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I

The Electrification of Cloud and Raindrops

BENJAMIN FRANKLIN'S pioneer experiments and success in extracting electricity from thunderclouds in the year 1752 initiated 200 years of speculation as to the magnitude and causes of rain-cloud electrification. Franklin's direct resort to experimentation was, of course, a mark of his genius because at that time the capabilities of the powerful team of scientific experiment and mathematical analysis were but dimly recognized.

Within the last two years our laboratory has made tremendous advances, both experimentally and in an understanding of the basic processes responsible for the observed electrification of cloud droplets and rain. It is our purpose here to review and summarize the principal experimental and analytical results. Space does not permit our exploring in detail the important role that electrified drops and droplets play in the production of lightning, the stability of clouds, the control they exercise in determining rates of precipitation, and their function in removing the fine particle pollution normally present in the atmosphere. One may note only that droplet electrification influences all these matters to an appreciable extent, and their exact relationships may be investigated once a quantitative understanding of the electrification processes of cloud droplets and rain is available. Benjamin

Franklin would have immediately recognized the importance of these matters had he access to the modern facts on this subject.

Reliable observational data concerning the electrification of cloud and raindrops have been scarce and difficult to obtain. Accordingly, our laboratory has been actively working to fill this gap in scientific knowledge and to supplement the new measurements by careful analyses of the basic processes. It appeared a few years ago that little or no progress could be hoped for in the understanding of the basic electromechanics of rain cloud electrification because of the apparent complexity of the problem. However, recent studies provided clues that have reduced the fundamental processes to quite simple terms and these succeed in describing, in a highly satisfactory way, practically all the observed phenomena. One first considers the fundamental electrification processes in the clear atmosphere.

1. ELECTRICITY OF THE CLEAR ATMOSPHERE

It is well known that any electrically charged and highly insulated conductor in the atmosphere systematically loses charge to the surrounding air. This loss shows that the air is a poor electrical conductor, and it is a well-established fact that this conductivity results from the presence and motion of ions produced in the atmosphere by cosmic rays and local radioactivity. Under unusual conditions the normal conductivity may be supplemented by other processes. Measurements show that in clear weather a negative electrical charge approximating 4×10^{-4} esu per cm^2 resides on the surface of the earth and that a current of downwardly moving positive ions is thereby maintained of such magnitude that the surface charge would be largely neutralized in about 500 sec unless systematically replenished. From measurements of this current and the surface electric charges we may determine that the normal conductivity near the surface of the earth approximates 2×10^{-4} esu. Such a conductivity implies that about 700 highly mobile ions are normally maintained in a cubic centimeter of the air by some ionizing agency. Roughly 10 ion pairs per cm^3 sec are continuously produced near the surface by the ionizing radiations. It is important to notice that both a positive and negative ion are always generated simultaneously.

The aforementioned quantities are descriptive of the electrical state at the earth's surface. However, at increasing altitudes the ionic mean free paths increase as does the rate of ion production by cosmic rays. Therefore, the electrical conductivity and ionic densities systematically increase to a considerable altitude and at 5 km a charged body loses most of its charge in 140 sec. The mean ionic density at this level approximates 1100 ions per cm^3, while the rate of ion pair production approximates 12 ion pairs per cm^3 per sec. It may be noticed, therefore, that the ionic population and its rate of generation are considerable at ordinary rain-forming levels. These ions have a profound influence on the electrification of cloud droplets.

2. ELECTRICITY OF CLOUDS

The generation of cloud droplets in the earth's atmosphere produces marked changes in the normal clear air electrical state. The electrical conductivity within a stable cloud is much less than in the clear air, and charges are normally observed to collect on the droplets.

Several measurements have been made on the charges carried by natural cloud droplets. For example, both Wigand [14] and Scrase [12] have measured charges on the cloud elements particularly when the cloud was in the nature of a wet fog. More recently, Gunn [6] explored the matter using airborne equipment to sample independently the free charges carried by cloud droplets and by the associated air. The apparatus shown in Fig. 1, consisting of a centrifuge for separating out the droplets from the environmental air and a device for capturing the remaining ions, was installed in the nose of a B-25 bombing plane. Clouds of many different types were analyzed. It was found that most nonprecipitating clouds were essentially neutral and that the net charge carried by the larger cloud droplets was opposite in sign to that on the associated air and water molecules. When the clouds were slightly unstable, the net charge on the droplets was sometimes observed to be positive and sometimes negative, whereas the measured space charge droplet densities were typically 5×10^{-6} esu per cm^3. Measurements with somewhat similar equipment at ground levels by Webb and Gunn [13] showed a similar type of electrification and suggested that the *net* charge on cloud droplets is always quite small except when the clouds are precipitating.

It became clear from these measurements within natural clouds that the average charge on the droplets was not particularly significant and what was required was a complete analysis of the distribution of charges on cloud droplets. There are serious practical difficulties in obtaining such measurements in the free atmosphere, but we have

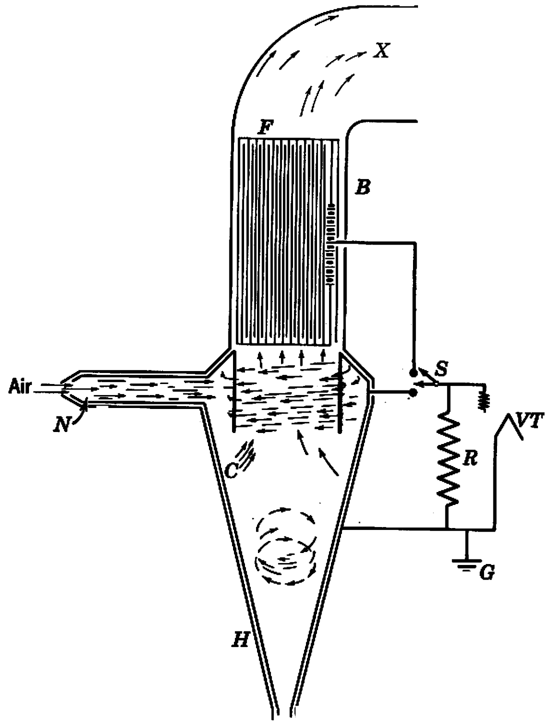

Fig. 1. Schematic diagram of cloud droplet centrifuge *C* and ion filter *F* mounted in the nose of a B-25 airplane and connected to current amplifier *VT*. The entire unit is shielded by conductor *H–B*. Apparatus permits separate determinations of the free charge carried by cloud droplets and by the associated air.

been entirely successful in determining the charges on cloud droplets artificially produced in the laboratory. Clouds may be produced in the Weather Bureau's giant cloud chamber that reproduce the processes of nature and these clouds have enabled us to attack the problem in a perfectly straightforward manner under favorable controlled conditions. This giant cloud chamber is shown in Fig. 2. By letting individual cloud droplets fall through a smaller chamber that is pervaded by a strong horizontal electric field which can be varied cyclically both in magnitude and sign, it is possible to determine from the motions imposed on a falling cloud droplet the magnitude and sign of its free charge together with a reliable estimate of its mass. By producing a typical cloud and letting a few hundred droplets fall successively through such a chamber, it is possible to photograph their

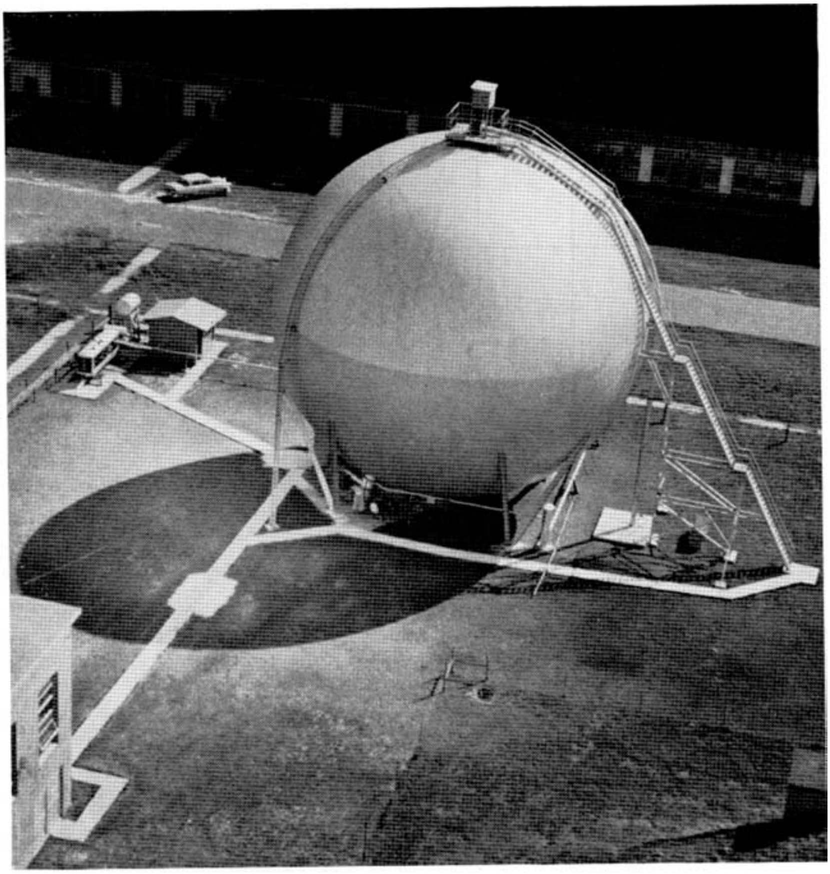

Fig. 2. Giant cloud chamber of the Weather Bureau designed to bring cloud processes under scientific control within the laboratory.

trajectories and determine the distribution of the fractional numbers of droplets carrying any selected free charge. The first distribution curve of cloud droplets obtained using this technique is shown in Fig. 3. It will be seen that somewhat more than half the droplets carry positive charges, whereas the remaining fraction carries negative charges. The slight observed asymmetry results from different values for the positive and negative light ion conductivities inside the cloud.

A long series of similar measurements on droplets of various types has provided a capital clue to the basic mechanisms responsible for the droplet electrification. For example, Fig. 4 shows the measured

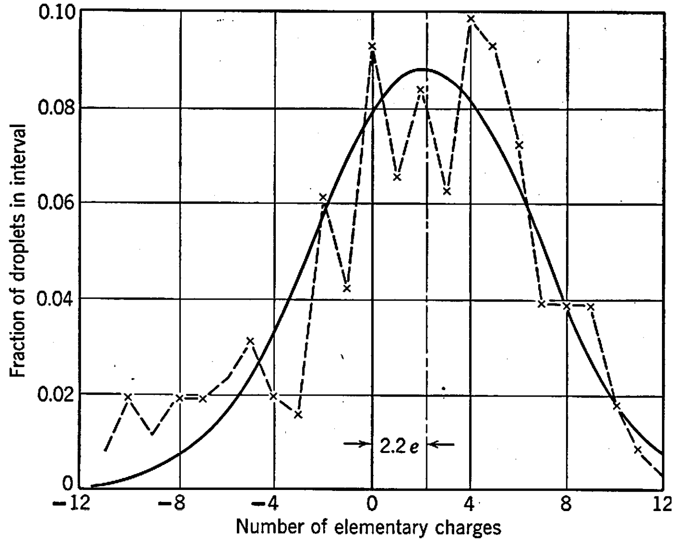

Fig. 3. Distribution of the fractional number of droplets in relation to their charge. Observed data on 250 cloud droplets of mean radius 1.15×10^{-4} cm (dashed curve). Solid curve is calculated from Eq. 2 (p. 12).

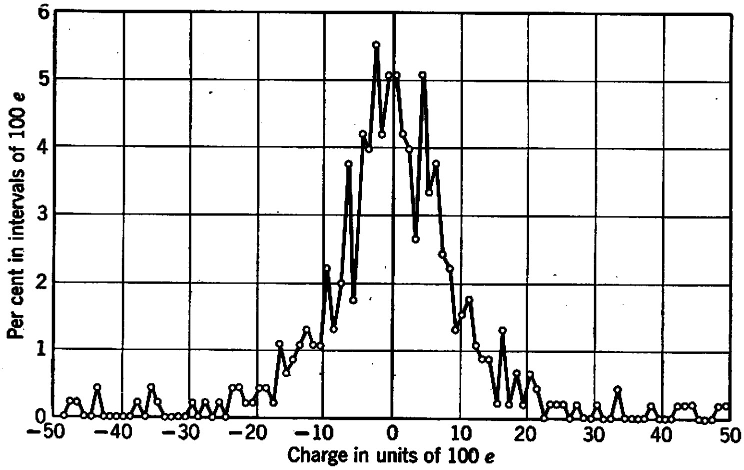

Fig. 4. Cloud formed by sprayed water. Distribution of charges immediately after dispersal. Notice the large number of highly charged particles.

distribution of charges for cloudlike droplets produced by the energetic spraying of ordinary tap water. It may be noticed that large numbers of highly charged particles are produced as well as a rough distribution of weakly charged particles.

Entirely similar effects are measured if the spray cloud is replaced by various dust clouds dispersed into the air by an energetic blast of air. Further measurements were made on clouds produced in the cloud chamber by the condensation of water vapor. It was at once observed that such cloud particles, when initially formed, were essentially neutral and very few droplets had as much as one ion on them. It has been observed that when any of these clouds were exposed to X-rays or other ionization sources they very shortly became electrified and exhibited a distribution as shown in Fig. 5, the curve *B*. Measurements of these general types were made on a number of different clouds produced in a variety of ways, and *it was found that no matter what the state of electrification of the aerosol was initially, upon exposure to copious ionization, a distribution shortly developed that was essentially Gaussian in nature and similar to the theoretical curves given in Figs. 5 (the curve* A) *and 6.* This demonstrates very clearly that a single basic process is responsible for the equilibrium

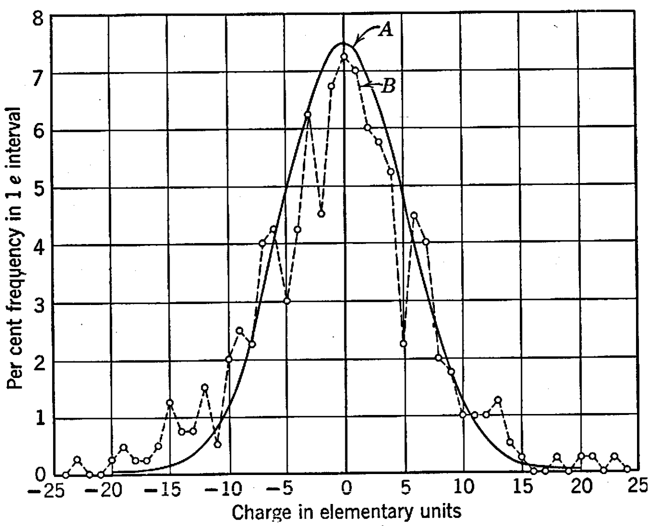

Fig. 5. Water cloud formed by condensation of vapor. This condensed cloud was initially uncharged (radius 1.63×10^{-4} cm). Dashed curve *B* gives distribution after droplets were exposed to copious ionization. Solid curve *A* is calculated distribution according to Eq. 2.

electrification of all aerosols and clouds and that the process is somehow related to the presence of ions in the atmosphere.[15]

A cloud consists of large numbers of droplets, and measurements show that, although each individual cloud droplet may carry from 1 to 20 or 30 elementary charges of a single sign, the distribution of these charges among the droplets is generally such as to make the cloud, as a whole, neutral. That is to say, equal numbers of positively and negatively charged droplets normally exist in a typical cloud. This situation is made manifest by electric field measurements within natural clouds which show that stable, nonprecipitating clouds are essentially neutral and the electric field in their vicinity is small. Unstable associating clouds, on the other hand, usually exhibit a measurable *net* electrification.[6]

3. THE ELECTROMECHANICS OF DROPLET CHARGING

An analysis of the data summarized in the foregoing paragraphs and comparison with detailed theoretical estimates show very clearly that cloud droplets are primarily electrified by the diffusion of atmospheric ions onto the droplets. In general, both positive and negative light ions are present in the atmosphere and are reasonably abundant at cloud-forming levels. Thus, the known thermal jostling of the ions normally results in a transfer of selected ions to the surfaces of the various droplets. The number and rate of charging of the droplets are clearly determined by probability considerations.

Two independent droplet-charging regimes by ionic diffusion are immediately evident,[3,8,9] namely: (*a*) Systematic charging that occurs when the probability of a positive ion striking a droplet is systematically different from the probability of a negative ion striking the same droplet; (*b*) Random charging that normally results when cloud droplets are bombarded by positive and negative ions under conditions such that the probability of the capture of a positive ion is exactly the same as the probability of capture of a negative ion. It should be noticed, however, that as a cloud droplet accumulates a considerable number of ions of a single sign, the probability of capture of ions having the same sign becomes systematically less due to the repulsion. In the same way the accumulated charge systematically attracts and thus increases the probability of capture of ions having an opposite sign. The magnitude of the equilibrium charge is thereby limited.

4. SYSTEMATIC CHARGING

Consider a cloud droplet in the ionized atmosphere. The droplet is surrounded by both positive and negative ions that bombard the droplet as a result of their thermal motions. The probability of a positive ion striking a droplet is proportional to both the number of ions per unit volume and to the speed with which the ion diffuses which is, in turn, measured by the electrical mobility of the ion. Thus, if the product of ion density and mobility is the same for both positive and negative ions, the long time average of the charge on the cloud droplet will be zero. However, if for any reason the density and mobility product for either ion exceeds that of the opposite type, the droplet will acquire and maintain a positive or negative *net* charge. In a recent paper [8] the detailed electromechanics of these charging processes has been worked out and it has been shown that the free systematic charge Q on a freely falling droplet is given by

$$Q = \left[1 + F\left(\frac{aVe}{2\pi kTu}\right)^{1/2}\right] \frac{akT}{e} \ln\left(\frac{n_+u_+}{n_-u_-}\right) \tag{1}$$

where a is the radius of the droplet, k is the Boltzmann constant, T is the absolute temperature, e is the elementary ionic charge, V is the velocity of fall, u the mean ionic mobility in the transition layer, and u_+ and u_- are the respective mobilities. This expression has been tested in the laboratory using a small wind tunnel employing ionized air as a carrier, and the agreement of Eq. 1 with observation has thereby been established.

5. RANDOM CHARGING

The random charging of cloud droplets is important when the probability of capture of a positive ion is exactly the same as the probability of the capture of a negative ion. Therefore, the charge on a particular droplet averaged over a long period of time will be zero. However. statistical fluctuations constantly occur, and at any given instant there is a high probability that any particular droplet will have an accumulation of ions. Because the probabilities of ion capture are the same for both types of ions, it is clear that for every positive droplet carrying a given charge there is likely to be a similar negatively charged droplet in the same vicinity.

6. FUNDAMENTAL AEROSOL DISTRIBUTION

The author's quantitative investigation of the probabilities of ion capture by cloud droplets has shown that a Gaussian-like distribution of charged cloud droplets is shortly established.[9] The fractional number of cloud droplets carrying x elementary charges is given by *the fundamental aerosol-electrification equation*

$$\frac{F_x}{F_t} = \left[\frac{e^2}{2\pi akT}\right]^{1/2} \exp\left[-\frac{\left[x - \frac{akT}{e^2}\ln\left(\frac{n_+u_+}{n_-u_-}\right)\right]^2}{2\frac{akT}{e^2}}\right] \tag{2}$$

where F_t is the total number of droplets per unit volume, F_x is the number per unit volume carrying x elementary charges, a is the droplet radius, e is the elementary charge, k the Boltzmann constant, T the absolute temperature, n_+ is the ionic density for the positive light ions, and u_+ is their mobility. It may be noticed that n_+u_+/n_-u_- is also the ratio of the positive and negative light ion conductivities. Plots of Eq. 2 for droplets of various sizes are shown in Fig. 6. This fundamental aerosol-electrification equation includes both the systematic charging represented by Eq. 1 (when V is small) and the random electrification just mentioned. Many laboratory measurements confirm the essential correctness and reality of Eq. 2.

When the systematic electrification is zero, corresponding to $n_+u_+ = n_-u_-$, this equation degenerates to a symmetrical Gaussian form from which it is easy to show [9] that the average charge on both the positive and negative *fractions* of the cloud droplets is

$$\bar{q}_+ = \bar{q}_- = \left[\frac{\pi akT}{2}\right]^{1/2} \tag{3}$$

By rewriting this expression it is interesting to notice that an equipartition is established between the mean electrical potential energy carried by each droplet and the mean thermal kinetic energy of the bombarding ions.[9] This is an important consequence of our investigations and a somewhat similar equipartition will be mentioned in connection with the electrification of rain.

The mathematical analysis necessary to establish Eq. 2 is quite complex but the basic physics is easily understood. To illuminate this

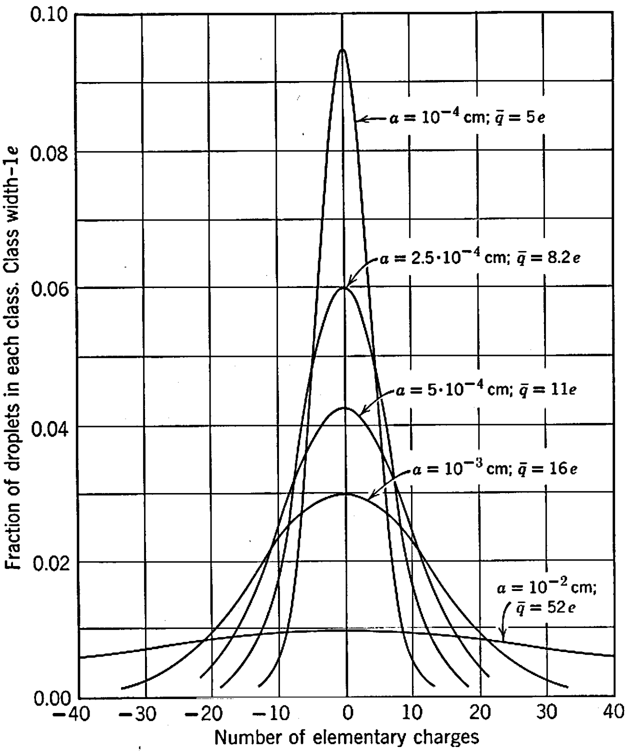

Fig. 6. Calculated distribution as deduced from Eq. 2 of charged cloud droplets having the radii specified on each curve. $\bar{q}$ is the average number of elementary charges, irrespective of sign.

fundamental process one may refer to Fig. 7 wherein the charges communicated to a group of cloud droplets may be quickly estimated on the assumption that the probability of capturing a positive ion is exactly the same as the probability of capturing a negative ion. Starting for convenience, with 1024 droplets it is evident that after each droplet captures 1 ion, half of them will have 1 positive ion and the other half 1 negative ion. If these two groups capture a second ion, it is clear that half of each group will capture a positive ion and half a negative ion. This results in 256 of them having 2 positive ions while 256 will have 2 negative ions and 512 of them will be neutral. Furthermore, if each one of these new groups captures a third ion, it is clear that 128 will have 3 positive ions and 128 will carry 3 negative ions while half of the remainder will have 1 negative ion and half 1 positive ion. By following through such a scheme as shown

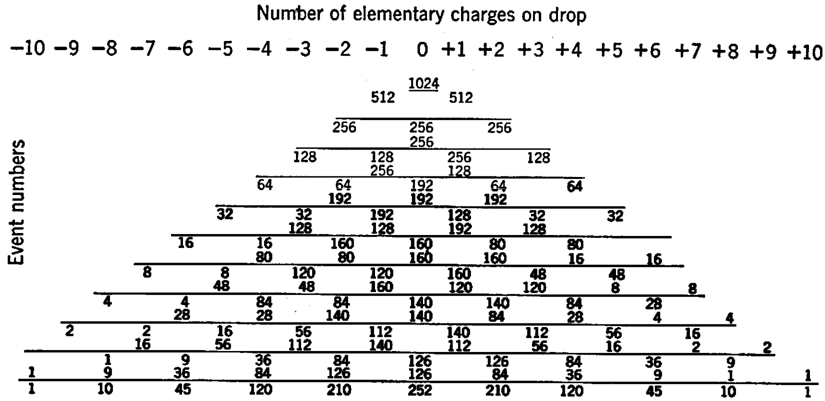

Fig. 7. Schematic representation of the number of cloud droplets carrying indicated numbers of positive and negative elementary charges as a function of the number of collision events. The final distribution on the bottom row corresponds to the binomial point expansion of statistical theory when the probability of capture of positive and negative ions is the same.

in Fig. 7 it may be seen that the distribution after 10 collisions is that shown. This distribution corresponds to the binomial point distribution of statistical theory. It is a well-known fact that this distribution approaches the Gaussian normal distribution as the number of capture events increases to large values. Thus, one may understand the fundamental electromechanics underlying the derivation of Eq. 2.

The reader may find it of interest to construct a diagram like Fig. 7, wherein the probabilities of capture for the positive and negative ions are somewhat different, and satisfy himself that the resulting distribution will be skewed toward a greater abundance of droplets having a sign the same as the predominant electrical conductivity. Such an analysis will show that the resulting distribution closely approximates that given by Eq. 2.

7. ELECTRICITY OF RAIN

The author has believed for many years that the compilation of data on the free electrical charges brought down by rain would illuminate the fundamental problems of cloud and raindrop electrification. Considerable effort has, therefore, been devoted to the invention and development of new apparatus and new techniques. Fig. 8 shows an apparatus that was built to collect data on the size and charge carried by rain. The apparatus is so designed that an untouched drop

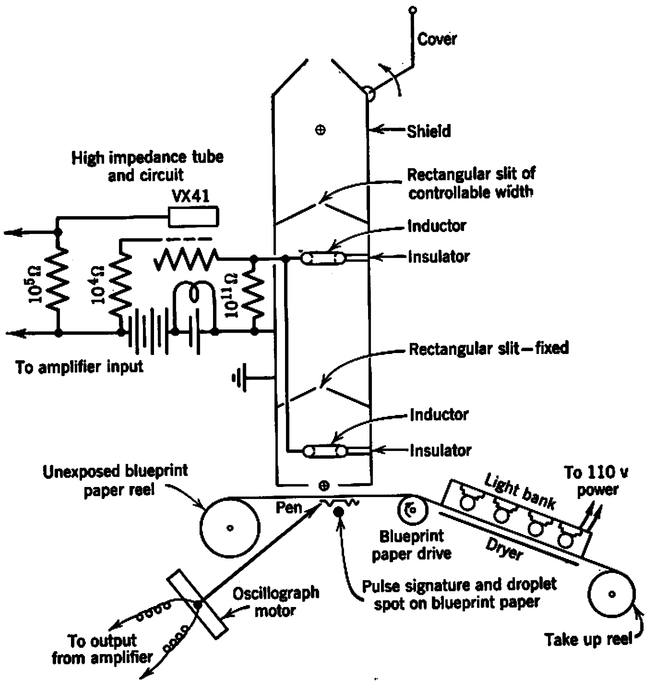

Fig. 8. Induction apparatus for recording the sign and magnitude of the free charge on freely falling raindrops together with their velocity of fall and mass.

from the sky falls through a collimating tube and two highly insulated inductor rings. When the charged raindrop passes the first ring, it produces a pulse in an amplifier that is amplified and passed to the oscillograph. After falling another meter, the same drop passes through another inductor and puts a second pulse on the oscillograph paper. The oscillograph paper is pulled through the oscillograph at a uniform speed and consists of ordinary blueprint paper upon which the raindrop ultimately falls to make a spot. This spot is developed and made permanent by the indicated light bank and the paper is then wound on a reel. With this apparatus the sign and magnitude of the produced pulses determine the charge on the droplet. The time it takes for the droplet to fall between inductors separated by a meter determines the velocity of fall of the droplet, and the size of the spot permanently recorded on the blueprint paper determines the droplet mass. The complete history of the drop is therefore recorded.[5] This apparatus, and modifications suitable for use on aircraft, has been of great value in our raindrop electrification studies.

The first investigation of the charges carried by individual raindrops was reported by Gschwend [2] who also measured the size of the drops. His early measurements of a relatively few drops have been generally verified by later observers, and these all show that the free charge per droplet at the ground is usually of the order of 10^{-3} esu, except for electrical storm rain when it sometimes approximates 10^{-2} esu. An outstanding characteristic noted by Gschwend and other observers is that a mixture of both positive and negative droplets normally is observed below all rain clouds and that after one or two drops of a single sign are captured there is a high probability that the next drop will be of opposite sign. It is fair to remark that this fact has puzzled geophysicists for a good many years but the electromechanics underlying these observations will be made clear presently.

A long series of measurements of drop charge by Chalmers and Pasquill [1] gave average values as summarized in Fig. 9. More recently, using the apparatus described in Fig. 8, Gunn [5] and Gunn and Devin [7] have made further measurements which generally confirm the earlier reported values. The available data on raindrop charges are summarized in Table 1.

Since the atmosphere through which the rain is falling is slightly conducting, electrified raindrops discharge as they fall. Calculation shows that a raindrop falling 2 or 3 km in clear air will discharge a large fraction of its initial electrification. Therefore, charge measurements at ground level are not very significant. In order to determine the magnitude of the free charges on rain at the rain-forming level, it was necessary to fly into such regions with experimental aircraft and specially developed electrical equipment. The Army-Navy Precipitation Static Project that the writer directed at Minneapolis, Minnesota, during the war, provided an opportunity to make such measurements. A modification of the induction method apparatus shown in Fig. 8 was developed to measure the charges on raindrops. Under the right wing of a B-17 airplane was mounted a highly insulated inductor ring that was protected from rain and cloud droplets by a truncated sheet metal cone attached to the airplane. The small circular opening of this cone that faced into the oncoming precipitation permitted raindrops to pass through both it and an internally mounted and highly insulated inductor ring. A large fraction of the raindrops would traverse the metal cone inductor ring without touching either. A few drops would strike the leading edge, splatter, and produce a signature on an oscillograph that could be easily separated out from the signature of raindrops that traversed the inductor ring without

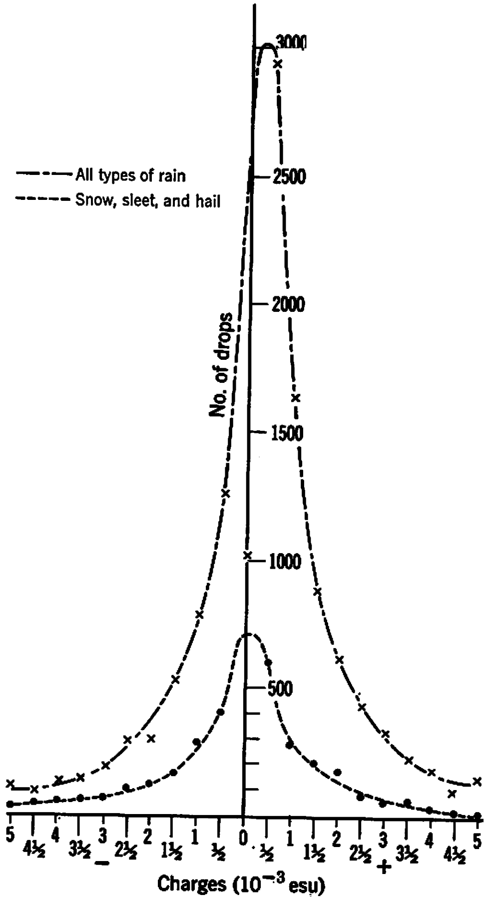

Fig. 9. Distribution of raindrop charges measured at the surface of the earth in England by J. A. Chalmers and F. Pasquill.

touching it. Charged raindrops passing through this ring induce an electrical pulse on the ring that can be amplified and passed to an oscillograph that permits the measurements of the sign and charge carried by the original raindrop.

In a mild cold front, near Minneapolis, coherent measurements were made on the charges carried by raindrops in rain-forming regions and at a number of different levels. These data have been published,[4] are summarized in Table 1, and their distribution plotted as a function of the drop charge in Fig. 10. It is important to notice that the charges measured at the rain-forming levels are some 10 to 30 times

TABLE 1. AVERAGE FREE ELECTRICAL CHARGE ON INDIVIDUAL DROPLETS (ESU × 10^3)

Observer	Altitude (ft)	Charge	Quiet rain	Shower rain	Electrical storm rain	Quiet snowfall	Squall snowfall
Gschwend (1921)	surface	+	0.24	1.75	8.11	0.09	5.64
		−	0.53	5.43	5.88	0.06	4.78
Banerji and Lele (1932)	surface	+		6.4	6.9		
		−		6.7	7.3		
Chalmers and Pasquill (1938)	surface	+	2.2	1.3	3.7 *		10.5
		−	3.0	2.3	9.2 *		5.7
Gunn (1947)	4,000	+		†			
		−		24			
	12,000	+		41			
		−		100			
	20,000	+		63			
		−		†			
Gunn (1949)	surface	+			15	0.67	
		−			19	1.0	
Gunn (1950)	5,000	+			81		
		−			63		
	10,000	+			148		
		−			112		
	15,000	+			123		
		−			76		
	20,000	+			52		
		−			62		
Gunn and Devin (1953)	surface	+			22		
		−			31		

* Actual lightning activity doubtful.

† No droplets of this sign were observed at the indicated level.

greater than those typically measured at the ground and that a mixture of positive and negative drops was usually present. Raindrop charge analyses were carried out in both shower rain in which no appreciable vertical convection or electrical activity was noticed and also in active thunderstorm electrical conditions.

An outstanding characteristic of the charges measured at active rain-forming levels is that the charges on many of the drops are so great that the electric field at their surface is an appreciable fraction of the dielectric strength of air. Thus, many of the drops are as highly electrified as they can possibly be. Moreover, it is found that in such clouds, as well as at the earth, a roughly Gaussian distribution of droplet charges is established. The solid line of Fig. 10 shows the distribution of drop charges as measured at the rain-forming levels in a mild cold front in Minnesota on July 27, 1945.[4] Thus, within a cloud there is some process which systematically places exceedingly large charges on some droplets and exceedingly large charges of opposite sign on other drops. The basic physics that could produce such a distribution has been obscured for a long time. However, a well-fitting key to the problem is now available, and one turns to a consideration of one of the fundamental processes whereby rain is electrified.

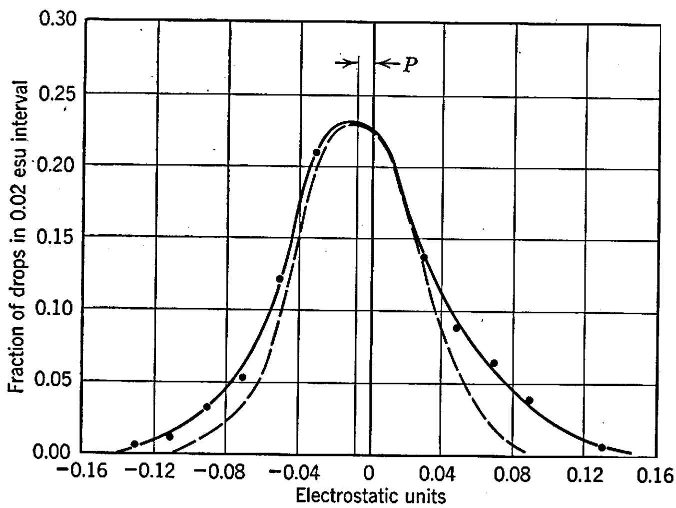

Fig. 10. Distribution of free electrical charge on "moderate rain" within a mild cold front in Minnesota on July 27, 1945. Measurements made at or near rain-forming levels by use of aircraft.

According to the foregoing discussion a typical cloud consists of large numbers of droplets in which about half of the droplets carry a positive charge that is typically 11 elementary units, while the other half typically carries 11 negative units. Normally 4 per cent or less of the droplets are uncharged. Suppose that a small raindrop falls down through such a cloud and grows by association with the cloud droplets. The falling raindrop is accordingly bombarded in a purely random manner by cloud droplets which it successively intercepts. If there are equal numbers of positively and negatively charged cloud droplets, the probability of the drop colliding with a positive droplet is the same as the probability of its colliding with a negative droplet. The statistical distribution of charge may, therefore, be worked out in a manner precisely like that used to determine the charge on the cloud droplet when it was bombarded by ions. The fundamental difference between the electrification of the cloud droplet and the raindrop is that the cloud droplet encounters ions by their thermal agitation, whereas the raindrop is bombarded as a result of the relative gravitational motions of the large raindrop and the small electrified cloud droplets. Two raindrop electrifying regimes by droplet association are evident. The initial or nonequilibrium regime describes the early stages of electrification and is descriptive as long as the probability of collision of a droplet with a charged drop is constant. This regime is gradually converted into the equilibrium regime which is established whenever the accumulated raindrop charges become large enough to control the probability of collision.

Whenever the number of collisions between the raindrop and the cloud droplets is limited and the probability of collision is constant, the average charges *for the distributions* illustrated in Fig. 7 may be estimated by the binomial point equation of statistical theory. The mean *nonequilibrium* charge accumulated on raindrops $\hat{Q}$, *averaged without regard to sign,* is nearly

$$\hat{Q} = \left[\frac{2K}{\pi}\right]^{1/2} \bar{q} \tag{4}$$

where K is the number of collisions that establish the charge on the raindrop and $\bar{q}$ is the mean charge on the parent droplets irrespective of their sign. Since K may be large, it is clear that very large drop charges may sometimes accumulate.

In the special case where there are more cloud droplets carrying one kind of charge than the other, and their numbers per unit volume are C_+ and C_-, one may show that the mean *systematic* charge $\bar{Q}$ accumulated on the raindrops, *averaged with respect to sign* is nearly

$$\bar{Q} = \frac{K\bar{q}}{2} \ln \left(\frac{C_+}{C_-}\right) \tag{5}$$

The above nonequilibrium expressions for raindrop charges are applicable only when the number of collisions is known and the accumulated charges are inadequate to modify appreciably the probability of droplet collision.

Whenever there are sufficiently large numbers of collisions with the cloud droplets so that the charges accumulated by the raindrop become large enough to repel or attract the charged cloud droplets and thus modify their probability of collision, it becomes necessary to work out the *equilibrium* distribution. A mathematical analysis of this complex problem shows[10,11] that the distribution is much like that given by Eq. 2 or

$$\frac{D_{\Omega q}}{D_t} = \frac{\bar{q}}{\left[\dfrac{\pi(r_1 + r_2)U_R^2}{2(1/m_1 + 1/m_2)}\right]^{1/2}} \exp\left[\frac{-\left[\Omega\bar{q} - \dfrac{(r_1 + r_2)U_R^2 \ln (C_+/C_-)}{4\bar{q}(1/m_1 + 1/m_2)}\right]^2}{\dfrac{(r_1 + r_2)U_R^2}{2(1/m_1 + 1/m_2)}}\right] \tag{6}$$

where D_t is the total number of raindrops per unit volume, $D_{\Omega q}$ is the number per unit volume carrying a charge $\Omega\bar{q}$, $\bar{q}$ is the mean cloud droplet charge irrespective of sign, Ω is an integral number, m_1 and m_2, and r_1 and r_2 are the masses and radii of the cloud and raindrop, respectively, and U_R is the relative velocity of the two types of drop. It may be noticed that this expression is similar in form to Eq. 2 and is analogous to it in many ways. Using this expression one may calculate the mean charge on both the positive and negative *fractions* of the falling rain and show thereby that this charge is given by

$$\overline{\Omega\bar{q}} = \bar{Q}_+ = \bar{Q}_- = \left[\frac{\pi(r_1 + r_2)U_R^2}{8\left(\dfrac{1}{m_1} + \dfrac{1}{m_2}\right)}\right]^{1/2} \tag{7}$$

As in the case of Eq. 3, this expression may be rewritten to show that an approximate equipartition is established in which the electrical potential energy carried by the average falling raindrop is equal to the energy of bombardment of the falling raindrop by the smaller cloud particles. Accordingly, the mean charge, irrespective of sign, is determined principally by the mass of the smaller cloud droplets and the relative velocity of the raindrops and cloud elements. It may be noticed that the *equilibrium* charge on the raindrops does *not* depend upon the charges carried by the cloud droplets and this quantity influences only the fraction of droplets carrying a given charge.[11]

It should be clear from a consideration of the above basic mechanisms that the electrification of droplets at the rain-forming level must be much greater than at the earth and that nearly equal numbers of positive and negative droplets are likely to be captured by any measuring equipment. This is exactly what is observed. By assuming that the rain was "medium rain" and that droplets of 0.05 cm radius fell through a cloud of mist-sized droplets of radius 0.005 cm, one may calculate a curve according to Eq. 6, and this is plotted as the dashed curve in Fig. 10. A comparison of the observed and calculated curve shows that the agreement is perhaps better than one has a right to expect, since the basic assumption that there were drops of only two sizes certainly is not exactly true in nature.

In Fig. 11 the results of the foregoing analysis have been summarized. This figure gives the mean equilibrium droplet charge, irrespective of sign, that may be expected on falling rain at the rain-formation level. The raindrops of radii corresponding to the abscissa are assumed to fall through various uniform clouds having the droplet radii specified on each curve. The resulting equilibrium electrical charge is then given by the ordinate. An examination will show that the largest raindrops are so highly charged that they would discharge by corona if further charge were added to them. This surprising state of affairs was first noticed by the author in 1947[4] and is adequately explained by the previously considered electromechanics of drop electrification.

8. CONCLUSIONS

The rather simple concept of falling raindrops and cloud droplets being statistically bombarded by charged cloud particles and ions has been exceedingly fruitful in describing the known complex electrical characteristics of rain and cloud droplets. The distributions closely

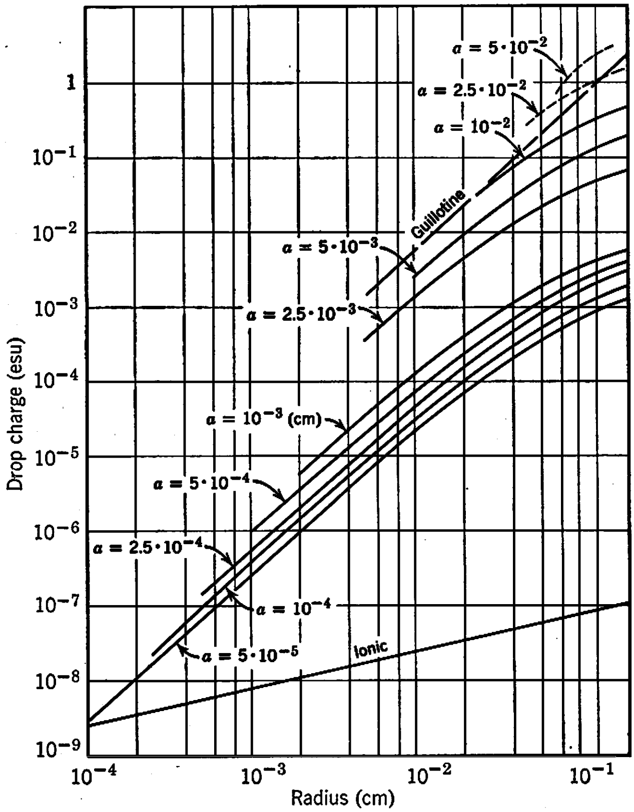

Fig. 11. *Equilibrium* free charge on raindrops calculated in accordance with Eq. 7. Each curve corresponds to a cloud of smaller droplets (having mean indicated radius *a*) through which larger drops, of radius given by abscissa, fall. Lower straight line is equilibrium charge placed on droplets by thermal diffusion of the atmospheric ions as estimated from Eq. 3. Drop charge corresponding to a surface electric field of 15,000 v/cm is labeled "Guillotine." These values apply only at the rain-formation level and must be corrected for discharge to represent the values after the drops fall to the surface.

approximate those normally observed at rain- and cloud-forming levels and, when corrected for electrical discharge as they fall in the free atmosphere, well describe the observed electrifications at the earth's surface. A series of investigations now being prepared for publication shows that the calculated electrification is adequate, when combined with new influence processes, to describe most of what is now known about thunderstorm electricity and related problems. The concepts are capable of extension to the description of volcanic lightning and, indeed, to electrical storms on other planets or on the stars. Because of the universal character of the electrification processes, the effects are likely to be present in a large number of cosmic and terrestrial phenomena.

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