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The Electrification of Individual Cloud Droplets

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Abstract

The results of some observations of the electric charges carried by individual cloud elements are described. Measurable charges were found on many droplets, and a reversal of polarity was observed which appeared to be associated with the presence of ice particles. The different mechanisms of charging are discussed in the light of the experimental results, and reference is made to the possible significance of droplet electrification in the precipitation process.

1. Introduction

The physical properties of many colloidal suspensions are known to depend on the electric charges carried by the suspended particles. By analogy it would be expected that the charges carried by the droplets in a natural cloud could be an important parameter where cloud stability and coagulation are concerned. Comparatively little is known, however, about this aspect of cloud physics. A few measurements have been made (GUNN, 1952; WEBB and GUNN, 1955; WIGAND, 1926) but in all cases only the net charge per unit volume of cloud could be measured by the methods used; no information was therefore available concerning the charges carried by individual cloud elements and the relation (if any) between charge and size.

In experiments in 1954 a technique was developed which allowed the charge on individual cloud elements to be determined in sign and magnitude. Some preliminary results were obtained by allowing the droplets under observation to fall through a liquid (kerosene). These results indicated that many positively charged droplets were present in water clouds, while on some occasions negative charges were measured which appeared to be associated with the presence of the ice phase in the cloud. The method was then modified to allow the measurements to be made with droplets falling in still air. The present paper is mainly concerned with reporting results obtained with the modified technique; reference is also made to the possible implications of the results obtained.

2. Experimental technique

In order to measure their electric charge, droplets freely falling between a pair of parallel plates are subjected to a strong horizontal electric field and the deflection recorded photographically. The applied voltage (6 – 12 kV) is switched in a manner which results in a charged droplet tracing out an asymmetrical "zig-zag" path from which terminal velocity, charge-to-mass ratio, and the polarity of the charge are directly obtainable. (As terminal velocity is a known function of drop size, diameter and charge can then be readily calculated.) Falling patterns of charged droplets in the applied field can be seen in Figs 1 and

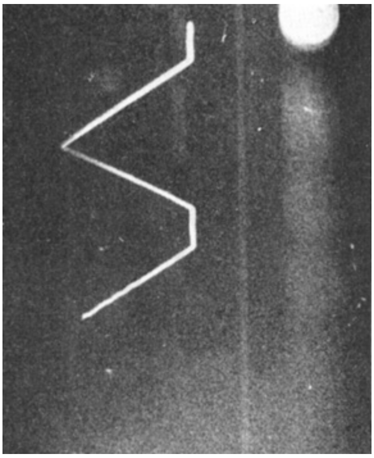

Fig. 1. Photograph of the traces produced by a cloud of highly charged small droplets in the laboratory.

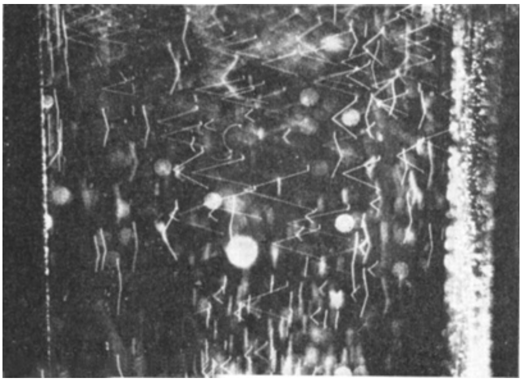

Fig. 2. Photograph of a trace produced by a highly charged natural cloud droplet; $d = +3 \times 10^{-2}$ e.s.u., $q = 20\,\mu$).

2. The measurements herein reported were more sensitive than the earlier measurements, as a higher voltage was available. As used, the method was suitable for droplets in the diameter range $5 - 100\,\mu$ although it was best suited for observations of droplets in the range $10 - 40\,\mu$. The minimum charge measurable was dependent on droplet size and was as follows:

Droplet diameter (μ)	Minimum charge (e. s. u.)
(μ)	(e.s.u.)
10	10^{-9}
50	10^{-7}
100	10^{-6}

By further increasing the applied field it would be theoretically possible to reduce the limits to one-eighth of the above values but this would involve the use of an applied field very close to the breakdown field in air, and this seemed most undesirable, both for instrumental reasons and because of the possibility that the release of ions by corona discharges might give rise to spurious charges on the droplets under observation.

In the laboratory it was possible to produce uncharged droplets which remained undeflected in the highest field available. This indicated that the droplets did not acquire a charge during their passage into the observation chamber and through the applied electric field. There was in fact no obvious way in which the droplets sampled in natural cloud could become artificially charged – they were permitted to fall freely through a large opening in the roof of the trailer in which the apparatus was housed, and entered the observation chamber through an opening (5 cm × 5 cm) in the top of the chamber. However, as an added precaution, when an observation was being made, the high tension voltage was applied and the camera shutter opened simultaneously.

3. Experimentel results

(a) *Observations in Winter 1955*

During July 1955 the apparatus was set up at the summit of Mt. Wellington, a 4,160 ft peak near Hobart, Tasmania. Measurements were made in stratocumulus and stratus clouds, winds being mainly in the south-westerly sector. With winds from this direction the sampling location was exposed to clean maritime air which had travelled several thousands of miles over the Southern Ocean. The possibility of the results having been affected by man-made contamination could therefore be disregarded.

The observations showed that a large proportion (around 50 %) of the cloud droplets sampled carried detectable charges. The samples were taken during the afternoon and early evening and included both precipitating and non-precipitating clouds. Cloud bases were on the average about 500 ft below the summit. The temperature at the sampling location varied from a few degrees below freezing to a few degrees above freezing.

Positive charges almost exclusively were found on the cloud droplets when the liquid phase only was present in the cloud.[1] In such cases, 80 % or more of the charged droplets carried positive charges. In Fig. 3 a charge has been plotted against diameter for all measurements of positively charged droplets. On occasions when *negative* charges were found it was noted that the ice phase was present in the cloud, ice crystals being visible in the intense beam of the illuminating lamp. The percentage of negative charges among the charged droplets varied from 40 % to 100 % when the ice phase was present. The results of the observations of negative charges are plotted in Fig. 4. Throughout the observations a proportion of the traces recorded represented droplets with appreciable charge, but were distorted (e.g. by turbulence within the observation tank) so that polarity could not be determined. All such observations have been omitted, as also have the many observations in which parts of the traces of large charged drops were recorded, but where enough of the "zig-zag" patterns to determine polarity was not available.

These experiments confirmed qualitatively, at least, conclusions previously drawn from experiments carried out on Mt. Wellington in winter 1954, utilizing the deflection of droplets in kerosene. The conclusions referred to were as follows: (i) the majority of cloud droplets sampled at a mountain summit carried appreciable electric charges; (ii) on any one occasion one sign usually predominated, although mixed charges were sometimes observed; (iii) positive droplets were found in clouds which were thought to be composed of liquid water droplets only – negative charges were found only when the ice phase was present, but it could not be ascertained whether these negative charges were carried by water droplets or ice crystals or both.

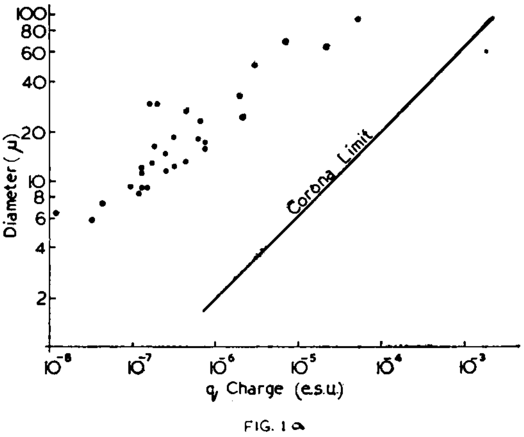

Fig. 3 a. Relation of observed charge to droplet diameter (positive charges)—July 1955 results.

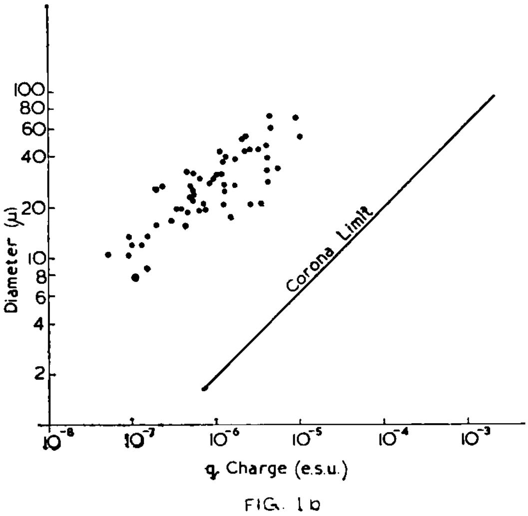

Fig. 3 b. Relation of observed charge to droplet diameter (positive charges)—February 1956 results.

(b) *Observations in Summer 1956*

In order to ascertain whether similar charges are found in warm clouds, a second series of observations was carried out during February 1956, at the same location. Measurements were again made in stratocumulus clouds, with maritime air from the east, cloud base some 1,000 – 2,000 ft below the mountain summit and cloud tops rarely more than 2.000 ft above the summit. The temperature at the sampling location ranged from 8 °C to 17 °C. It is certain therefore that the clouds rarely, if ever, reached freezing level and it can safely be assumed that the ice phase was absent.

The results, which are plotted in Fig. 3b,

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[1] A few isolated measurements of cloud droplet electrification made in trade-wind cloud on the slopes of Mt. Haleakala, Maui, Territory of Hawaii, in January 1955, with the same equipment, led to signs and magnitudes similar to those reported and discussed here. Drop diameters were from 7 μ to 26 μ and charges ranged from $+10^{-7}$ e.s.u. to 4×10^{-6} e.s.u.

showed that about 80 % of the cloud droplets carried positive charges, negatively charged droplets being absent. The relation between charge and diameter was very similar to that found for the positive charges measured in winter time.

The above results thus confirmed the previously deduced association between liquid cloud droplets and positive charge. The clouds sampled were typical (usually non-precipitating) stratocumuli; the diameters of the cloud droplets lay mainly in the range 10 – 40 μ, with a median drop diameter between 25 μ and 30 μ.

4. Discussition

(a) *Positive charges*

From Fig. 1 a, in which the observed values for droplet charge have been plotted against droplet diameter for the positively charged droplets sampled in July 1955, it is seen that there appeared to be a relationship between charge and diameter of the form $q = Ad^n$, the exponent n lying between 2 and 3. The individual values of course showed large deviations, but there certainly appeared to be a significant relationship: the correlation coefficient drawn from the original data for Fig. 3 a was 0.85, while the regression equation was

$$q = 5.4 \times 10^{-10} d^{2 \cdot 34} \text{ (where } q \text{ was in e.s.u. and } d \text{ in microns).}$$

For comparison the charge which would give the breakdown field strength (for air) at the surface of the droplet has also been plotted in Fig. 3 a – this probably represents the maximum charge which a droplet of given diameter can carry.[1] It is seen that the charges measured were always considerably less than a tenth of this limiting value.

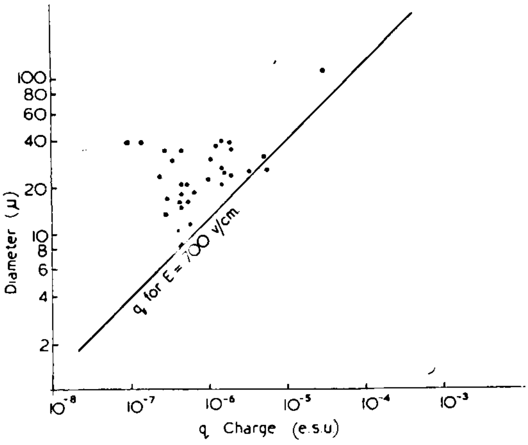

Fig. 4. Relation of observed charge to droplet diameter (negative charges)—July 1955 results.

The data plotted in Fig. 3b yielded a correlation coefficient of 0.80, and the following regression equation:

$$q = 9.9 \times 10^{-10} d^{2 \cdot 05}.$$

The latter is seen to be very similar to the regression equation drawn from the earlier data.

In Fig. 4 charge has been plotted against droplet diameter for the negatively charged droplets sampled. It is seen that the scatter was greater than was the case with positive charges – in fact there is very little ground for drawing a curve through the points plotted. The correlation coefficient for these points was 0.48, considerably less than that obtained in the case of positively charged droplets.

The relationship existing between charge and diameter for positively charged droplets suggested that a straightforward charging mechanism was responsible. Two processes which would give rise to such an ordered distribution of droplet charge are (a) diffusion of ions into a droplet (GUNN, 1955a) and (b) the electrification observed by BLANCHARD (1955) when minute droplets are formed by bursting bubbles at an air-sea water interface. However, neither of these mechanisms provides a complete explanation of the observed effects: Gunn's theory and also his laboratory experiments indicate that the charges would be distributed statistically with a slight excess of positive charges, due to the superimposition of a very small systematic positive charge. The magnitude of the charges given by Gunn's theory is also considerably less than the charges measured in these experiments[1] – for example,

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[1] However it has been suggested by Telford (private communication) that a field much higher than the breakdown field can exist at the droplet surface without the occurrence of corona discharge; this arises from the fact that the field falls away rapidly with distance from the surface and hence the average field over a few diameters may be less than the breakdown field although the field at the surface exceeds this value.

[1] In a recent paper, GUNN (1955b) shows that mean charges of the same order of magnitude as those discussed here, can arise as a result of the collisions of droplets charged by ionic diffusion; equal numbers of positive and negative charges, however, are expected.

the mean charge for droplets with diameter 20 μ would be only 16e ($7 \cdot 7 \times 10^{-1}$ e.s.u.) with a fraction less than 0.005 of the total population possessing charges in excess of twice this mean charge. The corresponding observed values were of order 10^{-6} e.s.u.

Blanchard's results were obtained for droplets of sea water, newly formed from bursting bubbles at an air-sea-water interface. Although the charges found by Blanchard were positive and of the same order of magnitude as those reported here, the suggestion that this process could account for the charges found on natural cloud droplets is subject to criticism on two main grounds. Firstly, a large proportion of the total population of cloud droplets observed carried measurable charges; the concentration of saline nuclei in the free air is almost certainly less by several powers of ten than the concentration of droplets in a cloud, so that it is not at all likely that each charged droplet observed contained a sea salt nucleus. Secondly, the work of GUNN (1954, 1955a) suggests that a highly charged droplet would be rapidly discharged (in a time of the order of ten minutes) to an equilibrium value determined by ionic diffusion. For these reasons therefore it seems reasonable to disregard the bursting bubble mechanism as the main source of cloud electrification.

At the present juncture a diffusion process of the kind described by Gunn seems most applicable to the explanation of the observed effects. The order of magnitude of the charges computed by Gunn would no doubt be greater if the adsorption of ions was selective. It is known, mainly from balloelectric phenomena (NATANSON, 1950; PANNETIER, 1952), that a regular arrangement of ions exists at a water surface, negative ions congregating at the surface in the case of pure water, with a balancing excess of protons in the interior of the liquid. This dipole layer at the surface does not affect the electric field external to a droplet but it is possible that forces may exist in the transition layer which allow positive ions to be adsorbed more readily. PHILLIPS and GUNN (1954), however, while measuring the electrification of a metal sphere by moving ionized air, observed that surface contaminations did not have any appreciable effect on the charge collected by the sphere. That selective adsorption would be sufficient to account for the charges measured follows from Gunn's computations and also from the work of ARENDT and KALLMAN (1925). The latter measured the charge on droplets in an environment in which ions of one sign only were present and found charges which would lead to charge-to-mass ratios and surface fields greater than those reported here.

The contention that the observed charges were produced by a diffusion process is supported by the relationship between charge and droplet diameter. It has been shown that the charges measured tended to vary according to the 2.34 power of the diameter, in the case of the observations in July 1955, or the 2.05 power in the case of the observations in February 1956; computations of the charge produced by diffusion always lead to an approximately square-law relationship.

(b) *Negative charges*

The negative charges found seemed to have a connection with freezing or melting of the cloud elements, charges of this sign being apparently associated with the presence of the ice phase in the cloud. As mentioned earlier it was not possible to ascertain whether the negative charges were carried by liquid droplets or ice particles or both. However, it is fairly certain that some at least of the negative charges were carried by ice crystals because it was sometimes possible to identify the traces of falling ice crystals by the discontinuous, "dashed" appearance of the traces (corresponding to the scintillations often observed visually from ice crystals). Some of the negatively charged elements gave traces of this kind and it was therefore concluded that at least some of these elements were in fact ice particles. However this did not serve to indicate whether ice particles alone, or both ice particles and liquid droplets, carried negative charges. However, it is relevant to note that LUEDER (1951) found that a body collecting supercooled droplets by being rotated through a natural cloud below 0 °C acquired in the process a large negative charge; the maximum charge density was given as 0.2 coulombs per cm^3 of collected water and it was found that the charging process ceased when the potential gradient at the surface reached a limiting value of 700 volts/cm. The charge which would produce this potential gradient at the surface of a droplet or spherical ice particle has been plotted on Fig. 4. It may of course have been fortuitous that this line fell where it did, but it is definitely thought-provoking that the points plotted did appear to be bounded by this line. If in fact we suppose that the observed negative charges were produced by a mechanism of the type found by Lueder, it is seen that the sign and magnitude of the charges are readily explained. The scatter of the charge values would also be readily explainable if the charging was caused through the collection by a frozen droplet or ice crystal of supercooled liquid droplets by collision: according to Lueder's findings the charge produced on a cloud particle would be a linear function of the volume of supercooled water collected, which would be expected to vary considerably from particle to particle. It is of some interest to compute, for a few values of droplet diameter, the volume of supercooled water the collection of which would give rise to the maximum observed charge values on the assumption that each cm^3 of collected supercooled water causes a charge of 0·2 coulombs (6×10^2 e.s.u.). Reference to Table 1 shows that on this hypothesis the freezing of a droplet, the volume of which represents a very small fraction of the total volume, would be sufficient to account for the largest charges observed on cloud elements. It is possible to account for the largest individual charge observed (2.5×10^{-3} e.s.u.) by the collection of one supercooled droplet with a diameter of only 2 μ. The cessation of charging at a potential gradient of 700 volts/cm as found by Lueder would explain the absence of extremely high charges.

From the foregoing it is seen that the mechanism of charge generation by collection of supercooled water furnishes an attractive hypothesis for the interpretation of the observations concerning negatively charged cloud droplets.

Table 1

Droplet diameter (μ)	Volume (cm^3)	Maximum observed charge (e.s.u.)	Vol. equivalent to observed charge assuming 6×10^8 e.s.u. per cm^3 (cm^3)	Diameter of spherical droplet of this volume (μ)
10	5×10^{-10}	6×10^{-7}	10^{-15}	0.125
50	6.5×10^{-8}	2.5×10^{-5}	4×10^{-14}	0.425
200	4×10^{-6}	1.5×10^{-4}	2.5×10^{-13}	0.78

(c) *The possible role of electric charges in cloud physics*

The electrification of cloud droplets may affect cloud stability in two ways: the coalescence of cloud droplets may be inhibited if charges of the same sign and of sufficient magnitude are carried by the droplets; similarly the coalescence rate may be increased if the droplets carry charges of adequate magnitude and mixed polarity. Appreciable effects produced by electrification have been observed in laboratory experiments on the coalescence of droplets by TELFORD, THORNDIKE and BOWEN (1955). Both the sizes of the drops and the charges involved, however, were considerably larger than those discussed here.

The possibility that electric charges on cloud droplets may be sufficient to enhance or diminish the stability of a cloud is particularly interesting when considered in conjunction with recent theoretical work by TELFORD (1955) who examined some statistical aspects of the mathematics of droplet collisions. Previous computations (BOWEN, 1950; LANGMUIR, 1948) indicated that the formation by coalescence of drops of raindrop size would require times of the order of one half hour or more. However, Telford's computations suggested that raindrops can be formed within a few minutes, assuming that the collection efficiencies of cloud drops are determined by the aerodynamics of the process alone. This finding, however, is contrary to observations, which show that large clouds often persist for times of the order of an hour or more without precipitating. These apparently conflicting factors can be reconciled if one assumes that collection efficiency is reduced greatly because the droplets in a cloud carry charges of the same polarity and of sufficient magnitude to inhibit the coalescence process.

The charges measured were probably large enough to affect coalescence, particularly that of the smaller droplets (for which the charge-to-mass ratio was greatest). This was suggested by consideration of the magnitude of the electrostatic forces between charged droplets in close proximity; for example, the force between a pair of 10 μ droplets carrying equal charges and just in contact would equal the weight of either droplet if the charge carried was 7×10^{-7} e.s.u. The actual values of the observed charges were not much below this figure. TELFORD et al. (1955) found that charges of 3×10^{-4} e.s.u. were sufficient to increase the coalescence rate in the case of 150 μ drops; on the assumption that the charge-to-mass ratio is the appropriate one to consider where coalescence problems are concerned, it follows that the observed charges would indeed have a significant effect on the collection efficiencies of cloud elements.

The above considerations suggest that there may be an aspect of the Bergeron precipitation mechanism which has not been given much attention: if a cloud composed entirely of liquid water droplets possesses a degree of stability due to the positive charging of a considerable proportion of the droplets, then the glaciation of part of the cloud may drastically affect the cloud stability, not only as a result of the vapour-pressure difference between water and ice, but also because the growing ice particles may acquire a negative charge sufficient to increase their collection efficiency when they fall to the lower and warmer parts of the cloud where positively charged droplets are present.

It must be pointed out that the above suggestions are largely conjectural. They are based on measurements made in cloud on mountain tops, which do not necessarily provide results which can be applied generally to clouds in the free air. However, measurements of this kind are the only source of information available at the present juncture. If in fact the charges measured were a result of the mechanisms suggested earlier, it seems very likely that the charges in a free cloud would follow a pattern similar to that described.

5. Conclusions

Measurements made on a mountain summit showed that a high proportion of cloud elements sampled carried appreciable electric charges. Drops in liquid water clouds were consistently positively charged, negative or mixed charges occurring in clouds containing the ice phase. The magnitudes of the positive charges were clearly correlated with diameter, ranging from around 10^{-7} e.s.u. for droplets 10 microns in diameter to above 10^{-5} e.s.u. for 100 micron droplets. The negative charges were of a similar order of magnitude but were not clearly correlated with droplet diameter.

The charges measured should be sufficient to reduce significantly the coalescence rate in the case of cloud elements of the same polarity or to increase it in the case of encounters between elements of opposite polarity. Hence it seems probable that electric charges play an important part in the physics of rain formation.

It is suggested that positive charges were accumulated by diffusion of ions into the droplets. It seems necessary to postulate that positive ions are preferentially adsorbed, possibly as a result of the arrangement of molecules in the liquid surface layer. The production of negatively charged cloud elements is attributed to a process of the kind described by Lueder, in which the collection of supercooled water resulted in the collecting body acquiring a negative charge.

Further observations, both in freezing and non-freezing cloud, are desirable. Valuable information would result if a technique could be developed for airborne measurements of the charge carried by individual droplets. Laboratory investigations into the charging of droplets formed by condensation and the ice crystals formed by the freezing of such droplets might also make a useful contribution to our knowledge of cloud electrification and cloud physics generally.

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