observations on the breaking of drops in a current of air. His first experiments, with water from the Simla mains, showed no sign of electrification of the water; but, when they were repeated with distilled water, it was at once found that the mere breaking up of large drops into spray, on an air jet, gave to the water a positive charge.

The apparatus used by Simpson in his first series of observations is shown in Fig. 5.*

A metal tray, 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, the glass tube was connected, by means of a short rubber tube, to another glass tube S, coated inside and outside 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 with a metal cylinder C. The glass tube was filled with wires, by means of 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

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(i) Kahler.. Ann. d. Phys. 12, p 1119, 1903. * P 134

(ii) Aselmann... Ann. d. Phys.. 19, p 960. 1906.

cylinder C was insulated from the funnel, and could be connected to earth or to batteries, according 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 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 into a symmetrical crown about 4 cm. above the nozzle, and the greater part of the drops so produced fell directly into the tray. The roof shown in the diagram was to prevent spray being blown over the sides of the tray, while the whole apparatus was placed inside a wire-gauze cage to protect it from extraneous electric fields.

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 half a 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 deflections after each 100 drops had fallen, until 500 had been counted, when the flow of water was stopped.

The table below gives the results from a typical experiment with distilled water.

Number 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. Therefore charge per drop = 4.2×10^{-3} e.s.u.

The question then arose as to how much of this charge could reasonably be ascribed to the breaking up of the drops on the jet of air.

Simpson recognised that there were three possible sources of error...

(1) The charging might be due to the blast of air alone.

(2) That the drops might be electrified before being broken up.

(3) That the result 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 up on the jet, but when they splashed on the water in the bottom of the tray.

For the first two of these Simpson made experimental tests, and found that they could be neglected. 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. Simpson found that the drops falling into this,acquired a slight negative charge,when the blast was not in action. He therefore felt justified in concluding that the positive charge found in experiments in which the drops were broken on the air jet, was not due to the " Lenard effect".

Further experiments were made to investigate the extent to which the process was affected by any charge already on the drops. For this purpose it was only necessary to connect the cylinder C, to a battery. The actual charge carried by the drops was measured by allowing them ~~tp~~ to fall into a small box, (shown dotted in the figure), and measuring the charge obtained in the absence of the air blast.

Some typical results for both types of experiment are given below...

Distilled water... uncharged.

Volume of each drop 0.24 cc.

Number of drops broken.	Mean charge produced by a drop breaking on the air jet.
500	5.0×10^{-3} e.s.u.
500	4.2
400	5.8
400	5.1
400	5.8
400	5.8
Total 2600	Mean 5.2×10^{-3} e.s.u.

Distilled water. .. drops positively charged.

Number 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 = 19.5×10^{-3} e.s.u.

The drops in this case were caught in the little box.

Small box removed, and drops broken on the jet.

Number 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. = 40 volts. Charge per drop = 23.9×10^{-3} e.s.u.

∴ Original + ve charge	19.5×10^{-3} e.s.u.
Increased to	23.9×10^{-3} e.s.u.
∴ Increase due to breaking	4.4×10^{-3} e.s.u.

Results of all experiments with charged distilled water.

Number of drops broken.	Mean charge on drop before breaking 10^{-3} e.s.u.	Mean charge due to breaking. 10^{-3} e.s.u.
1000	+ 19.6	5.6 } 6.4
1200	+ 59.1	7.2
1000	− 19.5	4.9 } 4.7
1200	− 58.0	4.5
Total 4400	Mean	+ 5.6 × 10^{-3} e.s.u.

Summary of all results.

Initial charge on drop 10^{-3} e.s.u.	Electricity added to the drop in consequence of the breaking on the air jet. 10^{-3} e.s.u.
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 × 10^{-3} e.s.u.

In these experiments the falling drops impinged on a concentrated jet of air, and, probably, no such violent scattering of the drops could take place in the atmosphere. For this reason Simpson used the apparatus shown in Fig. 6,* in another series of experiments, to ~~to~~ produce a more natural breaking of the drops.

BB was a vessel of tinned iron, 65 cms. in diameter and 45 cms. high. In the middle of the bottom of this vessel was a hole, 7 cm. in diameter, surrounded by a conical rim, 7 cm. deep; so that 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

* P. 134.

arrangement for opening and closing them, to allow of the passage of water at will. Soldered underneath the main vessel was a smaller one of the shape shown, 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 BB, according to the experiment to be made. The whole apparatus 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 a rotating fan F.

When the fan was in action, and the tubes open, water poured 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. The final method of observation adopted, in order to minimise error due to the"Lenard effect", was as follows... The vessel B was connected to earth, and A to a Wilson electroscope, and the water and the blast set in action. When the electroscope indicated a definite potential, the blast and the water were stopped, and the quantity of water ~~xm~~ caught in A run off and measured.

Typical results are given below...

Experiments with rain water;	charged to 9 volts before run off.
	Amount of water collected in A.
1st experiment	300 cc.
2nd "	280 cc.
3rd "	290 cc.
4th "	230 cc.
5th "	265 cc.
	Mean 273 cc.

Capacity of system = 135 cm.

Charge on 273 cc = $\frac{135 \times 9}{300}$ e.s.u.

Charge per cc. of water = 15×10^{-3} e.s.u.

These experiments indicated that the charge per cc. of water was of the same order of magnitude as that found when single drops were more violently broken up on the air jet.

The two series of experiments described above measured the amount of electrical separation by the charge on the water. Simpson then began experiments to measure the charge taken away on the air, using the apparatus shown in Fig. 7.[*]

AA was a zinc cylinder, 8.5 cm. in diameter and 60 cm. long, the lower end of which 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 tube a jet of air was passed in a similar way to the previous experiments.

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 electric charge, an Ebert apparatus was connected to AA, through a short tube about 5 cm. above the place where the drops were broken. When the fan of this apparatus was in action, it drew air through the holes in the top of the cylinder AA, which swept the air of the jet with it through the instrument.

An experiment was made as follows.... The central cylinder of the Ebert apparatus was charged to a potential which could be read by the divergence of the leaves of the attached electroscope. The air of the jet was then put in action, and a reading of the electroscope taken. The fan was then allowed to draw air through the apparatus 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 an

[*] P. 138.

interval of 10 minutes between them, and the number of drops which had fallen in that time was noted. The difference between the readings of these two experiments gave the charge imparted to the air by the breaking of a known number of drops, and therefore the amount due to the breaking of a single drop could be calculated. Experiments were made with the central cylinder of the Ebert apparatus (i) charged positively and negatively.

The results given below are for distilled water.

Sign of charge of air	Loss of volts in 10 mins. Air jet, no drops	Loss of volts. Drops broken on jet	Loss of volts due to break-ing of drops.	Number of drops broken in 10 mins.	Loss of volts due to one drop.	Mean of two exper-iments.
— ve.	1.1	30.3	29.2	394	0.074	0.071
— ve	1.9	27.9	26.0	384	0.065	
+ ve	2.0	12.3	10.3	385	0.027	0.024
+ ve	2.7	10.8	8.1	411	0.020	

Capacity of Ebert apparatus = 14 e.s.u.

Mean negative ionisation caused by the breaking of one drop

$$= \frac{0.07 \times 14}{300} = 0.0033 \text{ e.s.u.}$$

Mean positive ionisation caused by the breaking of one drop

$$= \frac{0.024 \times 14}{300} = 0.0011 \text{ e.s.u.}$$

Excess of negative ionisation caused by the breaking of one drop

$$= 0.0033 - 0.0011 = 0.0022 \text{ e.s.u.}$$

(i) The Ebert apparatus was based on the well known apparatus due to Zeleny(Trans.Roy.Soc.A,195,p 193, 1900) for measuring ionic mobilities. It was later adapted by Gerdien for measuring the absolute conductivity of the air(Phys.Zeit.6,p 800, 1905; Terr.Mag.10,69,1905 Ebert developed the same idea and constructed an"ion counter" for measuring the number of ions per cc. of air (Phys.Zeit.2,662; Arch.de Geneve 12,97,1901; Verh.d.D.Phys.Ges. 7, pp 2-34, 1905.

A good account of the apparatus is given in Hess.. " The conductivity of the Air", pp 24 - 28; 39 - 43.

In general the results of this last series of experiments showed that ... (1) The breaking of drops of water was accompanied by the production of both positive and negative ions.

(2) Three times as many negative ions as positive ions were released.

The difference between the negative and positive charges should correspond to the charge remaining on the water. The first experiments showed that 5.5×10^{-3} e.s.u. of positive electricity was retained by the water of each drop after breaking, and those just described gave the value 2.2×10^{-3} e.s.u. per drop found in the air. Simpson thought that this was reasonably good agreement, as not all the ions produced would be drawn into the Ebert apparatus.

The conclusions to be drawn from all these experiments may be summed up in the following general statement.

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.

Note:- Before 1910, similar observations to those described here, were carried out in connection with the bubbling and spraying of liquids, by Townsend(i), J.J.Thomson(ii), Kosters(iii), and Bloch(iv). The results of these experiments, which do not specifically concern us here, are described in full, in a treatise by J.J.Rey(v). In what follows we describe in detail the work done by J.J.Nolan and his collaborators, at Dublin; work carried out, like that of G.C.Simpson, with the express purpose of elucidating the problem of the origin of the electricity of rain.

(i) Townsend..Camb.Phil.Soc.Proc. 9,part 5, 1908.
(ii) J.J.Thomson..Phil. Mag. p 352, 1902.
(iii) Kosters.. Wied.Ann. 69, p 12, 1899.
(iv) Bloch.. Comptes Rendus. 145, p 54 1907.
(v) J.J.Rey.. " Sur l'ionisation de l'air par les chutes d'eau ".
(Gauthier Villars,1912)

2.

B. The Dublin experiments on the electrification of water by splashing and spraying.

Experiments of a similar nature to those we have just described, were begun ~~in~~ at Dublin, in 1914, by J. J. Nolan. In this work (1) an attempt was made to find a connection between the charge produced on the liquid, and the extent to which it was broken up. Two methods were used, (1) Drops of distilled water were allowed to splash against an air blast, and (2) Distilled water was broken up by spraying.

First method. Splashing distilled water against an air blast.

This method resembles Simpson's, but in this case the breaking-up was more effective, and the splashed water was more easily examined. Drops were allowed to fall into a very strong horizontal air current, and each drop as it entered the stream of air was immediately shattered. In this way a mixture of small drops of different sizes was produced, including a small number of drops of medium size, as well as a great number of exceedingly fine drops. These drops were carried forward through different distances by the impetus given by the air blast, the larger drops being carried further. A rough sorting out of the drops into different sizes was thus effected, and it was possible, by allowing the drops to fall into a vessel set at different points, to compare the charge per cc. of water for drops of different sizes. Experiments conducted in this manner, showed at once that the charge per cc. depended on the size of the drops into which the water was broken, the charge being greater as the size of the drops decreased. The drops were found to be positively charged.

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(1) J.J.Nolan.. Proc.Roy.Soc. A, vol 90, pp 31-42, 1914.

It was found that if the receiving vessel was placed immediately below the water-dropper, the size of the drops falling into it was fairly constant, but it was difficult to prevent a few large-sized drops entering the receiver. The size of the drops was varied by varying the strength of the air blast, and the height of the water-dropper.

The experimental arrangement shown in Fig. 8[*] was finally adopted. A Sirocco fan B, driven by a motor, provided a strong horizontal air blast. The water-dropper A, was made of glass, and the cork at C contained 18 short pieces of narrow-bore tubing. The upper part of A was filled with distilled water, and a rapid succession of drops, of radius about 0.25 cm., was produced. The receiving vessel D, 30 cm in diameter, was insulated on paraffin (F), and connected to a Dolezalek electrometer.

By making an experiment when the fan was not acting, it was possible to show that the water was not charged before it was broken up. The amount of water entering the receiving vessel in a given time was found from the increase in weight of a piece of blotting paper placed in the vessel. The number of drops falling on a given area within a certain time was found by exposing a ruled surface to the drops. There were two possible sources of inaccuracy here, (1) the number of drops falling into the receiver per second might vary during an experiment, and (2) the number of drops falling per unit area into different parts of the receiver might be different. Any such errors were masked by the ordinary irregularities of the experiment.

In one experiment the procedure was as follows... A weighed paper was placed in D, and the fan was started. The dropper was then filled up with water, and the charging up of the receiver observed until the dropper was empty. The time was taken (generally 2½ mins.), the electrometer reading noted, and the paper rapidly weighed(to avoid

[*] p. 138.

errors owing to evaporation). At the beginning and end of each experiment, a piece of metal, 4 cm. square, ruled in centimetre squares, was introduced at H, and exposed for 10 seconds(this did not seriously affect the amount of water entering D, or the rate of charging.).

The results below are those of a typical experiment.

Duration of experiment 2¼ minutes.

Electrometer deflection 143 Positive.

Capacity of electrometer and vessel 292 cm.

Sensibility of electrometer 846 div/volt.

∴ Positive charge received $= \frac{143 \times 292}{300 \times 846} = 0.164$ e.s.u.

First weight = 8.743 grams. Second weight = 9.015 grams.

∴ Weight of water collected = 0.272 grams.

∴ Charge per cc. $= \frac{0.164}{0.272} = 0.60$ e.s.u.

Mean number of drops per sq.cm. in 10 seconds. = 3.

Area of vessel = 660 sq.cm.

∴ Volume of each drop $= \frac{0.272}{3 \times 2\frac{1}{4} \times 6 \times 660} = 102 \times 10^{-7}$ cc.

Therefore charge per cc. corresponding to drops of volume 102×10^{-7} cc. is 0.60 e.s.u.

Nolan found that when suitable conditions were arrived at as regards the strength of the air blast, and the height of the dropper, the drops were generally fairly uniform in size. It was impossible to perform an experiment without the presence of one or two large drops, and for this reason the results of many experiments were rejected. He considered the results given below to be reliable.....

Positive charge per cc. on distilled water broken up into drops of different sizes.....

Charge per cc. (e.s.u.)	Volume of drops.	Radius of drops.
0.54	106×10^{-9} cc	13.7×10^{-3} cm.
0.60	102	13.5
0.68	100	13.4
0.79	84.7	12.7
0.80	46	10.3
0.86	50.5	10.6
0.92	20	7.8
1.01	18.3	7.5
1.36	8.6	5.9

From these results, Nolan plotted a graph showing the connection between E, the charge per cc., and $\frac{1}{r}$, r being the radius of a drop. The points lay approximately on a straight line through the origin, showing a simple connection between the two quantities, i.e. $E = \frac{K}{r}$.

It was then shown that a relation similar to this could be deduced theoretically, assuming that the charge on the water was proportional to the area of new water surface created.

If a drop of radius R is broken into n drops of radius r , then the increase in surface area is $4\pi r^2 n - 4\pi R^2$

Therefore, if σ is the charge on the water per unit area of new surface, then the total charge is $4\pi\sigma(r^2 n - R^2)$

$$E \text{ (charge per cc.)} = \frac{4\pi\sigma(r^2 n - R^2)}{4/3 \cdot \pi r^3 n}$$

$$E = 3\sigma\left(\frac{1}{r} - \frac{R^2}{r^3 n}\right) = 3\sigma\left(\frac{1}{r} - \frac{1}{R}\right)$$

Therefore, if R is large compared to r, $E = \frac{3\sigma}{r}$

The table on the next page gives the values of σ calculated from the observations......

E (e.s.u.)	σ (e.s.u.)
0.54	2.46 10
0.60	2.70
0.68	3.04
0.79	3.34
0.80	2.74
0.86	3.04
0.92	2.39
0.95	2.88
1.01	2.52
1.34	2.63
1.36	2.67
	Mean 2.76×10^{-3}

Although there was a considerable variation in the value of σ, Nolan thought that the results were as good as could be expected, and he considered that there was no doubt as to the general law expressing the electrical separation that occurs when water is splashed. This law may be re-stated as follows... $Q = \sigma . dA$
(Where Q is the positive charge on the water, and dA, the increase in area of the water surface.)

Second Method Spraying distilled water.

The apparatus used in these experiments is shown diagrammatically in Fig. 9.*

The spray used was an ordinary scent spray, which, when driven by air under pressure, gave a copious supply of water in fine drops. The size of the drops could be varied by varying the air pressure. The subsidiary experiments were carried out in the same way as before. In the use of this apparatus there were two possible sources of error...(1) The "water-dropper" effect could occur at the nozzle ... this could be prevented by effectively shielding

* P. 139.

the nozzle from external electrostatic fields.

(2) The water might be charged by friction at the nozzle.. ... this was allowed for by observing the rate of charging of the nozzle.

The results of these experiments are summarised in the tables below ...

Charge per cc. of water sprayed at different pressures.					
Pressure. cms. of mercury	Charge per min. in receiver e.s.u.	Charge per min. on sprayer e.s.u.	Corrected charge per min on water e.s.u.	Volume of water sprayed per min. e.s.u.	Charge per cc. e.s.u.
7.6	+ 12.4	+ 4.6	+ 17	23	0.74
11.6	+ 29.0	− 0.6	+ 28.4	32	0.88
19.6	+ 62.7	− 8.9	+ 53.8	40	1.34

Volume and charges of sprayed drops.				
Pressure cms. of mercury	Volume of drops cc	Radius of drops cm.	E e.s.u.	σ e.s.u.
7.6	46.2×10^{-7}	10.3×10^{-3}	0.74	2.54×10^{-3}
11.6	32.5	9.2	0.88	2.70
19.6	9.5	6.1	1.34	2.72

The values of σ calculated from the results of these experiments agree with those obtained from the splashing method.

In considering the results of these two sets of experiments there is another source of error to be taken into account. There is a very great difference in the two methods, as regards the air which carries away the corresponding negative charges. In the first case the negative charges are carried away in the current of air from the fan, and the drops of water on which the charge is measured fall directly out of the air current. In the second case the positively charged water and the negatively charged air are blown in the same direction by the sprayer.

In spite of this difference, Nolan considered that there could be no doubt as to the identity of σ in the two cases.

As the value of σ was comparatively high, it was thought that it would be possible to measure the charge due to small changes in a water surface. With that object in view, a number of experiments were made. Water was allowed to ascend into a funnel-shaped vessel so that the area of the water surface increased rapidly, but no charge could be detected on the water. No difference was detected when a strong current of air was used to remove the negative ions, if any were produced. When a jet of air was played on a water surface, and ripples produced, no charging could be detected until the strength and direction of the air blast were such that the water surface was in motion, and drops carried off in the blast. Under these circumstances only, did the water become charged....positively.

These observations seem to indicate that some sort of violent and disruptive action is necessary in order to produce the charge on a water surface. It would appear that it is necessary to produce a virgin liquid surface, and that merely to expand an old surface is ineffective. These conclusions agree with the experiments quoted by Rey (i).

Experiments on the splashing and spraying of different liquids agreed with those of Lenard(ii) and J.J.Thomson.(iii) The Dublin tap-water gave only one-tenth of the effect observed with distilled water. Various strong solutions gave no charge; weak solutions a positive or negative charge, depending on the solute and the concentration.

The air was also examined, to find how the negative charge was carried. It was found that the air contained large numbers of ions of both signs, with excess of negative ions. The ions were of

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(i) Rey... loc. cit.
(ii) Lenard... loc. cit. 1892.
(iii) J.J.Thomson..... loc. cit.

different classes, each class having a definite mobility. The values of the mobilities varied from those of the ordinary atmospheric ions, to those of the large ions found by Langevin(i), Pollock(ii), and McClelland and Kennedy (iii).

Later experiments at Dublin.

Work of a very similar nature to that described above was carried out at Dublin, in 1922, by Nolan and Enright.(iv) After trial of the two methods, it was felt that, as the splashing method gave drops of very variable size, great sources of error were introduced into the results, and, consequently, into any calculations therefrom. For this reason the sprayer method was used throughout these experiments. The apparatus was essentially the same as that used previously. The sprayer was made of metal, and the spray was projected horizontally, being caught in a shallow zinc vessel, 120 cm. long and 60 cm. broad, which was placed horizontally, 40 cm. below the level of the sprayer.

Throughout the work three purities of water were used. In order to find the connection between the charge per cc. of the water, and the amount of breaking up it suffered, the sprayer was driven at different pressures, and the charging noted. The relation between these two quantities is shown in Fig. 10.* The figures by the side of the curves show the specific conductivity of the samples of water (in Ohm^{-1}). The most noticeable feature of these curves is that they show that the charge per cc. depends on the purity of the water; the charge per cc. increasing as the conductivity decreased. In addition the values of the charges were much higher than had previously been observed.

(i) Langevin...Comptes Rendus. 140, p 232, 1905
(ii) Pollock.. Le Radium, Vol 6, p 129, 1909.
(iii) McClelland & Kennedy.. P.R.Ir.Acad.Soc. 30, A, p 72, 1912.
Kennedy " " " " " 32, A, p 1, 1913.

(iv) Nolan & Enright..Sci.Proc.Roy.Dub.Soc. Vol 17, p 1, 1922.

* P. 139.

The next problem was that of measuring the drops, and it was here that considerable refinement was introduced into the experiments. The method finally adopted was as follows..... Glass microscope slides were prepared by spreading out on each a layer of thick dark oil (density 0.9). When one of these slides was exposed to the spray, the small drops falling on it passed into the oil layer, and were there suspended, sinking very slowly. The rate of movement through the oil was so slow that the smallest drops did not reach the bottom of the layer until after 48 hours. While they were suspended in the oil, the diameters of the drops could be measured by means of a low power microscope. The scale in the eye-piece of the microscope had 16 divisions to 1 mm., and drops were classified as having diameters of ½, 1, 1½,.. divisions; those of diameter between ¾ and 1¼, say, being put in the 1 division class.

The results below constitute a typical " census " of drops produced from a sample of water at a certain spraying pressure. The table gives the number of drops of each standard size captured on microscope slides at different parts of the spray.

Dia. of drops. Scale div.	Horizontal distance of slide from nozzle. cms.									Total n	nd^2	nd^3
	5	15	25	35	45	55	65	75	85			
½	9	13	19	27	22	20	10	7	--	127	31.7	15.8
1	11	14	13	15	14	16	8	6	2	99	99.0	99.0
1½	5	6	4	3	2	1	--	1	--	22	49.5	74.2
2	3	7	3	2	2	1	1	1	--	20	80.0	160.0
2½	--	2	2	1	1	--	--	--	--	6	37.5	93.8
3	1	1	1	--	1	--	--	--	--	4	36.0	108.0
3½	--	--	--	1	--	--	--	--	--	1	12.3	43.0
4	--	--	--	--	--	--	--	--	--	--		
										$\Sigma nd^2 =$	346.0	
											$\Sigma nd^3 =$	593.8

This pulverisation can be expressed in terms of the area of new surface created.

If n_1 the number of drops of diameter d_1 divisions ($\frac{d_1}{160}$ cm.)
n_2 " " " " " " d_2 " and so on.

Volume of all the drops $= \sum n \cdot \frac{\pi}{6} \left(\frac{d}{160}\right)^3$ cc.

Total surface area $= \sum n \cdot \pi \left(\frac{d}{160}\right)^2$ sq. cm.

$\therefore$ The surface area per cc. $= \frac{960 \sum n d^2}{\sum n d^3}$ sq. cm.

For the above example, surface area $= \frac{960 \times 346}{594}$

$= 559$ sq. cm. per cc.

The results obtained by Nolan and Enright, with different pressures of the sprayer are shown in Fig. 11.*

The curves showed that the area of water surface per cc. of water sprayed, increased uniformly with the pressure, up to a spraying pressure of about 16 cms. of mercury, and the three samples behaved in the same way. The results indicated that for a given sprayer pressure the degree of pulverisation was greatest for the purest sample of water. The intercept on the vertical axis represented the surface area per cc. of the water issuing from the sprayer before it was broken up.

By combining the results shown in Fig. 10 with those in Fig. 11, then the relation between the charge per cc., and the new area produced was shown (Fig. 12†). It is at once noticeable that these curves do not support the earlier idea of direct proportionality between the two quantities.

The curves of Fig. 12 sum up the results of all the experiments, and three important points appear.....

(1) The effect of the purity of the water on the charge developed is most important for the smaller degrees of pulverisation.
e.g. The purest sample, when broken into drops of a certain

* P. 139 † P. 140.

comparatively large size, give a charge of 2 e.s.u./cc., while the other samples, for drops of the same size, give 0.8 and 0.2 e.s.u./cc.

(2) For high degrees of pulverisation it would seem as if the three curves were going to merge into one, which means that if the water is broken up into drops small enough the charge per cc. will be the same whatever the purity of the water. The only difference is that (as Fig. 11 shows), it is apparently more difficult to break up the impure water.

(3) The discontinuities on the curves for electric charge, which could not be associated with any value of the electric charge, or any value of the spraying pressure, appear now in all the curves for the same value of surface area per cc. i.e. for the same average size of drop. It would appear from these curves that, as the size of the drops in the spray becomes smaller, the electrical separation occurs with greater and greater facility, especially in the case of the pure water, until the average size of the drop reaches a certain value ($r = 6.5\times10^{-3}$ cm) At this stage there is a definite check. The further stages of the curve show, in the case of the less pure samples, a tilt up, suggesting, as has already been said, that they will fuse with the curve for the purer water.

This tendency of the three curves to fuse into one, which would seem to be, very approximately, a straight line through the true origin, Nolan interpreted as indicating that the charging of the water was a genuine surface effect; the charge produced being proportional to the area of new surface for any sample of water, if the water is broken up to a sufficient extent. The full electrical separation is inhibited by impurities present, if the degree of pulverisation is small.

On the whole, the measurements showed that the quantity of electricity associated with the formation of 1 square centimetre of new water surface, was about 0.02 e.s.u.

The outstanding feature of these results is the importance of the purity of the water when the degree of breaking up is small. Their full significance, in connection with the subject of the essay, is discussed at a later stage.

2.

C. The effect of the substances ordinarily present in rain on the charge produced by the spraying of water.

The work described above indicates the effect of the purity of the water on the charge produced when it is broken up. As the results are to be applied eventually to the case of raindrops breaking in the atmosphere, it naturally becomes important to ascertain, if possible, how the charges are affected by the substances ordinarily present in rain, in the concentrations in which they usually occur.

Experiments of this nature have been carried out by Nolan and Gill(1).

These experiments were carried out in the same way as those just described. Solutions of varying concentrations were used, with the sprayer working at a steady low pressure in each case.

The substances most likely to occur in rain in the free atmosphere are, nitrates and nitrites; Sodium chloride from evaporated sea spray; Hydrogen peroxide; and dissolved gases, Ammonia, Carbon dioxide, Oxygen and Nitrogen.

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(1) Nolan & Gill..Phil. Mag. 46, p 225, August 1923.

Nolan and Gill made experiments with distilled water to which these substances had been added, and, judging from their experiments, with the exception of Sodium chloride, they will not seriously affect the charge developed when a raindrop breaks.

The results below are for solutions of Nitric acid, Ammonia, and Sodium chloride.

Drops of average radius 7.5×10^{-3} cm.

Charges per cc. (all positive), in arbitrary units, the value for distilled water being taken as 100.

Standard solution of Nitric acid 94.5 mg/litre
" " " Ammonia 15.4 " "
" " " Sodium chloride 40.0 " "

Strength of solution	HNO_3	NH_3	NaCl.
2 % of Standard	82	89	95
5 % " "	53	83	86
10 % " "	22	74	66
20 % " "	14	57	57
30 % " "	--	47	47
50 % " "	10	45	38
100 % " "	7	42	23

The amount of Ammonia in rain collected in country districts may be taken as about 0.5 mg/litre. In the tropics it seems to be higher (i). The corresponding value for Nitric acid in the tropics is 0.2 mg/litre. (ii); the values found by Boussingalt, in Alsace, and the values found at Rothamsted range from 0.2 to 0.4 mg/litre. Taking the value for Nitric acid, 0.5 mg/litre, and for Ammonia 0.3 mg/litre, these concentrations correspond to $\frac{1}{3}$ % of the Standard solution in each case. The observations show that Nitric acid and Ammonia, in such quantities , would have no appreciable effect on the charge produced by breaking drops. Even in the

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(i) Marcato & Munz..Comp.Rend. 114,p 184, 1892 (ii) McClelland & Nolan, ditto, 108, p 1062, 1889.

concentrations reported in the tropics, these substances, while producing a noticeable effect, would not seriously interfere with the phenomenon. It is otherwise with Sodium chloride.

The concentration of Sodium chloride in the air varies widely, depending on the distance from the sea shore. McAdie (i), quotes the following values..

England (mean)	2.2 mg/litre.	Rothamsted	2.01 mg/litre
Troy (New York)	2.7 " "	Nantes	14.0 " "

In places remote from the sea shore, the concentration can sink below 1 mg/litre. This would correspond, roughly to about 2 % of the Standard solution of Sodium chloride, and the corresponding reduction in the charge on the water is only 5 %. The mean concentration for England would produce a reduction of nearly 20 % in the values for distilled water, while the figure for Nantes, which is no doubt exceeded at many coast stations, would reduce the charging to 45 % of the value found for pure water. Thus, in many cases the Sodium chloride content of the rain water is important; and, while in inland regions the charge developed when a raindrop is broken will have very nearly its full value, in sea coast regions this may be reduced to one-half, or one-third.

The observers found that the conclusions reached for Nitric acid and Ammonia held good for the remaining substances.

A few experiments were made on rain water. Water collected in Dublin gave 35 % of the effect of distilled water, while water from Cornsore Point (Wexford), which contained a good deal of Sodium chloride, gave 40 % of the effect. Considering the results as a whole, it can be said that, except in the neighbourhood of the sea, raindrops may be expected to give the same electrical effects as the distilled water used in laboratory experiments.

(i) McAdie... Principles of Aerography, p 164, Harrap 1917.

SUMMARY.

The results of the work described in this section of the essay may be summarised as follows.....

1. 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. The amount of electrical separation is independent of any charge previously on the drop.
2. Some sort of violent and disruptive action is necessary in order to produce the charge on a water surface; and it would appear that there is some connection between the charge produced and the area of the new water surface created.
3. The charge produced per cc. of water broken up depends upon the size of the drops into which it is broken. The charge increases as the size of the drops decreases.
4. For drops of the same size the magnitude of the charge produced depends upon the purity of the water. The charge is greater the greater the purity of the water.
5. The effect of the purity of the water on the charge developed is most important for the smaller degrees of pulverisation; though there is some indication that if the water is broken up into drops small enough, the charge per cc. will be the same whatever the purity of the water.
6. Except in the neighbourhood of the sea, raindrops may be expected to give the same electrical effects as the distilled water used in the laboratory experiments.
7. The charge produced per cc. of water is of the order of 10×10^{-3} e.s.u. (SIMPSON)
8. The quantity of electricity associated with the formation of 1 sq. cm. of new water surface is of the order of 0.02 e.s.u. (NOLAN & ENRIGHT)

NOTE :-

(1) Experiments of the same nature as those we have just described have been carried out more recently by W. Busse, (Ann. de Phys. 4, 76, p 493, 1925), but we have had no opportunity of examining this work in detail. He showed that by any kind of division of water, such as spraying, bubbling, and the falling of drops on an obstacle, positive and negative ions were formed; the amount being greatest during spraying.

(2) Experiments on the breaking of drops in an electric field are discussed at a later stage in the essay.

3. THE " BREAKING - DROP " THEORY.

3.

A. GENERAL OUTLINE OF THE THEORY.

The conclusions arrived at in the first two parts of this essay ... .. (a) The electric charge on rain is predominantly positive, and (b) When drops of water break up in the atmosphere, the water becomes positively charged .... form the basis of the " Breaking-Drop " theory of the origin of the electricity of rain. This theory was first put forward, in 1909, by G. C. Simpson (i), and there can be no doubt that it offers a very satisfactory explanation of the origin of the electricity of thunderstorm rain; it is, however, less satisfactory when applied to the case of the electricity of ordinary rain.

(1) Thunderstorm Rain.

Considering first the case of thunderstorm rain, the theory is based on the results of the observations summarised in (b), above. In order that the explanation may be satisfactory it is necessary to show:-

(1) That there is considerable breaking up of raindrops in a thunderstorm.

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

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

(i) The whole of this section of the essay is based on the work of G.C.Simpson, described in the following papers..(1) Phil.Trans.Roy. Soc.A,vol 209,pp 379-413,1909; (2) Phil.Mag. 30,p 1, 1915; (3) Proc.Roy.Soc. A, vol 111,p 56, 1926; (4) P.R.S. A,114,p 376, 1927. Detailed references and quotations, and references to the work of other observers, are quoted in the text.

We must consider first some experiments performed by Lenard (i), in 1904. Lenard made a number of experiments to determine the final velocity attained by drops of water of different sizes when falling through the 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. Some of his results are given below:-

Diameter of drops millimetres.	Velocity of the air which supported the drops = velocity of the drops in still air.	
	Observed metres per sec.	Calculated. metres per sec.
1.28	4.8	5.65
3.49	7.37	9.3
4.50	8.05	10.6
5.47	7.98	11.7
6.30	7.80	12.6

" One sees from this that the velocity quickly reaches a limiting value as the size of the drops increases (very nearly equal to 8 metres per sec.), above which it does not increase; it even decreases a little as the drops grow still greater ". (ii) He then sh~~eqeed~~owed that the apparent anomaly was due to the drops becoming deformed, so that, instead of retaining the shape of spheres, they became flattened out, thus presenting an increased resistance to the air through which they fell. In consequence of this deformation, large drops rapidly broke up into small drops, and Lenard found that drops of 4 mm. diameter were stable under all conditions, but that drops 5.5 mm. in diameter (and above) could not exist for more than a few seconds after attaining their final velocity relative to the air.

(i) Lenard..." Rain ", Met.Zeit. 21, pp 249-262, 1904.
(ii) ibid...p 259.

This fact must play an important part when drops of water are falling through ascending air currents. According to the table above, all drops of water of a smaller diameter than 4.5 mm will be carried upwards by a current of 8 metres per 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 per second, or more.

We may discuss the question of the ascending currents of air accompanying a thunderstorm 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.

Of 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. A wind having a horizontal velocity of 8 metres per second (29 Km or 18 m.p.h.), is defined as a moderate breeze, and wind velocities of 40 metres per second (approx: 100 m.p.h.) have been measured during tornadoes; thus we see that ascending currents having velocities many times greater than 8 metres per 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 idea of the upward velocity of the air current in which it was formed. Hailstones have been found of 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 per second to hold it in suspension; thus the ascending currents which produce larger stones must have enormous velocities.

It would therefore appear that those disturbances 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 per second necessary to hold water in suspension, and so it cannot be considered an unwarrantable assumption that in all thunderstorms a velocity of 8 metres per 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 it is imagined that the ascending current consists 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, and (c) a cap or crown in which the air rapidly spreads out in all directions so that the vertical velocities are small at a short distance above the head of the column. If the air in the base is saturated, then as it rises through the column its temperature will be reduced at the rate of approximately 0.5 degrees Centigrade for every 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 per 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 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.

For example, let us assume that the height of the column is 200 metres, so that the air which enters the base will be cooled 10 degrees Centigrade during the ascent, and let the initial temperature be 15 degrees Centigrade. 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 water accumulates at the top of the column, (which we may assume for the purposes of a rough approximation), 6 × 8, or 48 grammes of water will have collected over every square metre of the column in one second, i.e. 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, after 10 minutes there would be 36 drops, each of the maximum size 5.5 mm. diameter, over every square centimetre of the cross-section. Thus if the ascending current had a velocity of only 8 metres per second, enough water would be depositied for a considerable breaking up of drops.

Turning now to the second point in connection with this theory, a rough estimate may be made of the amount of electricity which could be separated under such conditions. For simplicity it is necessary here to make several 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 charge 8 e.s.u. per square centimetre. Thus sufficient drops must break over each square centimetre to provide 8 e.s.u. before a discharge can take place, and if we assume the breaking of each drops provides 5×10^{-3} e.s.u. (Simpson's experiments.. p 60), this will occur when $\frac{8}{5 \times 10^{-3}}$ or 1,600 drops have been broken.

Thus if one drop breaks over each square centimetre every second, a discharge can take place after twentyseven minutes; or if twentyseven drops break, after one minute. We have already seen that under certain conditions which are not at all improbable, thirtysix drops of water, each large enough to be broken up, will have accumulated in the course of ten 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.

It may also be considered how many times a given mass of water would have to be broken up in order to give the rain which falls from the cloud, the charges of electricity which are actually measured. Considering first the case of positively charged rain, according to the experiments at Simla, the positive charge carried down by the rain is of the order of 1 e.s.u. per cc. of water. The laboratory experiments at the same place showed that water which has splashed once has a charge of the order of magnitude of 10×10^{-3} e.s.u. per cc. Thus the water would have to splash about a hundred 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 readily absorbed by the cloud particles through which the air streams in its upward course, and it is very probable that in consequence large negative charges could 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 just made has been based on values which cannot be considered as anything more than the roughest approximations. It shows, however, that it is not necessary to assume ascending currents of more than 8 metres per 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.

A. (2) NON-THUNDERSTORM RAIN.

For the theory to explain the electrification of ordinary rain there must be a certain amount of breaking of drops. The difficulty is, however, that according to the experiments made by Lenard (i),

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(i) Lenard .... Met.Zeit. vol 39, p 257, 1904.

drops of water of less diameter than 4 mm. are not broken in falling through air. As in non-thunderstorm rain the majority of drops are much smaller than this, it would appear that there would be little or no breaking of drops. That this conclusion is not strictly true can be observed in a simple manner. If one stands during a rain shower in such a position that the falling drops can be seen against a dark background, "...then after a little practice the following will be noticed. The drops will be seen to be falling in parallel lines inclined from the vertical, the direction being determined by the wind. Suddenly, as a gust of wind comes, the angle of fall will change and the drops will become confused. At this moment a large number of very fine drops will appear. Whether these small drops are formed by the breaking of the drops due to the wind itself, or as a result of collisions, it is impossible to say, but there can be no doubt of the breaking of the drops by one cause or another."(i)

There is also the question of one drop overtaking another and colliding with it. Lenard has shown that such collisions are probably rare with real raindrops. At the same time there must be a certain amount of collision through one cause or another. When two drops collide it is very unlikely that they unite and continue as one large drop. On the contrary, they will " splash " against one another and, in all probability, break up into smaller drops than before the collision. It does not appear possible to deny some amount of breaking of drops; the only question is, how much takes place?

Assuming that drops do break, let us consider what the result of the splashing would be. If we take the case of the formation of a raincloud on a day with the normal potential gradient; until the rain begins to fall there is no separation of electricity in the cloud, and the normal potential gradient remains unaffected. The potential gradient indicates a negative charge on the ground, and

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(i) Simpson... Phil. Mag. 30, p 7, 1915.

the corresponding positive charge is in the form of a volume charge in the air above. When the rain commences and ~~the~~ collisions take place, the rain becomes positively charged and the negative charge remains behind in the cloud or in the air beneath it. Before very long, the rain has brought down sufficient positive electricity to the ground, and left sufficient negative charge behind to reverse the normal field. Thus during steady rain one would expect positively charged rain and a reversed electric field, and this is exactly what is found by observation. If the air from the rain area is carried over the surrounding country by the wind, it may have such a large volume charge of electricity, that it will reverse the field by itself. This accounts for the fact that as a rain shower moves across the country, the normal field is often reversed before the rain actually falls at the station. We see from this that the theory accounts for the facts qualitatively, but we must ascertain if it is sufficient quantitatively.

Schindelhauer (i) found that with non-thunderstorm rain (landregen) 92 % of the observations showed positive charge, of which 81 % gave a vertical current of between 1 and 5×10^{-15} amp/sq.cm. Baldit (ii), found for the same kind of rain 85 % was positive, and 86 % gave vertical currents between 0.1 and 10×10^{-15} amp/sq.cm. From these figures it will be safe to say that the average current produced by the descending positively charged rain is about 2×10^{-15} amp/sq. cm. This is equivalent to 6×10^{-6} e.s.u. per sq. cm. per second. The normal charge on the ground, assuming a potential gradient of 100 volts per metre, is -3×10^{-4} e.s.u. per sq. cm. Thus we see that the potential gradient would be reversed in $\frac{3 \times 10^{-4}}{6 \times 10^{-6}} = 50$ seconds. Hence the reversal of the field is easily accounted for by the electricity brought down by the rain.

(i) Schindelhauer.. loc.cit. see pp 29, 30, 31.of present **essay**
(ii) Baldit..... loc.cit. " " 31 - 37 " " "

It is more difficult to determine how much breaking of the drops would be necessary to give the charge found on the rain . Taking the mean charge on non-thunderstorm rain to be about 0.1 e.s.u. per cc., and accepting Nolan's (i) value that charges up to 1.36 e.s.u. per cc. could be given to water by breaking it up into fine spray, Simpson (ii) came to the conclusion that, " if one-tenth of the rain was broken up into fine drops, the observed charges would be produced".

In considering the above value, 1.36 e.s.u per cc., for the charge produced when water is broken up into very fine spray, it should be noticed that to produce a charge of this order, according to Nolan's early experiments, the water must be broken up into very fine drops,--- of radius about 6×10^{-3} cm. The amount of shattering which drops are likely to experience, even in the highly disturbed conditions associated with a thunderstorm, is very small compared with this complete pulverisation. Some writers deny that shattering of raindrops can occur in nature. While this is, no doubt, an extreme view, the experiments of Hochschwender, quoted by Lenard (iii), tend to show that, except in the case of the largest drops, a very considerable counter-acceleration is required to produce rupture. The question of magnitudes, therefore, remains a difficulty. There is a gap between the amount of charging produced in the laboratory corresponding to a certain degree of breaking up, and the amount of charge observed on rain -- thunderstorm and ordinary -- considered in the view of the amount of breaking up it is likely to have experienced.

In this connection we may consider again the experiments of Nolan and Enright (iv) described previously. These experiments showed that for water of Specific Conductivity 2.4×10^{-6} Ohm^{-1} , the quantity of electricity associated with the formation of 1 square centimetre of new water surface was about 0.02 e.s.u. This Specific

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(i) loc.cit. see pp 65 - 72. (ii) Phil. Mag. 30, p 9, 1915.
(iii) Ann. de Phys. 15, 1921. (iv) loc.cit. see pp 72 - 76.

Conductivity does not indicate an extremely high degree of purity. It is not unreasonable to suppose that a raindrop, formed in the well-filtered air of a thundercloud, is much purer than this sample. Hence for a moderate degree of breaking up, we might expect the thunder rain to acquire bigger charges than those observed by Nolan and Enright in their experiments. But even for water of the same degree of purity as the above sample, it can be seen that the charges observed in thunderstorm rain can easily be reached. If a drop of radius r breaks up into 27 equal drops, the change in surface per cc. is $\frac{6}{r}$. Taking a drop of diameter 4 mm. the change in surface per cc. will be thirty square centimetres, and therefore, according to Fig. 12, this would produce a charge greater than 0.2 e.s.u. per cc. Thus for the purer water of the thunderstorm, we need not demand any high degree of breaking up, or any very sustained repetition of the process, to produce the charges observed on thunderstorm rain.

In addition there is another process at work which tends to concentrate the charge... the evaporation from falling raindrops in a thunderstorm is very rapid. Evaporation no doubt also plays a part in increasing the magnitude of the charge per cc. on ordinary rain.

We must remember also, that the electrical effects will 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 (i) to form single large drops. Thus as the water becomes more and more highly charged, the drops will grow more rapidly 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.

Taking these last observations into account with the rest of the theory, we may therefore say that.... <u>If a moderate degree of purity</u>

(i) Rayleigh....Proc. Roy. Soc. Vol 28, p 406, 1879.

be assumed for raindrops in the upper atmosphere; the " Breaking-Drop " Theory is fully competent to account for the observed electrical phenomena of thunderstorms, and also to explain the sign and magnitude of the charge on the greater part of ordinary rain.

B. THE MECHANISM OF A THUNDERSTORM.

In the preceeding pages we have given a general account of the " Breaking-Drop " Theory, showing how it explains in general terms the known facts relative to the Electric Charge on Rain, as described in the first part of the essay.

In what follows we discuss the Theory in more detail, with particular attention to the way in which it may be used to describe the Mechanism of a Thunderstorm. It may seem that in this respect we are straying from the main issue, but there are three reasons why this problem is important....

(1) It is intimately connected with the validity, or otherwise, of the " Breaking-Drop " Theory.

(2) It indicates on what grounds alternative theories are based.

(3) It brings us back, ultimately, to the extremely interesting and fundamental question of the origin and maintenance of the Earth's negative charge.

The general meteorological conditions in a thunderstorm.

Thunderstorms are of two types (a) " heat " thunderstorms, and (b) " cold-front " thunderstorms. Both are due to instability in the atmosphere, but in the former the instability is produced through the heating of the surface air layers by intense insolation, while the instability in the latter is caused by the coming together of air currents having different thermal conditions. The most violent storms, and most of those of tropical regions, are of the "heat" type..... the processes in these are simple and more easily described, and the discussion below is limited to them. The main processes in all thunderstorms are similar, and the conclusions arrived at below can be applied easily to " cold-front " storms.

Fig. 13*, shows diagrammatically, and roughly to scale, the meteorological conditions in a thunderstorm of the " heat " type, after it has become fully developed. The thin unbroken lines represent stream lines of the air, so that they show the direction of the air motion at each point, and their distance apart is inversely proportional to the wind velocity. The air enters the cloud from the right and passes under the forward end of the cloud, where it takes an upward direction. We are concerned mainly with the vertical component of the velocity, and it will be noticed that although the actual velocity decreases along the stream lines, the vertical component increases as the air passes into the storm, and reaches a maximum in the lower half of the cloud. The oval marked 8, indicates where the vertical component is 8 metres per second; within the oval the component is greater than 8 metres per second and outside it is less. No water can pass downwards through this region, for the reasons mentioned earlier.

In the diagram, the broken lines represent the paths of raindrops. On the extreme left the drops fall practically vertically, in the

* P. 140.

right half of the storm the falling drops are deflected to the left by the air stream. The magnitude of the deflection from the vertical will obviously depend on the size of the drops. Drops of the largest size will be little deflected, while the smallest drops - cloud particles - will travel practically along the stream lines.. It is clear from the diagram, without any further description, that above the region of maximum vertical velocity, there will be an accumulation of water. Only large drops will be able to penetrate into the lower part of this region, to just above the surface where the vertical velocity is 8 metres per second. These drops will be broken and the parts blown upwards. The small drops blown upwards will recombine and fall back again, and so the process will be continued.

The region in which this process of drop breaking and recombining is large, is indicated in the diagram by a dotted curve which starts from the surface where the vertical velocity is 8 metres per second, and is shown to extend to a height of about 4 kilometres. All the time the water is within this region, it is being transferred to the left, where the vertical currents are smaller, and finally it is able to escape and fall to the ground to the left of the region of maximum activity.

The more violent the vertical currents, the higher the region within the dotted curve extends in the atmosphere, and with very violent storms, part of it extends above the altitude where the temperature reaches the freezing point. In these conditions hail is formed, and each excursion of the hailstone is recorded as a shell of clear or translucent ice. So long as the surface where the vertical velocity falls to 8 metres per second is not above the zero isothermal surface, water will accumulate and there will be breaking of drops.

The General Electrical Conditions.

The distribution of electric charge which will result from the conditions represented in Fig. 13 ~~are~~ is shown diagrammatically in Fig. 14.*

In the region where the vertical velocity exceeds 8 metres per second there can be no accumulation of electricity. Above this region where the breaking and recombining of water drops takes place - the region marked B in Fig. 14, - here, every time a drop breaks, the water of which the drop is composed receives a positive charge. The corresponding negative charge is given to the air, and is immediately absorbed by the cloud particles, which are carried away with the full velocity of the air current (neglecting the effect of the electrical field in resisting separation).

The positively charged water however, does not pass out of the region B so easily, for the small drops recombine and fall back again, only to be broken up once more and receive an additional positive charge. In this way, the accumulated water in B becomes highly charged with positive electricity, and this is indicated by the positive signs in the diagram. The air with its negative charge passes out of B into the main cloud so that the latter receives a negative charge. In what follows B is described as the region of separation, for here the negative electricity is separated from the positive electricity. The density of negative charge will obviously be greatest just outside the region of separation, and this is indicated in Fig. 14 by the more numerous negative signs entered in the region around A.

It should be noticed that it is not necessary for the air to have passed through the region where the vertical velocity exceeds 8 metres per second for electricity to be separated, and for the air to receive a negative and the rain a positive charge. Breaking of drops takes place in all parts of the air stream where rain is falling, and the relative velocity between the downward moving rain and the upward

* P. 140.

moving air always produces a separation of the positive and negative electricity. Thus the positive charge in the region of separation and the negative charge in the main cloud is not confined to the region between the stream lines which pass through the region where the velocity exceeds 8 metres per second. Similarly electrical effects would be produced as those indicated in Fig. 14 even if there were no vertical velocities greater than 8 metres per second; but in that case there would be no large accumulation of water, and it would be unlikely, but not impossible, that a sufficiently high electrical field would be produced to give rise to lightning.

The rain which falls out of the region of separation will obviously be positively charged, so one would expect the heavy rain near the centre of the storm to be positively charged. On the other hand, as one moves away from the region of ascending currents one would expect the rain to be negatively charged, for it has fallen entirely out of the negatively charged cloud. This is indicated in the diagram.

With regard to the lightning, one would expect the main discharges to start in the region where the positive electricity accumulates on the rain held up in the cloud - the region of separation - and to branch downwards towards the ground. An intense field may also be set up between the negatively charged cloud and the ground, especially if light rain has concentrated the charge on the lower part of the cloud. As a lightning discharge cannot start at a negatively charged cloud (i), any discharge between the ground and this part of the cloud must start on the ground and branch upwards. The chief characteristics of lightning which are to be expected according to this theory have been indicated in Fig. 14.

The above description of the meteorological and electrical conditions in a thunderstorm, according to the breaking drop theory,

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(i) See pp to .

gives an account of a thunderstorm in which the actual air motions, the rainfall and the distribution of electricity are combined together to complete the picture. It is now necessary to test the theory to see whether the electrical and meteorological quantities involved are of the right order of magnitude, and whether the phenomenon as a whole is in accord with the observations.

The Magnitude and Distribution of the Electric Charges.

The meteorological conditions impose certain limits on the extent of the region in which positive and negative electricity can accumulate according to the theory. In the first place the vertical extent of the cloud is limited by the height of the stratosphere. In Europe the height of the stratosphere is approximately 10 kilometres; in South Africa (latitude 33 deg.S.) about 15 kilometres; in tropical regions 20 kilometres or more. The diagrams, Figs. 13 and 14, are drawn for European conditions, the top of the cloud at 10 kilometres and the base at 1 kilometre. In South Africa the top is at 15 kilometres and the heights of the other regions are proportionally increased.

Given the regions shown in Figs. 13 and 14, it is necessary to calculate the electrical fields which would be set up by various distributions of electricity within them. To do this we must simplify the problem, for it is impossible to calculate the field produced by an irregular distribution of electricity. A satisfactory method of doing this, which allows of easy calculation, is represented in Fig. 15.*

Here the region B of Fig. 14 is represented by a sphere, having its centre 3 kilometres above the ground and radius 1 kilometre; in this sphere all the positive electricity is supposed to be confined. The region A of Fig 14 is represented as a sphere with its centre 7 kilometres above the ground and having a radius of 3 kilometres; thus this sphere, which contains the negative electricity, touches

* P. 141

the region of positive electricity at its lowest point and the top of the cloud at its highest point. The volumes of the spheres A and B of Fig. 15 are approximately the same as the volumes of the regions A and B of Fig. 14.

We have now to distribute the electricity over these spheres, for it is clear that the volume distribution is not uniform . This is done in each case by dividing the main sphere into four spheres haing radii $\frac{1}{4}$R, $\frac{1}{2}$R, $\frac{3}{4}$R and R, in which R is the radius of the outer sphere. We can now give to each of these spheres an approximate volume charge spread uniformly over the sphere, and so obtain a simple method of calculating the electric field at any point outside the sphere by assuming the charge concentrated at the centre.
If q'_1 , q'_2, q'_3 , and q'_4 are the uniform volume charges used for calculation and q_1 , q_2 , q_3 , and q_4 the actual volume charges in the regions 1, 2, 3 and 4 respectively, we have..

$$q_1 = q'_1 \qquad q_2 = q'_1 + q'_2 \qquad q_3 = q'_1 + q'_2 + q'_3 \quad \text{and} \quad q_4 = q'_1 + q'_2 + q'_3 + q'_4 \ .$$

We have now to decide the order of magnitude of the total positive and negative charges and then distribute them between the spheres. C. T. R. Wilson has shown (i) that the amount of electricity which passes in an average lightning discharge probably varies between 10 and 15 coulombs. But a lightning discharge does not neutralise all the electricity in a charged cloud, so these figures only give a minimum value of the total charge. It will be reasonable,therefore , to take the order of magnitude of the charge to be 100 coulombs, and distribute 100 coulombs of negative electricity in the A spheres and 100 coulombs of positive in the B spheres. It is more difficult to decide how this total charge should be distributed between the spheres. In reality there is practically no limit to the possible ways in which the density may vary over the charged region and any distribution from infinity to zero is possible, if not likely. All

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(i) C.T.R.Wilson.. Phil.Trans.Roy. Soc. A, vol 221, p 91, 1920.

that we need to do here is to take a distribution which is not obviously impossible.

In his paper on the subject, (i), G.C.Simpson took the actual volume charges in the four subdivisions of the spheres to increase in steps of powers of 5, that is, the actual densities in passing from sphere to sphere were taken to be q, $5q$, 5^2q, and 5^3q.

If we take these values, the density within the inner sphere is 125 times the density in the outer sphere, but it is only 18 times the density in the region as a whole.

We have now to consider what changes in the positions of these spheres of varying densities are likely to occur, for the field produced at points on the circumference of the outer sphere varies greatly according to the position of the various charges within the sphere.

Considering the B spheres first, we may assume that the greatest density in this region, the region of separation, is at some more or less constant distance above the surface where the vertical currents fall to 8 metres per second. Therefore as the velocity of the vertical currents increases and decreases, the position of the region of maximum density will rise and fall above and below a mean position. The extreme cases are shown in Figs. 15 b and 15 c.

The distribution of charge in the region of negative electricity, the A spheres, is not likely to undergo any large changes. The maximum density is likely to be quite near the region where electrical separation takes place and to decrease as one recedes from this position. The general distribution in the A spheres represented in Fig. 15 a , is therefore likely to remain unchanged by the fluctuations in the intensity of the vertical currents.

Applying the above values to the situation represented in Fig 15 a we obtain the following quantities.....

(i) G.C.Simpson.. Proc.Roy.Soc. A, vol 114, p 382, 1927.

Negative charge.

Total quantity = -100 coulombs.

Density in A_1 = -0.13 coulomb/km.^{3}

Density in A_4 = -16.3 coulomb/km.^{3}

Field at D due to − ve charge = -0.59×10 volts/metre

" " C " " " " = -0.09×10 " "

" at ground " " " " = -5.7×10 " "

Positive charge.

Total quantity = $+100$ coulombs

Density in B_1 = $+3.49$ coulomb/km.^{3}

Density in B_4 = $+436$ " "

	Distribution as in 15 b. volts/metre	Distribution as in 15 a. volts/metre	Distribution as in 15 c volts/metre
Field at D due to + ve charge	-0.51×10^6	-0.88×10^6	-5.13×10^6
" " C " " " "	$+5.17 \times 10^6$	$+0.94 \times 10^6$	$+0.52 \times 10^6$
" at ground " " " "	$+28.0 \times 10^4$	$+20.0 \times 10^4$	$+16.0 \times 10^4$
Combined field due to positive and negative charges.			
Field at D	-1.1×10^6	-1.47×10^6	-5.72×10^6
" " C	$+5.07 \times 10^6$	$+0.85 \times 10^6$	$+0.43 \times 10^6$
Potential Gradient at ground	$+22.0 \times 10^4$	$+14.0 \times 10^4$	$+10.0 \times 10^4$
" " " " 15 Km. away.		-900.0	

The potential gradient changes sign at 5.8 Km. from the storm. Fig. 16* shows the variation of the electrical force at different heights above the ground with the three different distributions of positive charge. The curves have not been calculated except at C and D, but they have been drawn to show the main features of the

* P. 141

field and are sufficiently accurate for the purpose.

Taking first the curve for the symmetrical distribution of the positive charge about the centre of the charged region, as in Fig. 15 a, it will be seen that there is a maximum positive field at D and a maximum positive field at C but in neither case does the field rise to the 3×10^6 volts per metre which is the field necessary to initiate a lightning discharge. Thus with the 100 coulombs distributed in this way there would be no discharge.

In the case of the distribution in which the positive charge is concentrated in the lower half of the charged region, as in 15 b, there is a flat maximum of negative field at D, but it does not reach 3×10^6 volts per metre therefore no discharge can take place. At C however, the positive field rises to 5.1×10^6 volts per metre. This field is two-thirds more than that required to start a discharge at C, therefore with this distribution a charge of much less than 100 coulombs would be sufficient to start a discharge, or, if the 100 coulombs is retained, the concentration in the lower half of the region need not be so marked as in the example shown.

In the case of the distribution as in Fig. 15 c, in which the positive electricity is concentrated in the upper half of the sphere, the field at C is naturally small and the maximum field occurs at D where the force is 5.7×10^6 volts per metre.. This is nearly twice the field required for a lightning discharge, hence with this distribution, 50 coulombs of positive electricity would be sufficient to initiate a discharge between the regions of positive and negative electricity.

We see thus that with 100 coulombs of positive electricity distributed in a sphere of 1 kilometre radius, and 100 coulombs of negative electricity distributed in a sphere of 3 kilometres radius directly above it, it is only necessary to concentrate part of this charge in quite a natural way to obtain lightning discharges, either downwards towards the ground or upwards towards the negatively charged cloud. It might be mentioned that with no negative charge above the positive charge, 58 coulombs of positive electricity distributed as in 15 b, is sufficient to initiate a downward discharge from C. With the distribution of positive electricity shown in 15 c, a discharge would be initiated from the upper point of the sphere, at D, with a positive charge of 58 coulombs and no negative charge; but in this case the discharge would not be a true upward discharge for it would travel along a line of force towards the ground just outside the charged region.

Having now demonstrated that charges of ~~electricity~~ electricity of the order known to occur in thunderstorms and distributed as required by the breaking drop theory can produce lightning discharge both upwards and downwards, from the region in which separation of electricity occurs, it is necessary to proceed one step further and show that sufficient breaking of drops can occur to produce the required separation of electricity .

The Accumulation of Water and the Number of Drops Broken.

It is quite impossible to calculate the amount of water which accumulates in the region of separation by direct meteorological methods; but a fair estimate can be obtained from consideration of the amount of ~~electricity~~ electricity carried down by the positively charged rain.

Measurements of the electricity of rain give charges per cc. of positively charged rain varying between 0 and 7 e.s.u. We may therefore take the magnitude of the positive charge on the water as 1 e.s.u. per cc. The whole region contains 100 coulombs, therefore the total amount of water in the region is $100 \times 3 \times 10^{9} = 3 \times 10^{11}$ grammes This amount of water, if spread uniformly over the cross section of the region in which it is contained, would give a layer of water

10 cm. deep This is certainly not an impossible amount of water from a meteorological point of view. It is interesting and important to form an estimate of the time necessary for the water to accumulate to this amount.

In Fig. 17*, the two line abc , a'b'c' represent the two stream lines enclosing the greater part of the region of separation. The air is suppoded to have at the ground a temperature of 30 degrees Centigrade and a relative humidity of about 60 % . As the air ascends, it reaches its dew-point at a height of 1 kilometre, where its temperature is 20 degrees Centigrade: this is the base of the cloud. It continues to ascend with increasing vertical velocity until it passes into the region where the vertical velocity reaches 8 metres per second. It leaves this region at a height of about 2 kilometres, indicated by the line bb', and enters the region of accumulating water. By hypothesis, it passes out of this region at a height of 4 kilometres - line aa'.

As we only require the order of magnitude, we may consider that the cross sections of the current at aa' and bb' are the same and equal to the cross section of the sphere. We may also neglect the changes in volume of the air due to changes in pressure. The upward velocity of the air at bb' is 8 metres per second, therefore the volume of air entering and leaving the region of separation is $\pi \times 10^6 \times 8 = 25 \times 10^6$ cubic metres.

This air carries with it all the water vapour which it contained at the surface, namely, 17 grammes per cubic metre. The total amount of water entering the region of separation is therefore $25 \times 17 \times 10^6 = 425 \times 10^6$ grammes per second. As the region of separation of electricity is practically the same as that of the accumulation of liquid water, the upper boundary of the region under consideration is the surface where the amount of liquid water carried out by the air current, is equal to the amount which falls

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back under gravity in the form of rain. The temperature here is 6 degrees Centigrade and a cubic metre of air at this temperature contains 7 grammes of water vapour, so the loss of water across the upper surface is therefore $25 \times 7 \times 10^6 = 175 \times 10^6$ grammes per second. The accumulation of water within the region of separation is $(425 - 175) \times 10^6 = 250 \times 10^6$ grammes per second. It would therefore take $\frac{3 \times 10^{11}}{2.5 \times 10^8} = 10^3$ seconds = 17 minutes for the water required to accumulate. This is [redacted] a reasonable period and is quite a short time for the birth of a thunderstorm.

We have now to consider the extent to which drops would be broken with this accumulation of water. As we are again only dealing with the order of magnitude, we may safely assume that half the water at any one time is in drops large enough to be broken up in the air current. A drop breaks when its radius is 0.25 cm, therefore its volume is then 0.067 cc. Thus the numberof drops available for breaking is $\frac{3 \times 10^{11}}{2 \times 6.7 \times 10^{-2}} = 2.2 \times 10^{12}$. According to the Simla experiments the breaking of a drop of water of the size of a raindrop produced 5×10^{-3} e.s.u. Therefore if every drop available for breaking broke at the same time $\frac{2.2 \times 5 \times 10^9}{3 \times 10^9} = 3.5$ coulombs of positive electricity would be produced. Thus the drops would only have to break 10 times to produce 35 coulombs, which is the average amount required for a lightning flash. This again seems a reasonable result, and there is no reason to believe that this amount of breaking of drops could not be reached with quite moderate ascending currents.

Considering the rain in the light of this theory, it will be noticed that according to Figs. 13 and 14, the heavy rain in the neighbourhood of the chief centres of activity of the storm has originated in two regions of the cloud. First there is the rain from the region of separation, which will be positively charged, and, secondly, the rain from the upper negatively charged cloud, which will carry a negative charge with it. Thus one would expect the rain here to be a mixture of positively and negatively charged drops, but that, on the whole, the positively charged rain should predominate. This is what is found by ~~app~~ all observers. In the Simla measurements heavy rain was predominantly positive; but often, with little change in the rate of rainfall, the electricity collected in consecutive " two-minute intervals " would change in amount and not infrequently in sign also. When the individual drops are investigated as we have seen was done by Gschwend, this is more clearly shown, for his observations exhibit a marked mixing of drops having positive and negative charges. In this region there is no reason why there should be any relationship between the size of the drops and the size of the charge carried. As one proceeds away from the region of the ascending currents, the charge carried by the rain is derived more and more from the negative charge carried by the cloud, until at considerable distances one would expect mainly negatively charged rain, although the occasional occurrence of positive rain is not excluded. Rain from this part of the cloud will be relatively light and uniform. The charge carried by a given quantity of water may here be very large, for the surface of the drops for a given amount of water increases greatly the smaller the drop, and the smaller the drop the more slowly it falls through the negatively charged cloud, so giving more time for the accumulation of charge. This is entirely in agreement with the Simla observations, which showed that the negatively charged rain was relatively the more frequent and the more highly charged the less the intensity of the rainfall. The most highly charged rain observed in the Simla experiments was light rain which carried a negative charge and fell exactly in these conditions (May 13, 1908).

From the above discussion it would appear that the theory under consideration is in conformity with the known facts of the air currents in a thunderstorm; that the quantities of electricity concerned, if suitably distributed within a thunderstorm cloud, are capable of producing upward and downward lightning discharges; that the accumulation of water necessary is not beyond what might be expected to occur with extensive upward currents; and that the frequencies with which the accumulated water would have to be broken up from large into small drops is not excessive. In addition the observed electrification of thunderstorm rain is such as would be expected on this theory.

CONCLUSION.

A. THE POLARITY OF A THUNDERCLOUD.

1. Evidence from the nature of lightning.

If the separation of electricity in a thundercloud takes place according to the method just described, then it should result in the elevation of the negative electricity over the positive, i.e. the base of the cloud should be the seat of positive electricity, and the top the seat of negative electricity. A cloud with the electricity distributed in this way is said to be of NEGATIVE polarity.

The problem of the polarity of thunderclouds has received considerable attention in recent years and there is still a great deal of divergence of opinion on the matter. G. C. Simpson (1), has put forward an explanation in favour of the idea of negative polarity based on observations on lightning and on a certain number of laboratory experiments.

A lightning discharge may be considered as a discharge through a gas at atmospheric pressure, and it may take three forms :-

(a) A discharge between a part of the atmosphere having a volume charge of electricity, generally a cloud, and the ground.

(b) A discharge between two parts of the atmosphere, each part having a definite volume charge of electricity, but of opposite signs.

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(1) G. C. Simpson... Proc. Roy. Soc. A, vol 111, pp 56-67, 1926.

(c) A discharge from a part of the atmosphere having a volume charge into a part of the atmosphere in which no initial volume charge is present.

If we neglect for the moment the method by which the electrical separation takes place in a thunderstorm, it may be assumed that :-

(i) The mechanism of a thunderstorm results in the concentration of electricity of one sign in the form of a volume charge throughout an appreciable extent of the atmosphere.

(ii) The air is unable to withstand more than a certain definite electrical intensity; if that intensity is exceeded ionisation takes place.

(iii) The mobility of the negative ions is so great in comparison with the mobility of the positive ions, that the latter may be considered not to move to any appreciable extent; while the former move with high velocity and are the chief vehicles of the transport of electricity.

Arguing from these considerations, Simpson was able to show that the following results should obtain:-

1. The conducting channel in a lightning flash originates in the region of maximum electric field and develops only in the direction of the seat of negative electricity.
2. A negatively charged cloud can only be discharged by a discharge which originates in a positively charged cloud or in the induced positive charge on the earth's surface.
3. A positively charged cloud may be discharged by discharges starting in the cloud and terminating either in the surrounding atmosphere or on the earth's surface
4. If a lightning flash is branched, the branches are always directed towards the seat of negative electricity.

In order to obtain support for these theoretical conclusions, Simpson made several laboratory experiments. In the first experiment he used two circular electrodes, each provided with a short piece of wire projecting from the edge. These were placed on a photographic plate, each being connected to the outer layer of a Leyden jar, the inner layers of the two jars being connected to the terminals of a Wimshurst machine. On causing a spark to pass between the ~~two~~ terminals of the machine, an induced discharge took place from the two circular electrodes over the photographic plate. The result is shown in Fig. 18.* The electrode A received a positive charge. We see that the discharge has left A in long, pointed and much branched channels, which have proceeded far into the surrounding region. It will also be noticed that each channel has a sharp boundary and that the ends of all the channels are pointed. The conditions are entirely different in the negative discharge from the electrode B. There the discharge has not proceeded along clear cut channels, but has simply spread out in a diffuse cloud at the end of the wire. The electrical intensity must have been approximately the same at the two electrodes; but in the one case the discharge has spread far from the electrode into the surrounding air, while in the other case the discharge has not spread appreciably farther than the small region in which ionisation occurred in consequence of the first intense field.

The next experiments were made using a brass ball to represent a cloud and mounting a brass plate opposite to it to represent the earth, the ball and the plate being connected to the poles of a Wimshurst machine. The brass ball, half an inch in diameter, was mounted on the end of a brass rod, pivoted so that the ball could describe a circle in a plane at right angles to the brass plate. The arm was first set a right angles to the plate so that the ball was at the minimum distance from the plate, about 1½ inches, and a discharge made. The arm was then rotated slightly, thus increasing the spark gap, and another discharge made. This was repeated, the result being a series of discharges, each having a longer spark gap.

* P. 142.

When the ball was positively charged and at its minimum distance from the plate, sparks passed between the ball and the plate. These sparks were branched towards the plate. As the spark gap was lengthened, branched discharges continued from the ball towards the plate, but did not reach it. A photograph of the effect is shown in Fig. 19,[*] which is strongly reminiscent of typical photographs taken during thunderstorms.

When the ball was charged negatively the conditions were entirely different. If the ball was sufficiently near the plate, strong unbranched discharges passed between the ball and the plate, but when the spark gap was lengthened these ceased entirely and there was only a small brush discharge on the surface of the ball. In this case, Fig. 20,[†] there was no intermediate discharge between a simple brush and a spark to the plate.

These experiments confirmed the theoretical conclusion that branched discharges " into the air " were possible from positively charged clouds, but not from negatively charged clouds. According to this evidence, discharges may pass between the earth and both positively and negatively charged clouds, but in each case the branching will be away from the seat of the ~~negative~~ positive charge. A discharge from a positively charged cloud will have the branches turned away from the cloud, while that from a negatively charged cloud -- which must always start from the earth or from a positively charged cloud -- will have the branches directed towards the cloud.

Having made these experiments, Simpson examined a large number of photographs of lightning, in order to find if these, considered along with his experimental results and his theoretical conclusions, would give any indication as to the distribution of electricity on the clouds concerned.

In all he examined 442 photographs, and he found that " 328

[*] P. 142

[†] P. 143.

photographs indicate positive clouds while only 89 indicate negatively charged clouds; this is a ratio of nearly 4 to 1, and even this, I am inclined to believe, is too small a ratio ". (1).

Figs. 21* and 22† are typical photographs of lightning discharges. They show the branching away from the cloud towards the ground, indicating that the charge which gave rise to the flash was positive.

The evidence discussed above would indicate that most lightning discharges take place from a cloud with its base positively charged, i.e. from a cloud of negative polarity. These observations then, support the idea of a thundercloud being positively charge at its base and negatively charged at the top, as is required if the separation of electricity takes place according to the " breaking-drop " theory.

2. Evidence from Field changes due to thunderstorms.

A great deal of quantitative information on the electrification of thunderstorms has been derived from measurements of the electric fields and field-changes produced by them at the surface of the earth. The development of these measurements and the interpretation of the results is mainly due to C. T. R. Wilson.

The general principle of the method was to keep an exposed conductor at zero potential by alteration in the capacity of a compensating condenser, when the charge induced upon the conductor by the field is equal to that given by the compensator to the system. In the measurement of rapidly changing thunderstorm fields, Wilson produced compensation automatically and practically instantaneously by the use of an " H " pattern of capillary electrometer. As the exposed conductor Wilson used a " test-plate " of the same type as that used in the induced charge method of studying the fine-weather

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(1) G.C.Simpson... loc. cit. 1926, p 64.

* p. 143
+ p. 145

field. For more distant storms he used an elevated sphere, and for very distant storms a form of wireless aerial. (i)

In discussing the field changes to be expected, we may consider that a thundercloud is essentially bipolar, electric charges of opposite sign being liberated at different heights in the cloud. We may speak of the upper and lower charges without specifying at the moment their exact positions or their relative magnitudes. At distances which are large compared with the dimensions of the charged portions of the cloud, we may treat these as point charges.

In Fig. 23,* A represents the upper charge, Q_2, at height H_2 above the earth, and B the lower charge, $-Q_1$, of opposite sign, at height H_1. P is the point at which the vertical electric field is measured. According to the usual convention, this field is called positive if its direction is downwards and negative if it is upwards.

The steady vertical field at P (the field at P when neither pole of the cloud is discharging or recovering from a discharge) is given by the expression..

$$F = \frac{2Q_2H_2}{(H_2^2+L^2)^{3/2}} - \frac{2Q_1H_1}{(H_1^2+L^2)^{3/2}} \quad \text{(ii)}$$

In general this expression shows that for distances L less than a certain critical value the second term and, consequently, the effect of the lower charge B predominates, while for distances greater than this critical value the first term is the greater and the sign of the field at P is set by that of the upper charge A. Thus with an increasing distance L between the cloud and the station the field will first be of the same sign as the charge upon the lower part, then become zero, and then reverse so as to be of the same sign as the upper charge. This reversal of the sign of the field with distance will only occur provided that the lower charge Q_1 is not less than H_1^2/H_2^2 times, nor greater than H_2/H_1 times the upper charge Q_2.

(i) C.T.R.Wilson.. Proc. Roy. Soc. A, vol 92, p 555, 1916.
Phil. Trans. A, vol 221, p 73, 1921.

(ii) " " loc. cit. 1921, p 96.

* P. 144.

Information as to the electrical nature of the cloud may also be obtained in another way, by examining the sign and magnitude of the changes of field caused by lightning discharges. Let us consider Fig. 23 to represent an isolated cloud in which the flashes of lightning pass nearly vertically between the two poles of the cloud, or between the pole and the ground. We may represent the former type of discharge by the symbol AB, and the two latter by AC and BC. Then the equation above shows that the sudden changes of field resulting from these three types of discharge are given by the following expressions:-

Discharge AC $\Delta F = - \dfrac{2Q_2 H_2}{(H_2^2 + L^2)^{3/2}}$

Discharge BC $\Delta F = + \dfrac{2Q_1 H_1}{(H_1^2 + L^2)^{3/2}}$

Discharge AB $\Delta F = -2Q_2 \left[\dfrac{H_2}{(H_2^2 + L^2)^{3/2}} - \dfrac{H_1}{(H_1^2 + L^2)^{3/2}} \right]$ if $Q_1 > Q_2$

or $\Delta F = -2Q_1 \left[\dfrac{H_2}{(H_2^2 + L^2)^{3/2}} - \dfrac{H_1}{(H_1^2 + L^2)^{3/2}} \right]$ if $Q_1 < Q_2$

For the two single pole discharges the sign of ΔF, the field change, is independent of the distance, but for the pole to pole discharge it evidently reverses as the distance L increases.

Considering a cloud of POSITIVE polarity, one in which the upper pole is positive and the lower one negative, the effects to be expected are shown in the tables below :-

Distant Positive Cloud.

Discharge	Sign of Sudden Field Change
AB	Negative
BC	Positive
AC	Negative.

Near Positive Cloud.

Discharge	Sign of Sudden Field Change.
AB	Positive
BC	Positive
AC	Negative.

For a cloud of polarity opposite to this, negative above and positive below, the sign of each of these field changes would be reversed.

From his experiments on the steady electric fields below thunderclouds, in 1916 and 1920, Wilson came to the conclusion that the great majority of thunderclouds are of positive polarity.

Experiments on the sudden field changes accompanying lightning flashes were performed by Schonland and Craib, in South Africa, in 1926 (i). Their results, considered in the light of the theory outlined briefly above, indicated that the clouds they examined were bipolar in nature, and that, in practically every case, they were of positive polarity.

Fig. 24* shows a typical photographic record of field changes.

In his paper on the Mechanism of a Thunderstorm, mentioned earlier (ii), Simpson considered the results of Schonland and Craib in the light of his own experiments on lightning and from the point of view of the " breaking-drop " theory. He considered that their evidence on the nature of the lightning flashes was not very clear, and showed that the results would fit in with the idea of a cloud of negative polarity, if the electricity was considered to be distributed as shown roughly in Fig. 25.**

Not satisfied that Simpson's criticisms were valid, Schonland and Craib repeated their experiments and took special care to observe the nature of the lightning discharges. (iii) These further experiments showed quite definitely that the conclusions reached in

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(i) Schonland and Craib...Proc. Roy. Soc. A, vol 114, p 229, 1927
(ii) G.C.Simpson....... " " " " pp 389-401, 1927
(iii) Schonland.... " " " " vol 118, p 233, 1928.

* P.144. ** P.144.

the previous work were correct, i.e. that the clouds on which the observations were made were of positive polarity.

Experiments of a similar nature to those of Schonland and Craib and Wilson were carried out in Sweden by H. Norinder (i), whose results were in complete agreement with those cited above.

More recently experiments on the polarity of thunderclouds have been carried out in South Africa by E.C.Halliday (ii). The method of experiment was the same as that of the other observers, but Halliday obtained closer correlation between the nature of the lightning flashes and the sign of the sudden field changes by actually photographing the flashes on every possible occasion. Again the results were definitely in favour of the idea of positive polarity.

It is of interest to note that experiments of the type developed by Wilson have furnished much valuable quantitative information about the electrification of thunderstorms. Among other results we may mention (a) the electric moment of a lightning discharge is of the order of 60 coulomb-kilometres, and (b) the average quantity of electricity conveyed by a lightning discharge is of the order of 20 coulombs.

3. Other Evidence on the Polarity of Thunderclouds.

Some information on the question of the polarity of thunder-clouds has been obtained from experiments on the currents carried by point discharges beneath them.

Experiments of this nature have been carried out by Schonland (iii) in South Africa, and by Wormell in England (iv).

(i) H. Norinder... Teknisk Tidskrift, 33, p 184, Stockholm, 1923
(ii) E.C. Halliday.. Proc. Roy. Soc., A, vol 138, p 205, 1932.
(iii) Schonland.. " " " " vol 118, p 252, 1928.
(iv) Wormell... " " " " vol 115, p 443, 1927.
" " " " " vol 127, p 567, 1930.

Schonland connected a small tree, mounted on insulators, to earth through a galvanometer, while Wormell used a sharp point carried by an elevated pole, and connected to a special form of water micro-voltameter by means of which the quantities of positive and negative electricity discharged by the point could be determined. Both authors found that over a long period there was a considerable net loss of positive electricity by the discharger. This excess of of upward current (positive discharge) was very [illegible] pronounced during thunderstorms and disturbed weather, thus suggesting that the thunderclouds were frequently of positive polarity

These regions of disturbed weather are considered by some authors to be the source of the replenishment of the earth's negative charge. Under rain and thunderclouds there are two processes at work which convey considerable quantities of negative charge to the earth. The first of these is the discharge from points mentioned above . The second process is the charge conveyed to the ground by lightning flashes from thunderclouds . According to Brooks (i), some 100 lightning discharges occur every second over the whole surface of the earth, each involving the passage of a charge of the order of 20 coulombs. Only a fraction of these, perhaps one in four on the average, strike the ground. The effectiveness of this process of transference of charge will depend upon whether more charges of one sign than another are conveyed to the earth. If, for example, practically all the charges transfered were negative, the process would be equivalent to a continuous compensation current of about 500 amperes. Though there is evidence that this is actually the case, the question is still under investigation.

An estimate of the total exchange of electricity between the earth and the atmosphere, over a square kilometre of ground at Cambridge, has been made by Wormell (ii), on the basis of his point discharge experiments and observations on lightning discharges.

(i) C.E.P.Brooks.. Geophys.Mem. No 24,(4th No of Vol 3), Met.Off.1925

(ii) loc. cit. 1930, pp 585-590

The air-earth conduction current loss, and the effect of rain and snow were estimated from average values of these quantities. The results were (i)....

	Coulomb/sq.km./ annum.
Fine weather current	60
Precipitation	20
Lightning discharges	20
Current carried by point discharges	100
Net gain of negative charge	40

Though such an estimate is only a very rough one, the results appear to show that the earth does gain a negative charge as a result of the four processes mentioned.

Returning to the problem of the polarity of thunderclouds we may mention finally the work of Appleton, Watson-Watt and Herd in this connection. They first of all made experiments on atmospheric wave forms,(ii) and then supplemented these by observations , at Aldershot, Cambridge, Helwan and Khartoum on the net changes in the earths electric field resulting from lightning discharges, using an aerial and a cathode-ray oscillograph (iii). In both sets of experiments their results were definitely in favour of a cloud of positive polarity.

The evidence we have discussed briefly in the preceding pages seems to suggest that thunderclouds are more often of positive polarity, as indicated in Fig. 26,* than of the polarity represented in Fig. 25 which is required by the breaking-drop theory.

(i) Wormell.. loc. cit. 1930, p 589.
(ii) Appleton, Watt and Herd..... P.R.S., A, vol 103, p 84, 1923.
(iii) " " " " P.R.S., A, vol 111, pp 615-678, 1926.

* P. 145.

B. Alternative Theories.

In the preceding pages we have given a detailed account of the " Breaking Drop " theory of the origin of the electricity of rain. We have shown also how this leads to a theory of the Mechanism of Thunderstorms, and, finally, how recent research does not altogether agree with this view in some respects.

Any successful theory must lead to a mechanism that will produce the observed range of visual and electrical effects, and be satisfactory from both a qualitative and quantitative point of view. Such a theory must be able to link together the electrical phenomena of fine weather, " quiet rainfall ", and thunderstorms, in a continuous chain.

There have been many attempts to explain how the initial separation of positive and negative electricity occurs.

We have mentioned earlier (p. 14), a theory due to Gerdien based on the observations of J.J.Thomson and Wilson on the condensation of water on the two sorts of ions. As we pointed out then, the effect of the sign of the electrification on condensation must be very small, and it has never been experimentally demonstrated.

There are several ways in which drops may conceivably acquire a charge after their original formation. It has been suggested by Schmauss (i), that the drops may acquire a negative charge through capturing more negative than positive ions from the surrounding air on account of the greater mobility of the negative ions. Again exposure to radiations of short wave-length (ultra-violet light or γ rays) may cause drops or ice crystals to emit negative electrons and so become positively charged (ii); this effect

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(i) Schmauss.. Ann.d.Phys. 9, p 224, 1902.
(ii) Rey.. Le Radium, 11, p 204, 1914.

would become most marked at great heights, where the ultra-violet light from the sun is appreciable, but it is difficult to see how it could come into operation at heights of about 2000 metres, the mean height of cumulus clouds.

There is also the possibility of electrification by friction of water drops with ice crystals, or of either of these with dust particles, in falling through the air, an idea suggested by Sohncke. (i)

In addition to these theories, several have been put forward based on the phenomena of influence. The earliest of these was suggested by Pellat (ii), as long ago as 1885. Pellat imagined a cloud to be similar to a semi-conducting body which became charged by induction in the earth's field, becoming positive below and negative above. This old view of a cloud being a conducting body in a non-conducting atmosphere is not now accepted.

Elster and Geitel's Theory.

Another theory based on the idea of influence, but from a different angle, is due to Elster and Geitel. This was first suggested in 1885, and set out more definitely by the same authors in 1913.(iii) They attribute the electric field of a thundercloud mainly to collisions of large and small drops in an already existing field. In a cloud in which the electric field is directed upwards, the upper half of a falling drop will be positively charged, the lower negatively. If a droplet carried up in the ascending air stream strikes the lower half of the larger drop and rebounds after making electric contact, it will carry off a negative charge, leaving the larger drop with an excess of positive electricity.

(i) Sohncke... Met. Zeit. 5, p 413, 1888.
(ii) Pellat.. Journ. de Phys. 3, p 4, 1885.
(iii) Elster & Geitel. Wied. Ann. 25, p 116, 1885.
" " Phys. Zeit. 14, p 1287, 1913.

The negatively charged droplet will be carried upward relatively to the positively charged drop by the upward air stream. If the electric force were directed upwards as assumed above,(i.e. if the potential gradient were negative) collisions would lead to the smaller cloud particles becoming negatively charged, the larger drops positively; the former would be carried up relatively to the latter, and there would thus be produced in the region between them an additional field of the same sign as the original field. The process would always result in an originally existing field within the cloud being increased in magnitude, and,(until compensating processes came into play) at a continually increasing rate. According to this view the thundercloud is in effect a large influence electric-machine; its polarity will depend on the initial sign of the electric field. In some cases it may be the ordinary normal positive potential gradient that determines the polarity of the cloud, which will then be positive.

The question as to whether the necessary electrical contact between the large and small drops can occur at the moment of collision, without coalescence at the same time occuring, is fundamental in relation to Elster and Geitel's theory. The very striking effect of electrification in causing the coalescence of water surfaces, and the high contact resistance when coalescence does not occur, are both well known from the experiments made by the late Lord Rayleigh (i), on jets of water. Simpson (ii) regarded these as decisive against Elster and Geitel's theory, but this argument has been answered by Gschwend (iii) with a laboratory demonstration of the required phenomenon. In cases where coalescence does result from the collision, it has been suggested by Wilson (iv) that " splinters " will be produced; the minute

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(i) Rayleigh.. loc. cit. (ii) Simpson..Phil.Mag. 30, p 1, 1915
(iii) Gschwend... loc.cit. p 45.
(iv) Wilson.. Dict. Applied Physics, vol 3, p 105.

droplets leaving the scene of the collision may reasonably be expected to be those with a charge subject to repulsion from the main surface, i.e. those carrying a charge of the same sign, and therefore those which will augment the field.

Wilson's Theory.

C. T. R. Wilson, in a paper mentioned earlier (1), and in lectures, first of all in 1924 to a joint meeting of the Physical and Royal Meteorological Societies on Ionisation in the atmosphere, and later to the Franklin Institute in America, has developed the " influence " idea still further. He considers that the capture of ions by initially neutral drops in an electric field is very important.

According to Wilson, a thundercloud is essentially bi-polar, and of positive polarity, and on this view the preponderance of negative potential gradients below shower clouds and thunderclouds is due primarily to the negative charge on the cloud being nearer to the ground than the positive; the cloud may in addition acquire an excess of negative charge when the loss of positive charge by conduction to the upper atmosphere exceeds the loss of negative charge to the ground. The prevailing positive charge on rain is on this view not the cause but the result of the negative potential gradient; the rain intercepts and returns to the earth a portion of the charge carried by the stream of positive ions which are being driven up by the negative potential gradient.

The cloud is to be considered as made up of large negatively charged drops and small positively charged droplets.

Such a cloud, originally neutral, will at once begin to acquire

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(1) C.T.R.Wilson.. Phil.Trans. 221, p 73, 1920
Proc.Phys.Soc. vol 37, Part 2, p 32D, 1925
Journ.Franklin Inst. vol 208, No. 1, p 1, 1929

a positive charge at the top and a negative charge at the bottom through the relative vertical motion of the two classes of carriers. The two equal and opposite charges thus accumulating at the top and the bottom may be separated by a great thickness of neutral cloud. The accumulation of a positive charge above and a negative charge below results in the development of an electric field within the cloud, which tends to hinder the negative drops from falling and the positive particles from being carried up by the air stream.

The rate of accumulation of the upper and lower free charges, and the resulting rate of increase of the field will become less as these charges increase, for two reasons. The field within the cloud opposes the falling of the negative drops and the carrying up of the positive cloud particles; and again the dissipation of the upper and lower charges by ionisation currents or otherwise increases as the charges increase. There may come a stage where a balance is reached and no further increase in the field results; or on the other hand the field may reach the sparking limit before such a balance can be attained, and we have then a lightning flash.

If such a discharge destroys the vertical field within the cloud while still leaving the positively and negatively charged carriers, the destruction of the field will be followed by its regeneration through the separation of the carriers by gravity. The relative rate of separation may be taken, from the results of experiments by Macky (1) on the behaviour of water drops in strong electric fields, to be the terminal velocity of a drop 0.15 cm. in radius, which is about 6 metres a second. Relative to such a drop the much slower droplets may be considered as stationary. The average rate at which the initial regeneration of the moment of the cloud takes place is 60/5 coulomb kilometres per second (using the data given on p 117), From these figures Wilson finds the average total charge

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(1) Macky.. Proc.Roy.Soc. A, vol 133, p 565, 1931.

on the positive or negative carriers in the neutral part of the cloud is about 500 coulombs occupying a volume of some 4 cubic kilometres. The charge per cc. of water he finds to be less than 30 e.s.u., a result which is in reasonable accord with measurements of the charge on rain from thunderstorms.

The mechanism suggested by Wilson as the cause of the opposite charges on large and small drops depends on the presence of ions in the cloud; in strong fields the positive ions would require to be of small mobility such as would result from their attachment to nuclei or small cloud particles.

A neutral drop falling through the air in a field of positive potential gradient, at a speed greater than that with which the positive ions are being driven by the field, will absorb negative ions at its lower positively charged surface; positive ions cannot reach its xxxxx negatively charged upper surface from above as they cannot overtake the drop. It is only positive ions which the falling drop has overtaken (or in other words which have been carried up by the air from below the drop) that can approach its upper negatively charged surface; and these have already suffered repulsion by the lower positive half of the drop before they come under the influence of the upper negatively charged half. The original neutral falling drop will at first catch only negative ions; and in air of equal conductivity for ions of both signs, it will continue to catch more negative than positive electricity till a resultant negative charge is acquired amounting to a considerable fraction of the induced charge.

The induced charge on each half of a spherical drop is proportional to the area of cross section and to the field. For a drop of one millimetre radius in a field of 10000 volts per cm., it is about ¼ e.s.u. If the drop acquires a resultant negative charge of one-tenth of this amount, (increasing the upper charge by one-twentieth and diminishing the lower positive charge by an equal amount), the net charge will be about 6 e.s.u. per cc. of water. A drop of one-tenth mm. radius only requires to gain a negative charge equal to one-twentieth of the induced charge in order that its net charge per cc. may reach the amount (30 e.s.u.) required for its weight to be supported by a field of 10000 volts/cm. In a thundercloud of the type we are considering, it is only for a small part of the time between two discharges that the field is much below the maximum.

If we assume that sufficient ionisation occurs, and that the positive ions have their mobility reduced to that of ordinary large ions, these will move through the air with a speed of a few cms. per second in a field of 10000 volts/cm. Then all drops which are large enough (more than a few thousandths of a cm. radius) to fall faster than these positive ions are moving, will acquire negative charges; the charge per cc. except in the case of the largest drops may approach that required to make the field support the weight of the drops. Drops smaller than the critical size will acquire positive charges.

The principal source of ionisation in the active thundercloud is probably the field itself. This is likely to act mainly by drawing out any specially large drops into pointed form and making them into very efficient point-dischargers; experiment shows that a field of rather less than the magnitude assumed has this effect on drops exceeding 2 mm. in radius.

The acquisition by the drops of the large charges, which we have to postulate to explain the rapid regeneration of the field after each discharge, may perhaps occur in some such way as that which has just been outlined. The original building up of the field of the cloud may be much more gradual; in the initial stages, the fine-weather positive potential gradient is likely to determine the sign of the polarity of the cloud; and the charge will ~~at first~~ be at first acquired from the ordinary ions set free by ionising radiations.

A bi-polar cloud of positive polarity will produce at the ground below it a negative potential gradient. Except for a short interval after a discharge, the gradient is generally sufficient to cause point discharges and thus an upward current of positive ions. Raindrops which were negatively charged in the cloud will generally not only lose their negative charges, but acquire a positive charge in falling through the upward stream of positive ions. Even when the field is insufficient to cause point discharges, the fall of drops through the air exposed to the normal sources of ionisation will, in a field of negative potential gradient, result in the drops acquiring a positive charge by a process like that which we have supposed to give them their negative charges when in the cloud.

The preponderance of positively charged rain will be the result of the preponderance of negative potential gradients below shower clouds.

It will be noticed that on this view, the sign of the charge on the rain when it reaches the ground is not a sure indication of its sign when it left the cloud.

As we have seen in the previous section of the essay there is much experimental evidence in favour of Wilson's view that thunderclouds are generally of positive polarity... a fact upon which this theory is based. His ideas on the capture of ions by drops have been confirmed by some recent experiments by Gott (1), on the electric charge collected by water drops falling through ionised air in a vertical electric field. Gott found that in the presence of ions of one sign only rising up to meet the falling drop, it collected a charge for all values of the field. When ions of one sign only were moving down in the same direction as the drop was falling, the charge collected depended on the velocities of the drop and the ions. If the descending ions had the greater velocity,

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(1) J.P. Gott.. Proc.Roy.Soc. A, vol 142, p 248, 1933.

so that they overtook the drop, then it collected a charge, but if the drop had the greater velocity, so that the descending ions could not overtake it, then it collected no charge. These results are in accordance with Wilson's theory as outlined above.

Again, if Wilson's views are correct, we should expect the total number of thunderstorms to be a maximum, when the most thundery regions of the earth were in the position with respect to the sun most favourable for thunderstorms. If the thunderstorms are the cause of the fine-weather field, the resulting daily variation in the total number of thunderstorms in action, should be associated with a simultaneous variation in the fine-weather potential gradient. It was pointed out some years ago by Mauchly, that the investigations of the Carnegie Institute (i), on Potential Gradient over the oceans, indicated that the maximum and minimum in the daily variation occur simultaneously over the whole globe. Whipple, (ii), has shown more recently that there is a close parallelism between the curves of daily variation of the total number of thunderstorms and of the fine-weather potential gradient over the whole earth.

(i) Mauchly... Terr. Mag. 28, p 61, 1923.

(ii) Whipple... Q.J.Roy.Met.Soc., 55, p 351, 1929.

C. The Present Position.

Whatever may be the merits or demerits of Wilson's theory it certainly brings out an omission in the " Breaking Drop " theory, i.e. that it appears to neglect the fact of the pre-existence of the fine-weather field. All the experiments we have quoted on the breaking up of water drops on air currents, ignored the fact that in practice the drops must break up in an electric field.

Experiments on the breaking up of drops in electric fields have been performed by several workers. In the intense electric fields known to exist in thunderclouds, large water drops may suffer disruption when electrical forces overcome surface tension. Following experiments by Wilson and Taylor (i) on the critical fields for rupture of soap bubbles, direct experiments have been made on the disruption of water drops by Nolan.(ii) According to these authors explosive bursting takes place in a field of F volts per cm. when the radius of the drop, r cm, is such that $F\sqrt{r}$ has a value of about 4000. Very large drops (r = 0.2 to 0.35 cm) were found to disintegrate, with less violence than in the explosive break up, under slightly smaller fields. The separation of the high induced charges which results from this disruption, has consequences in limiting the fields in the area in which the drops are present and in supplying charges for transport to other parts of the thundercloud, which have not yet been fully explored. Experiments of a similar nature and with the same results have been carried out also by Macky (iii). This author concluded from his

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(i) Wilson & Taylor.. Proc.Camb.Phil.Soc. 22, p 728, 1925.
(ii) Nolan.. Proc.Roy.Ir.Acad. 37, A, No. 3, pp 28-37, 1926
(iii) Macky.. loc. cit.

experiments, that no drops larger than 0.15 cm. in radius can be present in the fully charged cloud. In addition to thse results, Nolan mentions the fact that he could not detect the usual separation of electricity, when the drops were broken up in an electric field.

These facts certainly seem to indicate that the amount of separation supposed by Simpson, will not take place in an actual thundercloud. It appears that if drops are introduced in considerable numbers into an atmospheric electric field, or are produced there by growth or coalescence, their effect is to reduce the intensity of the field rapidly to a value determined by the force required to burst the largest drops. The formation of raindrops of any size may therefore be considered to act as a severe check on the building up of intense fields.

The question thus arises as to how the fields are built up. Simpson's theory points to the rupture of raindrops accompnaied by the Lenard or Ballo-electric separation of electricity, the water being positively, and the air, on the whole, negatively charged. It appeals to the differential action of gravity and a strong air current directed upwards to separate the positively charged water from the negative ions against the action of the electric field. The ions will, after a short time, have assumed low mobilities and consequently will not be turned back by the electric field. In the light of the experiments we have just mentioned the process of rupture of raindrops by upward moving air currents must not be supposed to occur within the space in which the electric field is established; if it did, the separation of the induced charges would destroy the field more rapidly than the ballo-electric action could build it up. We must suppose that there is a region in which the electric field is weak, but in which there is an abundance of drops and much bursting of these by the purely mechanical action of the air stream. Above this, the electric field is established by the transfer upwards of the negative ions by the ascending air. The region in which the field is established, must be supposed to contain very few drops of sufficient size to be broken up by a field of less than the sparking intensity.

We have mentioned earlier Simpson's work on the nature of lightning flashes, in order to show that thunderclouds are generally of negative polarity, as is required by his theory. In the light of several very recent experiments, it cannot be said that this evidence is very conclusive.

In a paper by N.E. Dorsey (i), a second theory is given for the formation and progress of a lightning flash which differs materially from Simpson's. It is based upon some peculiar lightning strokes, the effects of which indicate that the direction of a stroke is not dependent upon the direction of a pre-existent field due to a charged cloud, but is only initiated by such a field and progresses in a manner analogous to that of a beam of cathode rays. The path of the stroke is described as being formed by an elongated dart of flying negative electrons, which originates in a region of intense electrostatic stress and acquires sufficient velocity to maintain itself in weaker fields, and as an extreme case to penetrate an adverse field, until it strikes some solid object, such as xx a tree, with a resultant explosion as the dart is suddenly impeded. Trailing electrons combine with positive residues to form the flash, and while the path remains highly ionised, the cloud may be partly discharged with a heavy flow of current.

An experiment of C. V. Boys (ii), in photographing a flash of lightning with a special camera having a pair of separated lenses revolving in a circle before a stationary plate, has led him, after

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(i) Dorsey.. Journ.Franklin. Inst. vol. 201, p 485, 1926.
(ii) Boys..."Nature", vol 118, p 749, 1926.
" " vol 122, p 310, 1928.

stereoscopic examination of the images, to the conclusion that a lightning flash originates at both positive and negative ends nearly, if not quite, simultaneously. Some very recent work by Schonland and Collens in South Africa (i), using the original camera designed by Boys, supports this view. In addition these authors found that the polarity of such discharges was such as to make the cloud base negative and the earth positive. Similar experiments with this type of camera were carried out by Halliday, also in South Africa, and with similar results.(ii)

In addition to these experiments, mention may be made of some laboratory experiments performed by Schonland and Allibone (iii), which the authors assert showed that the forking of a lightning flash does not give any indication of its direction or of the polarity of the cloud from which it started.

Some information may also be adduced from photographs of lightning channels taken by a moving camera. Fig. 27* illustrates how the apparent branching of a flash observed by the eye is often the result of the superposition of a number of separate strokes whose tracks coincide in part. This photograph is of the same flash as that shown in Fig. 22. (iv)

We may note that Simpson's theory of the formation of a lightning flash requires that it originate at the seat of positive electricity; Dorsey's requires that it originate at the seat of negative electricity, while photographs of the Boys' type indicate that it originates at both ends and meets midway. This diversity indicates the speculative character of much of the discussion of lightning.

(i) Schonland & Collens.. Proc.Roy.Soc. A, vol 143, p 654, 1934.
(ii) Halliday... Phil. Mag. vol. 98, p 409, 1933.
(iii) Schonland & Allibone.. " Nature " vol. 128, p 794, 1931.
(iv) Photographs after Walter..... Phys.Zeit, vol 19, p 273, 1928.

* p. 145

What has gone before serves to show that the elasticity of the successful theory will be severely taxed. Almost any one of the theories we have described can be made, by the exercise of ingenuity, compatible with the conflicting evidence we have discussed, but the appeal of the theory suffers with every fresh exercise of ingenuity which it demands. None of the " influence--machine " writers has been so courageous - or so rash - as to give, in terms of his working theory, a full description of a thunderstorm and its related phenomena from start to finish. Simpson alone has put his " friction-machine " to this searching test. Most writers have been prepared to admit the simultaneous or separate action of several suggested mechanisms; Simpson alone gives the impression - perhaps inadvertantly, in the heat of the battle, in defence of a theory which, in its primitive outline, is unrivalled in elegance and economy - that he will admit no thunderstorm mechanism save his own.

The time for final judgement is not yet. Chree has said: " No simple explanation of thunder and lightning can be accepted without reserve. But there appears to be a general consensus of opinion that the theory proposed by Dr. G. C. Simpson is less open to criticism than any other". Wilson says: " There can be little doubt that the processes suggested by Simpson and by Elster and Geitel are both effective in thunderclouds; further work is required to determine their relative importance ".

We have mentioned the fact that Simpson interprets the lightning photographs examined by him as showing that " the preponderance of the lower clouds from which lightning discharges proceed are positively charged ". Banerji (i), has described eighteen Bombay thunderstorms which " had their front part negatively charged, the central part positively charged, and the rear negatively charged....

(i) K.S.Banerji... Journ.Roy.Met.Soc. vol. 56, p 305, 1930.

.... The distribution of charges therefore... agrees with Simpson's breaking drop theory." Perhaps the most diplomatic conclusion in current literature, is that of Nukiyama and Noto (i), that the inland thunderstorms of Japan are of the Simpson type; the coastal of the Wilson.

One thing, and one thing only, may be regarded as proven beyond any possibility of reasonable doubt. Mathias(ii) and several American investigators all join the group of workers we have mentioned, in concluding that the great majority of heavy lightning discharges which reach the ground, pass between a negative charge on the cloud, and a positive charge on the ground. With that certainty, and with the knowledge that the investigation of atmospheric electricity has never been so diligently and effectively pursued as now, we must for the moment be content. It seems probable that research on ionisation in the upper atmosphere, which is being carried out at present on an International scale, may throw considerable light on the problem.

(i) Nukiyama & Noto.. Tokio J.Astr.Geophys. 9, p 101-113, 1932.

(ii) Mathias.. Comptes Rendus.... several
Ann. des P.T.T., Nov 1927, July 1928
Bull. Obs. Puy de Dôme, 1930

DIAGRAMS

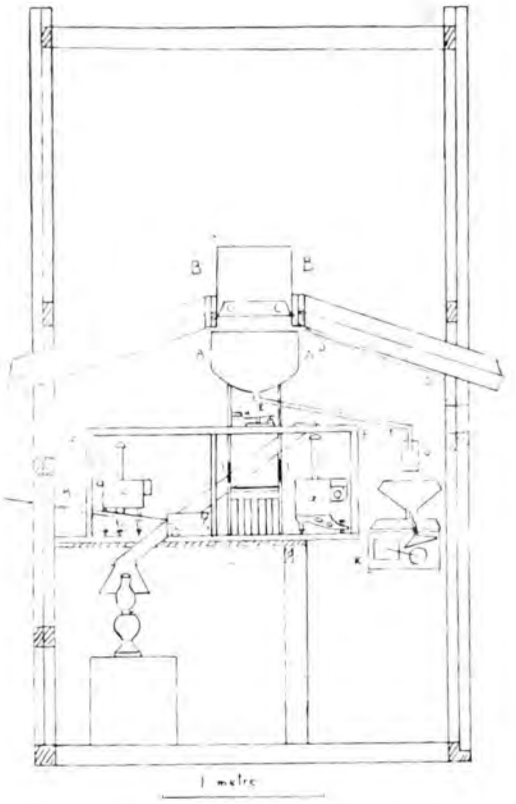


Fig 1

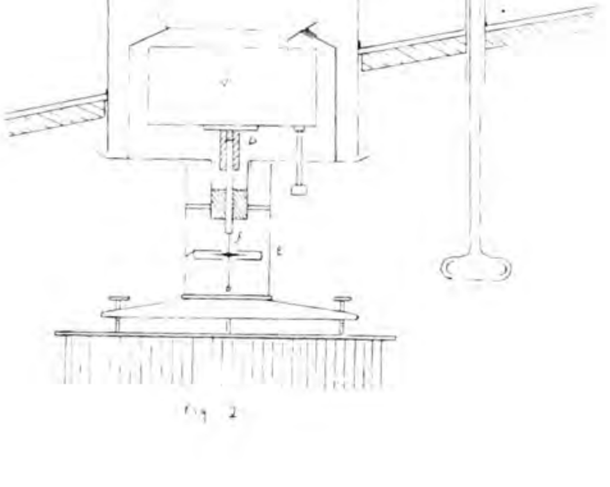


Fig 2

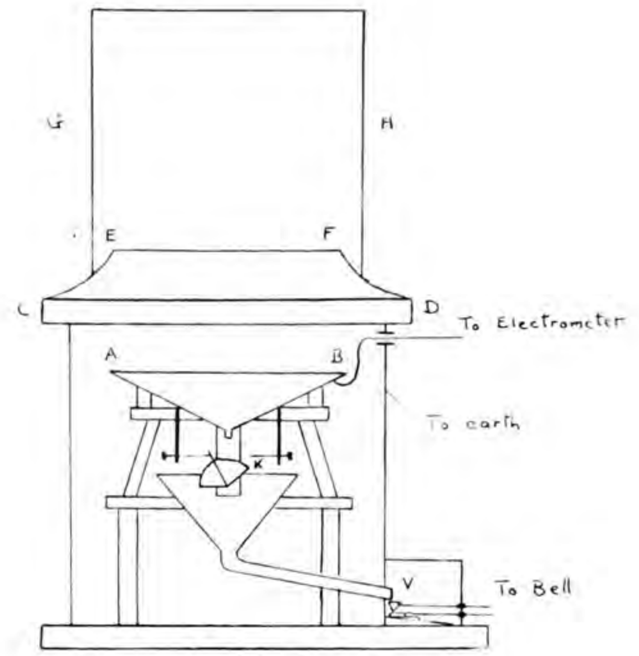


Fig 3

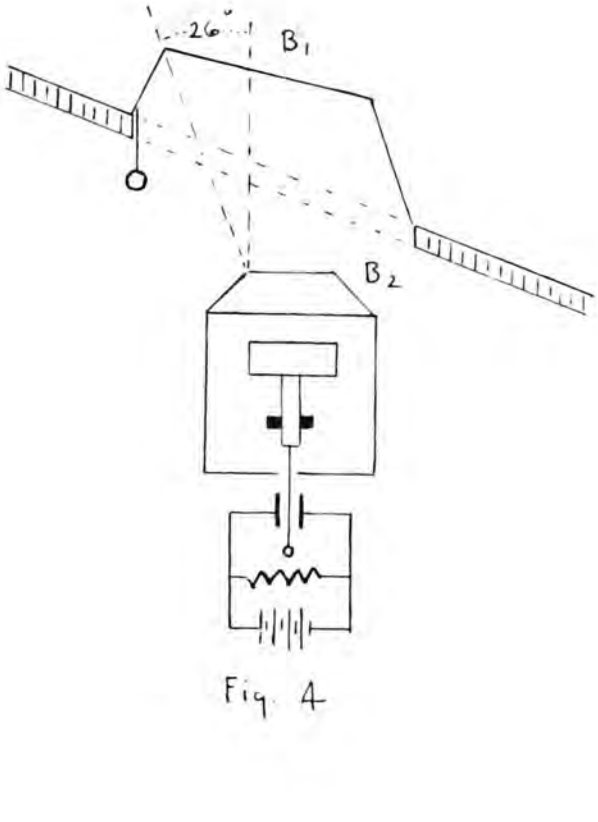


Fig. 4

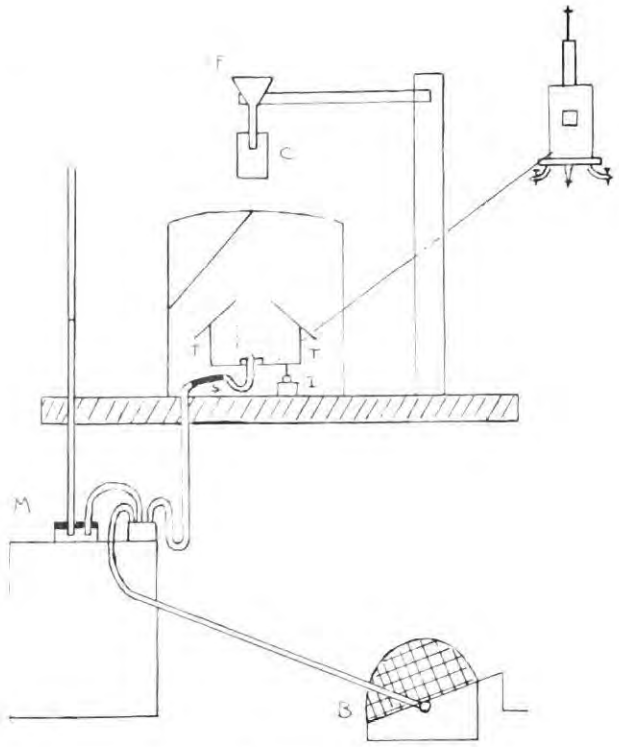
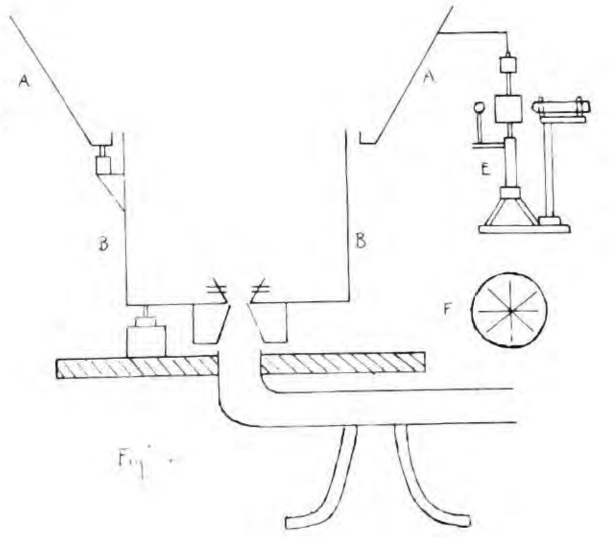


Fig. 5



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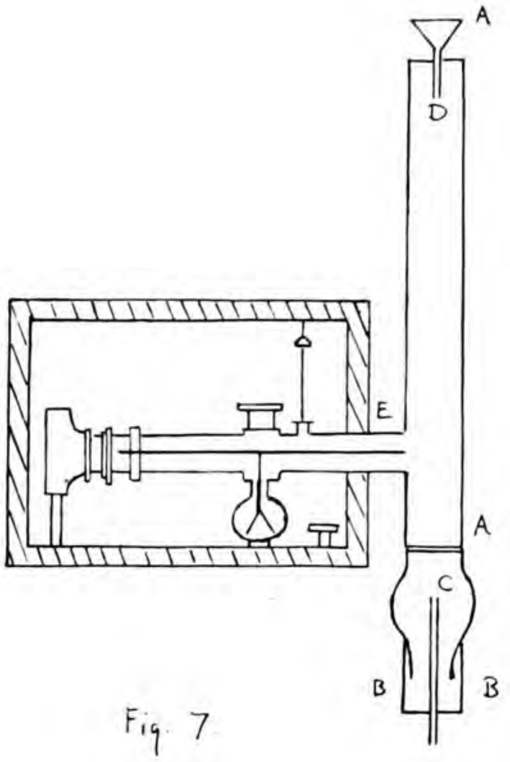


Fig. 7

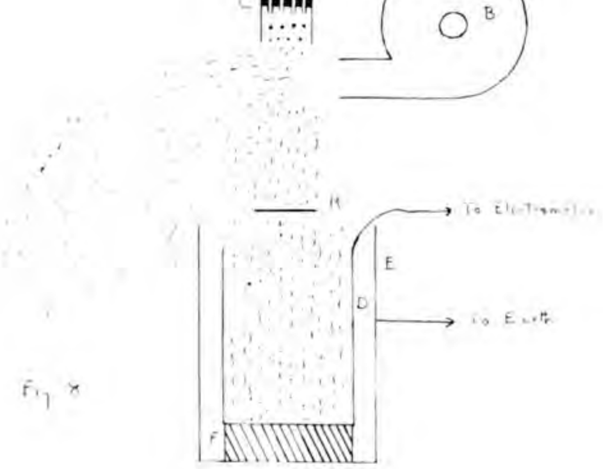


Fig 8

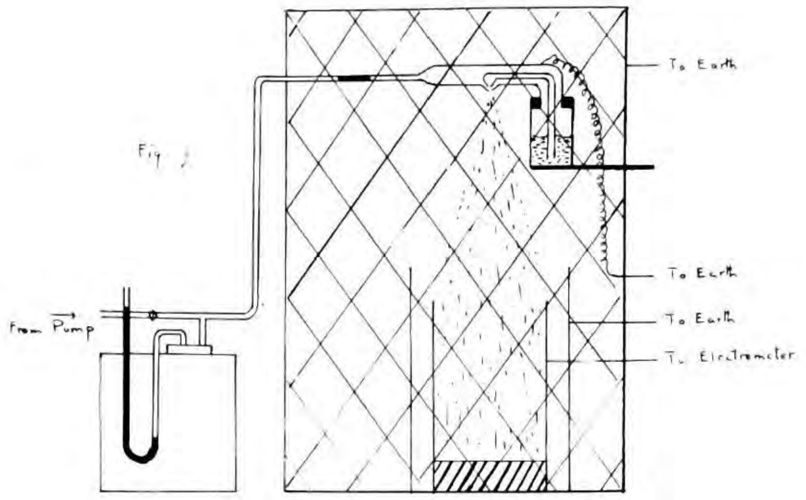


Fig 9

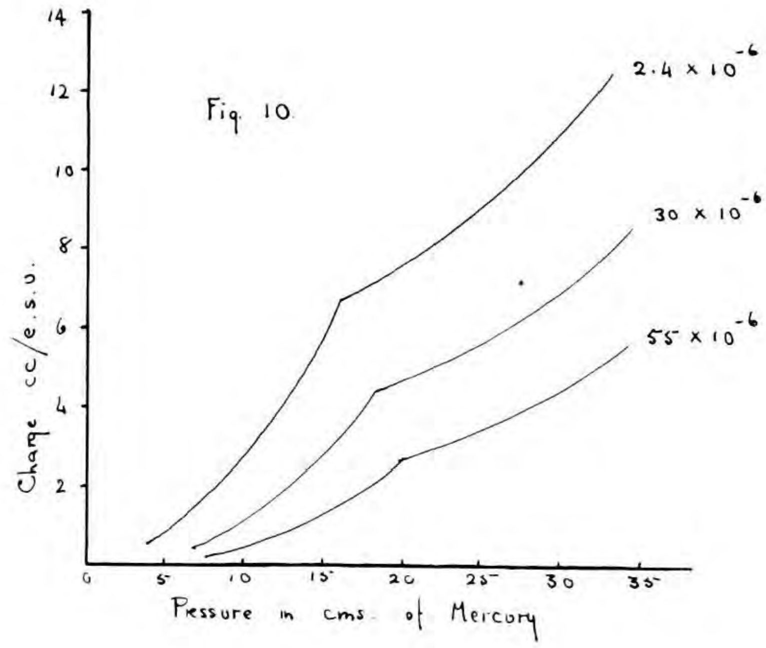


Fig. 10.

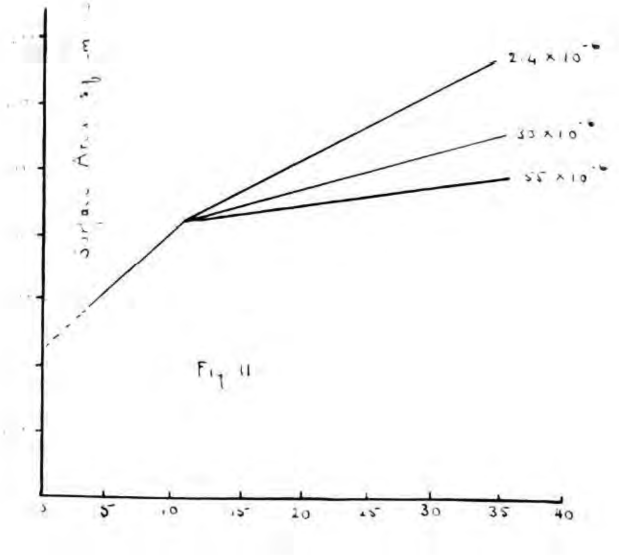
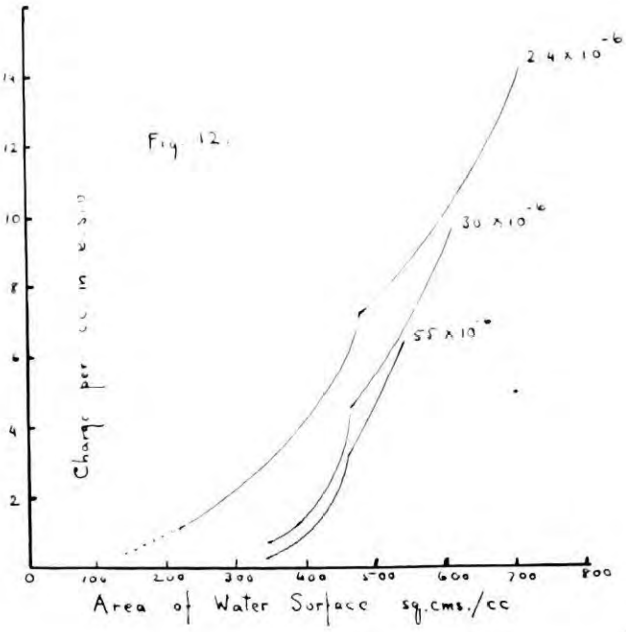


Fig 11



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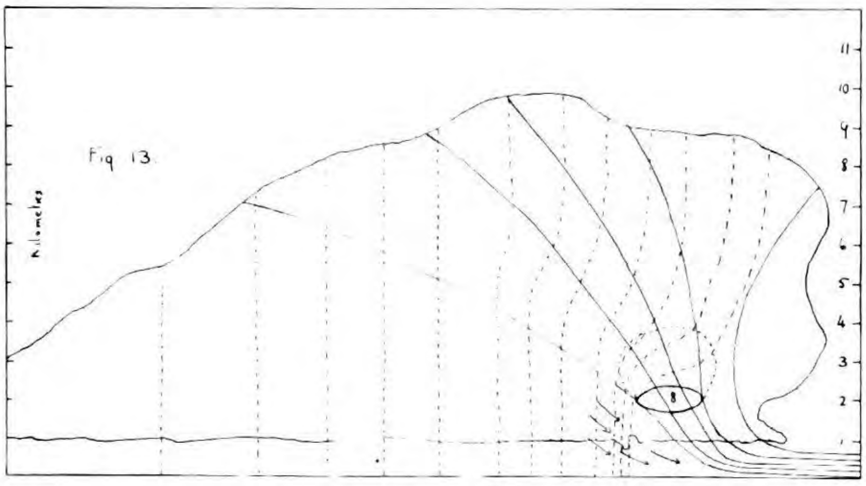

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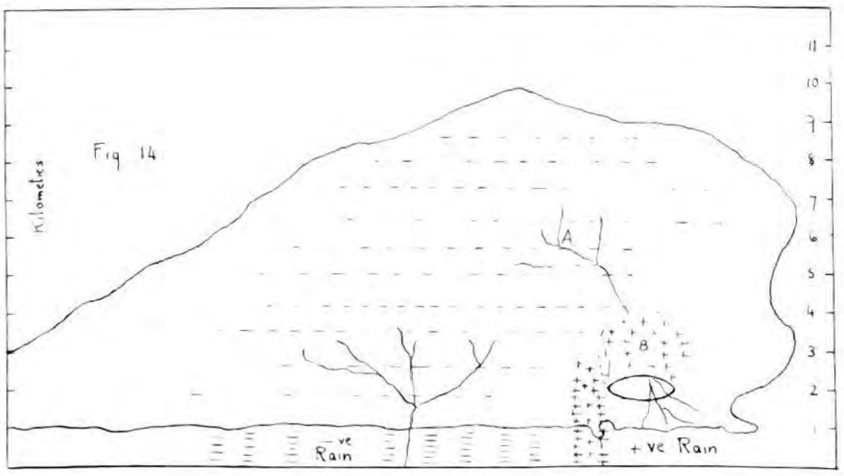

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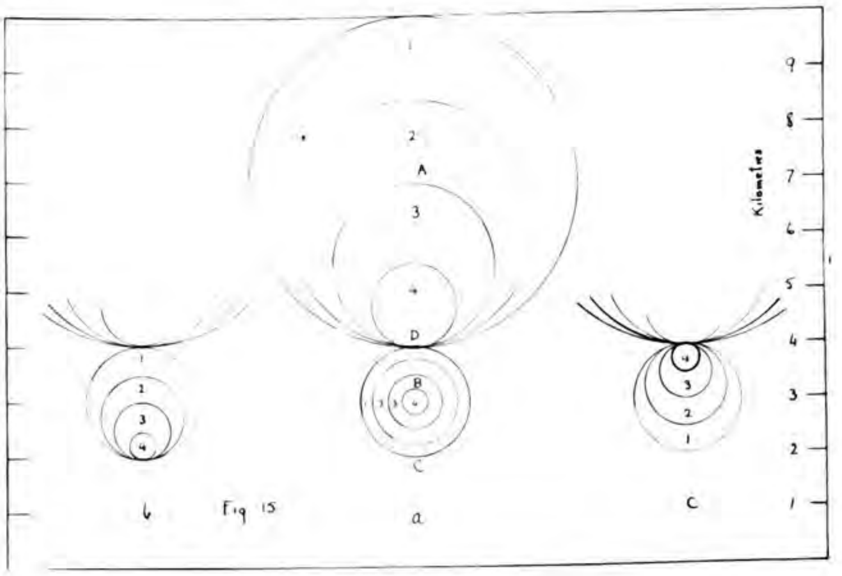

Fig 15

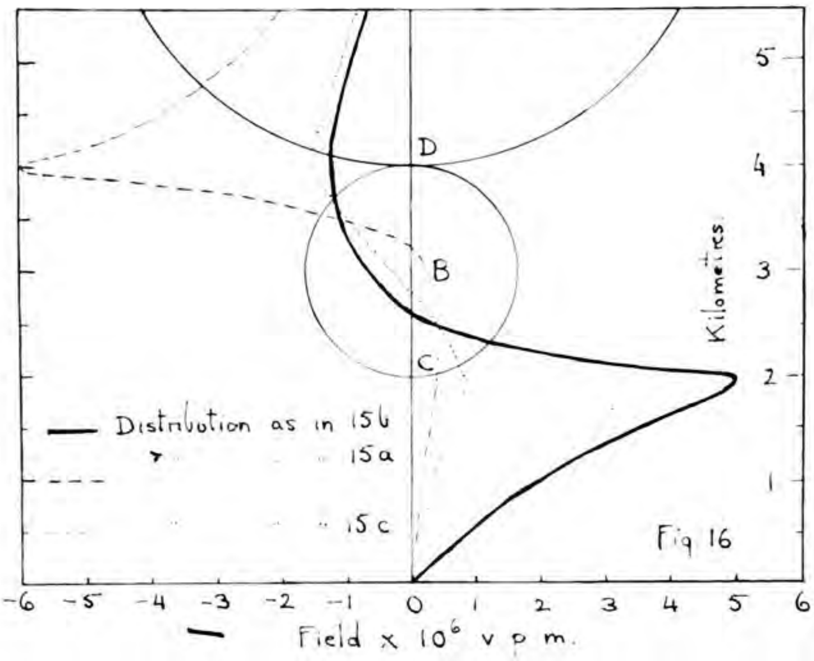

Fig 16

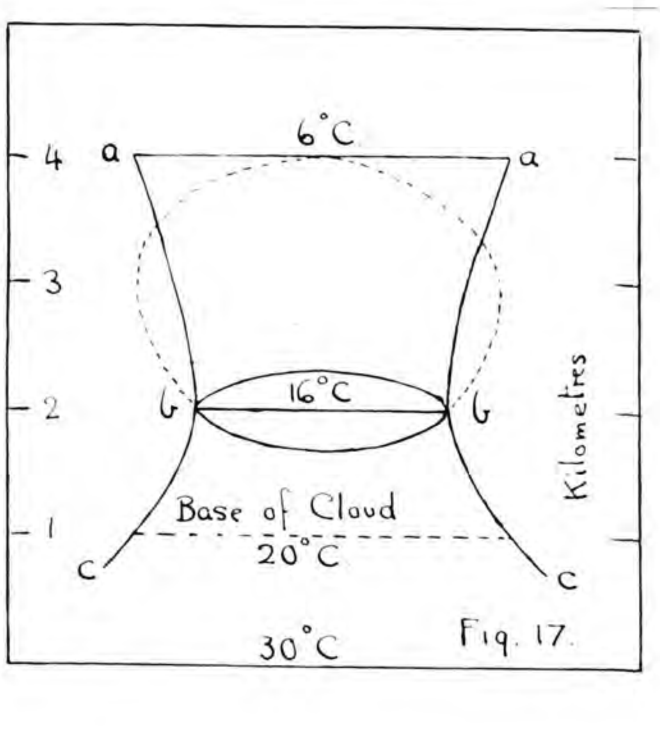

Fig. 17.

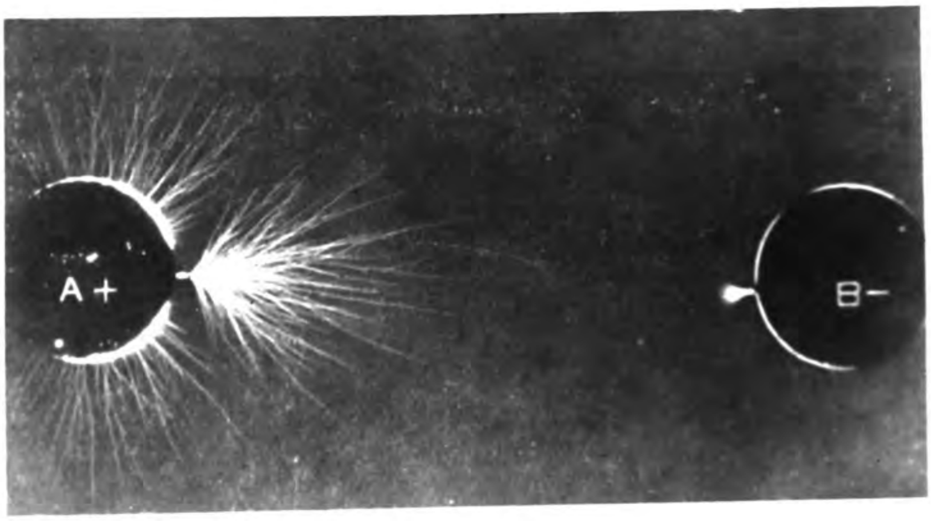

Fig. 18.

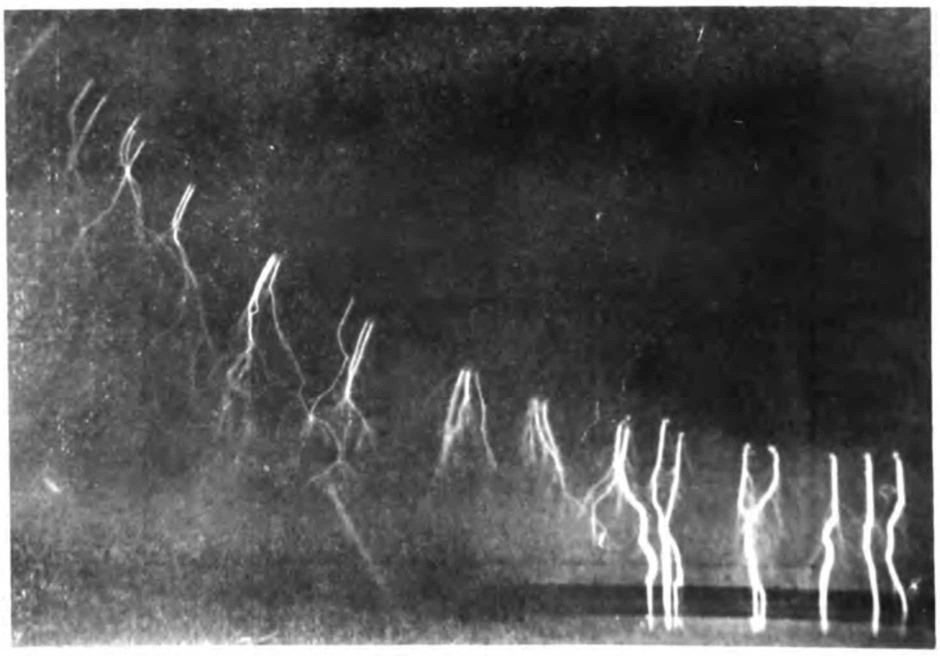

Fig. 19.

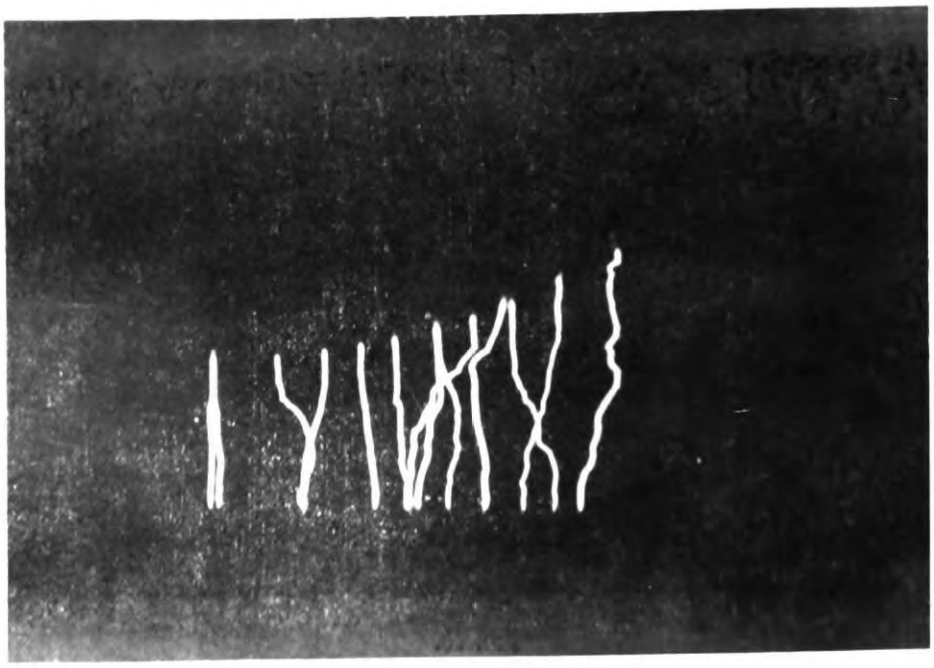

Fig. 20.

Fig. 21.

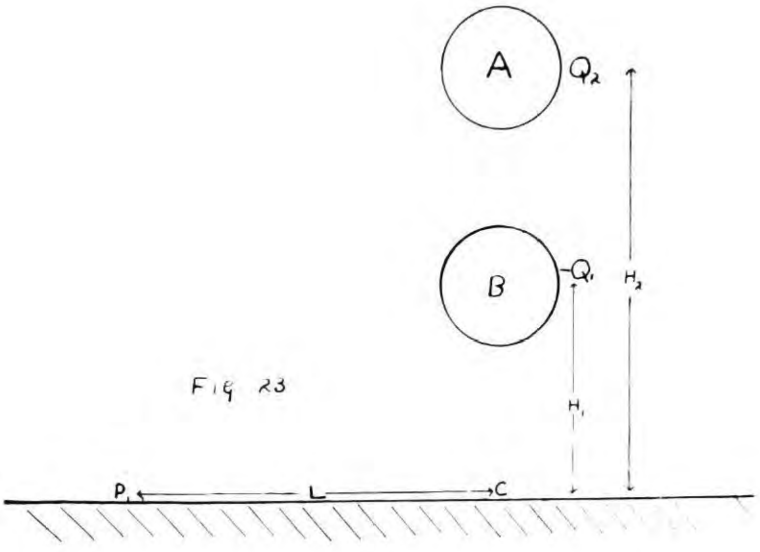

Fig 23

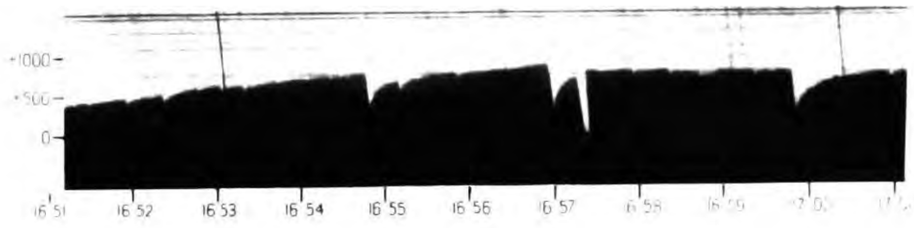

Fig. 24.

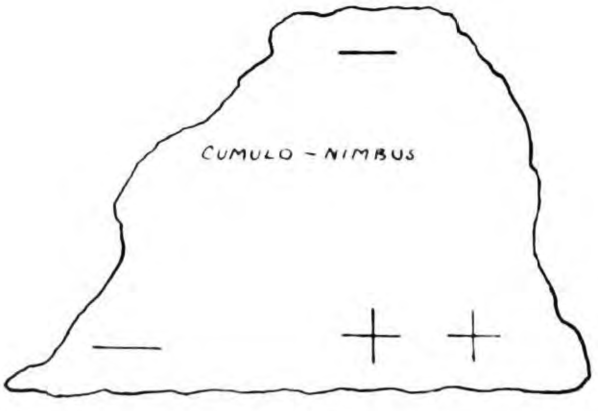

Fig 25

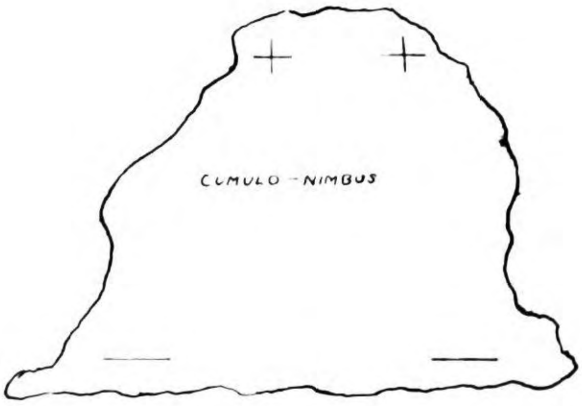

Fig 26

Fig. 27.

Fig. 22.