The Effect of Potential Gradient on the Charge Separation During Interactions of Snow Crystals with an Ice Sphere[1]

W. D. Scott and Zev Levin

Dept. of Atmospheric Sciences, University of Washington, Seattle

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ABSTRACT

Charge separation which occurs when polarized ice particles collide in a potential gradient has been found to be an extremely important charge generating mechanism. The fair weather potential gradient is sufficient to initiate considerable charge separation (3×10^{-5} esu per collision). Then positive feedback effects inherent in this polarization charging mechanism can readily explain the strong charging found in glaciated clouds or thunderclouds in general. This theoretical prediction is well corroborated by the present experimental results obtained during simulated experiments in the field with potential gradients <5000 V m^{-1}. However, higher potential gradients produced even more charge than predicted by theory. Also shown are distributions of the original charges carried by the ice particles, the charges transferred to the ice sphere, and the charges carried off after separation. The distributions also support the theory of polarization charging which predicts charging in proportion to the square of the ice particle radius.

1. Introduction

Many theories of charge generation involving ice particles within a thundercloud can be found in the scientific literature. Some deal with the effect of collisions between ice particles and water droplets; some deal with collisions between ice particles. The underlying physical principle in many of the theories is the thermoelectric effect (see Mason, 1953). Recent evidence indicates that the thermoelectric effect is either ineffective (Scott and Hobbs, 1968) or acts in the wrong direction to explain thundercloud electrification at temperatures $\gtrsim -10$C (Shio and Magono, 1968). In any case, charging has been observed in natural clouds and in the laboratory that is not easily explained by what is generally known as the thermoelectric effect.

Other theories involve rubbing or breaking of the interacting elements. For instance, Magono and Takahashi (1963) suggested a mechanism in which the surface of one of the ice particles is rubbed off onto the other one. Depending on the temperature and the surface state, separation can occur to give charges of either sign on the particles.

Apart from these theories are those requiring the presence of a potential gradient. The primary way charge generation can be effected in a potential gradient is by polarization of the larger particles. In a positive potential gradient these particles acquire a positive charge on their lower side and a negative charge on their upper side. As such a hailstone falls through a cloud momentary contacts with smaller ice crystals result in the hailstone acquiring a net negative charge. This effect (called "the polarization charging effect") was first considered in relation to interacting water drops by Elster and Geitel (1913). However, Sartor (1954) was the first to treat the problem of interacting water drops or ice particles in a potential gradient in detail. He found that sufficient charge is separated during a single interaction of precipitation-sized particles to explain the charge build-up in thunderclouds. Müller-Hillebrand (1954, 1955) applied the theory specifically to interactions of ice crystals with polarized graupel pellets and found the same result. Later, Sartor (1961a, b) calculated the field build-up to be expected by this general charge separation mechanism. He showed that this charge generating mechanism can build electric fields of thundercloud magnitude even with relatively few particle interactions.

Latham and Mason (1962) repeated Sartor's original calculations and found that, indeed, the mechansm is a powerful one. However, a laboratory experiment in which small ice particles collided with a cylindrical ice specimen did not show a significant increase in the charging as a result of an imposed potential gradient. Latham and Mason attempted to explain this discrepancy between theory and experiment by considering the relaxation time τ_R for charge transfer in ice and the contact time τ_c between the two ice pieces. The ice acts as an insulator to events which occur with characteristic times $\ll\tau_R$. As a result, no charge can be transferred if the time of contact is sufficiently short.

The relaxation time can be calculated from

$$\tau_R=\frac{\epsilon\epsilon_0}{K}, \qquad (1)$$

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where ϵ and K are, respectively, the dielectric constant and electrical conductivity of the ice, and ϵ_0 is the permittivity of free space, all in mks units. For pure ice, Latham and Mason calculated that τ_R was equal to 10^{-2} sec at -10C. They then indicated that τ_c would have to be greater than about 10^{-1} sec before polarization charging would be effective. Polarization charging was therefore considered ineffective in comparison to other charging mechanisms.

Of course, τ_R is not a definitive number the value of which must be exceeded by τ_c to allow any charging from polarization effects. The term, $\exp(-\tau_c/\tau_R)$, is roughly the fraction of charge not transferred in a collision by this mechanism. Some charging is thus to be expected even if τ_R is large, especially when potential gradients as high as 700 V cm^{-1} (values used by Latham and Mason) are applied to the ice specimens.

It is important, therefore, that further measurements be made to find the effect of polarization charging with ice. Experimental measurements in the field were performed by Burrows (1969) in which the net charge acquired by a sphere was measured. The atmospheric potential gradient was present and was measured; however, it was too variable for systematic evaluation of the data. No other such measurements appear to have been made. In this paper we report results of measurements designed to investigate polarization charging when natural snow crystals collide with an ice sphere.

2. Theory

In this section we outline a theory for the transfer of charge when a small ice pellet collides with a large ice sphere in the presence of a polarizing potential gradient. The treatment follows closely that of Latham and Mason (1962). The small and large ice pieces are approximated by conducting spheres of radii r and R, respectively. The solution is separated into two parts: one considers the case of two uncharged spheres in the presence of a potential gradient; the other considers two spheres which share their charge in the absence of a potential gradient. The total solution is then the sum of the two partial solutions.

If two uncharged conducting spheres are brought into momentary contact in the presence of a potential gradient E, the charge transferred to the larger sphere (in cgs units) is given by

$$Q_E=\gamma_1 E_0 r^2 \cos\theta, \tag{2}$$

where θ is the angle between the line of centers of the two spheres and the electric field, and γ_1 is a weak function of r/R, equal to $\pi^2/2$ when $r/R\ll 1$.

Next, the problem of two conducting spheres which are in contact and share total charge Q in the absence of an electric field is considered. Separation of the two spheres then results in a sharing of charge according to the relative capacitance of the two spheres, i.e.,

$$Q=Q_R+Q_r=Q_R+\gamma_2 Q_R(r^2/R^2), \tag{3}$$

where Q_R is the final charge on the large sphere and γ_2 is another weak function of r/R, equal to $\pi^2/6$ when $r/R\ll 1$.

Therefore, the charge left on the large sphere is

$$Q_R=\frac{Q}{1+\gamma_2 r^2/R^2}. \tag{4}$$

To a first approximation, then, the total solution when charged spheres collide in a potential gradient is the sum of the two solutions (2) and (4), i.e.,

$$\Delta q=\gamma_1 E r^2 \cos\theta+Q/(1+\gamma_2 r^2/R^2). \tag{5}$$

This is an analytic solution for two spheres which make contact. The series solution derived by Davis (1964) for the electric field between two spheres with a small but finite separation distance ($0.001r$) gives the same result when contact is simulated by setting this electric field equal to zero. Note that in the present experiment $r\ll R$ so Q is almost completely transferred to the large sphere.

Eq. (5) is derived for conducting spheres. Ice spheres may be considered conducting provided the time of charge transfer or the time for equilibration of charge carriers (relaxation time, τ_R) is short compared with the time scale of the experiment (in this case the time of contact, τ_c). Insertion of appropriate values for the physical properties of ice into Eq. (1) should establish the validity of this assumption.

Low-frequency values of ϵ and K are relevent. The static dielectric constant ϵ of ice at -5C is approximately 90 (see Cole and Wörz, 1969). The dc conductivity of pure ice is 10^{-8}–10^{-9} mho cm^{-1} at -5C (Bullemer *et al.*, 1969; Camp *et al.*, 1969; Ruepp and Käss, 1969). As a result of natural pollution, the conductivity of natural ice particles will be at least 10 times greater than this value or 10^{-7}–10^{-8} mho cm^{-1} (see Müller-Hillebrand, 1954, and Camp *et al.*, 1969). This is in agreement with the value of K for freshly fallen, partly compacted snow measured by Kopp (1962). This means the relaxation time is 0.1–1 msec.

In fact, the surface conductivity of the ice pieces is all important and has been shown to be approximately 10 times greater than the bulk conductivity (Bullemer *et al.*; Camp *et al.*; Ruepp and Kass). Also, impurities will be concentrated in the ice surface and tend to make K larger and τ_R even smaller (Camp *et al.*). Hence, this is an upper limit value for τ_R.

Signals generated during charge transfer from the ice pellets to the ice sphere had rise times in the millisecond range which suggests that the contact time is longer than the relaxation time. Therefore, to a first approximation the ice pieces can be considered as conducting spheres.

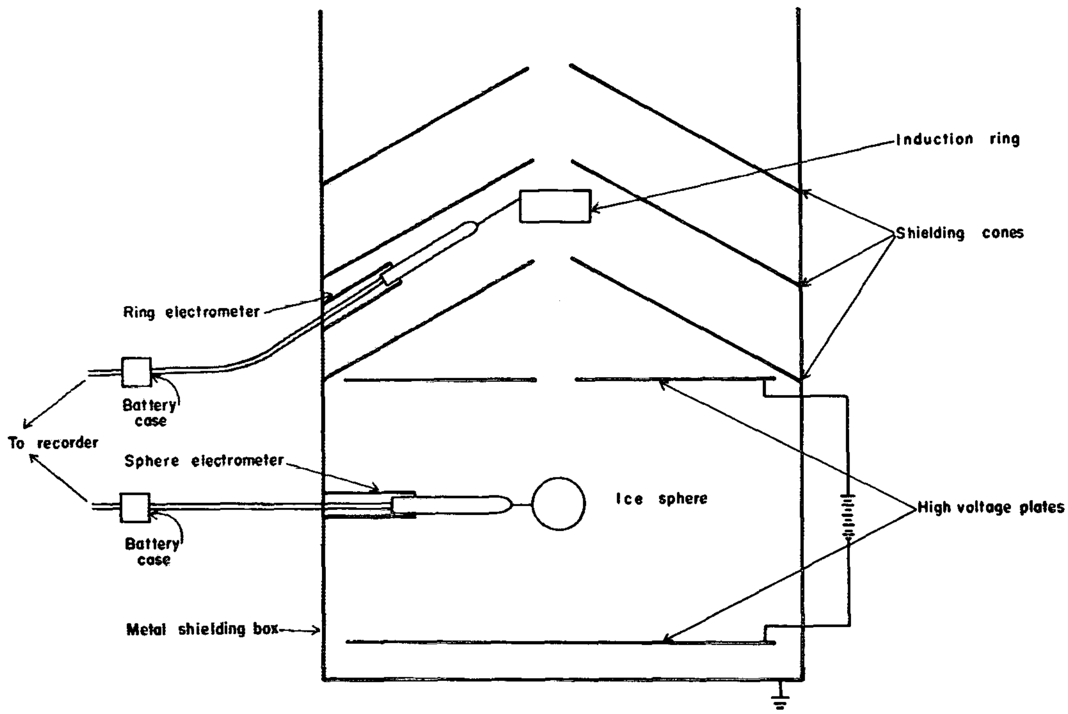

Fig. 1. Schematic diagram of apparatus.

3. The experiments

The apparatus is shown schematically in Fig. 1. It consists of a cylindrical tube $8\frac{3}{4}$ inches in diameter with axially centered, conical-shaped electrical shields. In the lower section an ice sphere was placed on the axis of the cylinder half-way between two parallel plates to which various potentials could be impressed by a battery. The ice sphere was connected directly to a sensitive electrometer (henceforth called sphere electrometer) which was developed in our laboratory. The electrometer was similar to the one described by Scott (1968); Fig. 2a shows the circuit diagram. Above, axially centered and shielded from the lower section, was an induction ring 2 inches in diameter by $\frac{3}{4}$ inch high, connected to another electrometer (henceforth called ring electrometer). The electronics of this electrometer were modified so that the device had a voltage gain of approximately 10 (see Fig. 2b).

The electrometers were shielded with two layers of Conetic and Netic foil and were rigidly mounted in a solid sheath of fused quartz. This, together with the external galvanized iron electronic shields and the use of batteries throughout resulted in a high signal-to-noise ratio. Both electrometers could detect charges as low as 10^{-6} esu.

A natural ice particle falling vertically entered the apparatus through a hole in the conical shield on top and passed through the induction ring. Passage of the particle through the ring caused a deflection on the oscillograph (Brush Mark 280) proportional to the charge on the particle. The crystal then fell through another conical shield which isolated the ring from the high electric potential on the parallel plates. In further fall the crystal entered the region of potential gradient and collided with the ice sphere. The charge transferred to the sphere was measured on the second pen of the recorder.

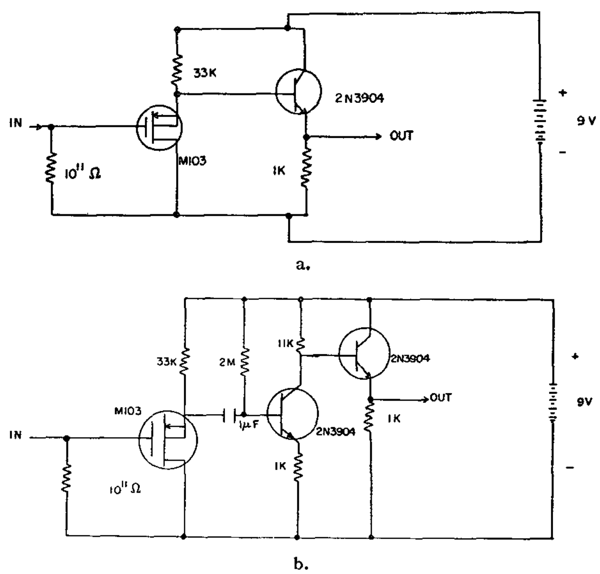

Fig. 2. Circuit of sphere electrometer, a., and ring electrometer, b.

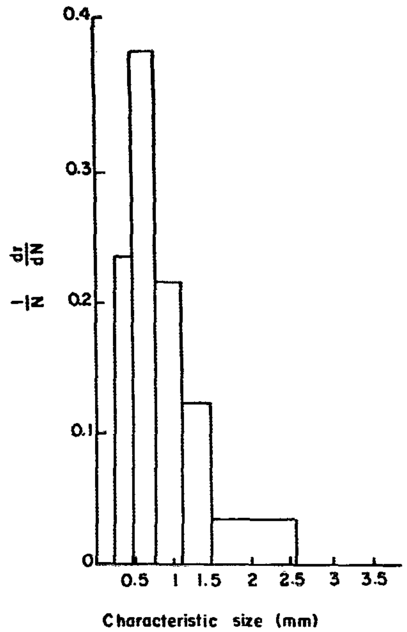

FIG. 3. Sample size distribution of natural ice crystals.

The entire apparatus was placed ~1 m above the ground outside in a clear area relatively free from electronic noise. The environmental temperature was recorded every few minutes and did not vary by more than 1C during an experiment. The falling crystals were generally stellar with a filled-in hexagonal pattern, but many broken crystals and some rimed crystals were noted. An approximate size distribution of the falling ice crystals was made by measurements from photographs taken during Experiment 6 (see Fig. 3).

Only crystals with very small horizontal velocities were chosen by the three conical shields. As a result, only a fraction of the crystals entering the apparatus passed through the ring and subsequently collided with the ice sphere; it took several minutes to obtain enough collisions for a charge distribution. The crystals generally collided with the ice sphere and passed on, but occasionally a crystal would stick on the top surface of the ice sphere. These crystals were removed by wiping the surface with a clean tissue.

4. The electrical pulses

The electrical pulses were recorded on the strip chart of the oscillograph, but an exact interpretation of their meaning is not possible without some knowledge of the physics of the interaction and how the pulses were modified by the electronics. The pulses recorded on the sphere electrometer are most easily understood; they appear to be the result of an abrupt transfer of charge accompanied by a slow bleed off of this charge through the large $10^{11}\,\Omega$ resistor. The time constants observed are, indeed, those that would be predicted if this were the case. Also, when known charges on water drops were transferred to the sphere electrometer, the peaks of the output signals were proportional to the charges.

Final calibration of the sphere electrometer was done by measuring the effective capacity C and calculating the charge Q from the relation $Q=CV$, where V is the peak value of the measured output voltage. The capacitance of the sphere electrometer was measured by noting the attenuation of a 1000-Hz signal when a precision 3-pF capacitor was placed in series with the input. The effective capacity of the sphere electrometer was 4.7 pF.

The signal output from the ring electrometer was calibrated relative to the sphere electrometer so that relative differences could be measured. For this purpose, the ice sphere was replaced by a wooden cup filled with steel wool and the capacitance of the sphere electrometer remeasured. Then simultaneous deflections from the ring and sphere electrometers were recorded when water drops with various charges passed through the ring and were caught in the wooden cup. Measurements of the initial height of the pulses from the ring electrometer gave a value of 6.0 pF for the effective capacitance of the electrometer.

As the equi-potential lines between the two plates are distorted due to the hole in the upper plate, it was necessary to determine the uniformity of the field near the ice sphere. To this end an equi-potential experiment was performed which simulated the apparatus in two dimensions. A two-dimensional view of the apparatus was drawn on graphite conducting paper with highly conductive silver paint. Voltages were connected to the simulated plates and the equi-potential surfaces were traced with a galvanometer. Fig. 4 shows the result of the simulated experiment. The figure clearly shows that near the sphere the equi-potential lines are parallel and uniform.

Due to the high sensitivity of the ring electrometer, all the charges on the crystals that collided with the sphere were recorded. However, occasionally no corresponding

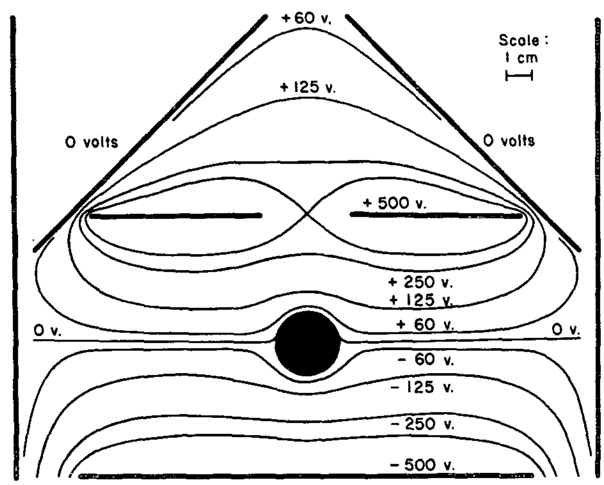

FIG. 4. Equi-potential surfaces around the ice sphere.

Table 1a. Summary of results.

Experiment no.	Ambient temperature (°C)	Applied potential gradient (V cm^{-1})	Average charges (msc)* On snow crystals	Average charges (msc)* Transferred to sphere	Average charges (msc)* Carried off	Median charges (msc)* On snow crystals	Median charges (msc)* Transfered to sphere	Median charges (msc)* Carried off	Total number of events recorded On ring	Total number of events recorded On sphere
1	−3	0	−0.0056	+0.0176	−0.0238	−0.020	−0.005	−0.0075	232	172
2	−3	59	−0.0118	+0.556	−0.569	−0.015	+0.075	−0.085	90	78
3	−3	−59	+0.0103	−0.602	+0.610	−0.013	−0.097	+0.085	50	42
4	−3	59	−0.0083	+0.574	−0.58	−0.015	+0.122	−0.125	51	41
5	−2	0	−0.0039	+0.0194	−0.0235	−0.012	+0.015	−0.020	134	120
6	−2	102	−0.0203	+1.58	−1.00	−0.020	+0.36	−0.45	62	43
7	−2	−102	−0.0177	−1.16	+1.14	−0.015	−0.12	+0.10	122	78
8	−2	51	−0.0158	−0.30	+0.285	−0.021	−0.12	+0.090	122	108
9	−2	−51	−0.0158	+0.378	−0.394	−0.022	+0.077	−0.11	158	106
10	−2	18	−0.0208	+0.15	−0.174	−0.022	+0.040	−0.075	213	183
11	−2	−18	−0.0215	−0.212	+0.189	−0.023	−0.080	+0.040	316	276
12	−3	0	−0.0330	−0.0230	−0.0093	−0.027	−0.017	−0.006	123	107
13	−4	59	−0.0231	+0.22	−0.241	−0.025	+0.078	−0.119	115	91
14	−3	−59	−0.0325	−0.325	+0.291	−0.027	−0.058	+0.026	95	66

* Millistatcoulomb (msc).

Table 1b. Correlation coefficients between charges.

Experiment no.	Applied potential gradient (V cm^{-1})	Correlation coefficients between charges: Originally on snow crystals and transferred to sphere (CRS)	Originally on snow crystals and carried off after separation (CRD)	Transferred to sphere and carried off after separation (CSD)
1	0	+0.428	+0.127	−0.842
2	59	−0.184	+0.246	−0.998
3	−59	−0.084	+0.143	−0.998
4	59	−0.096	+0.160	−0.998
5	0	+0.572	+0.284	−0.625
6	102	−0.162	+0.195	−0.999
7	−102	+0.192	−0.147	−0.999
8	51	+0.218	−0.102	−0.993
9	−51	−0.085	+0.180	−0.995
10	18	−0.122	+0.296	−0.984
11	−18	+0.286	−0.156	−0.991
12	0	+0.803	−0.177	−0.729
13	59	−0.120	+0.204	−0.996
14	−59	+0.231	−0.147	−0.996

signal from the sphere electrometer was observed because, perhaps, the trajectory of the crystal did not intercept the ice sphere. This explains the difference between the number of events recorded by the ring and the sphere in Table 1a.

Many events were recorded in each experiment, and the distributions of the original charges on the snow crystals, the charges transferred to the ice sphere, and the charges carried off by the small crystals after separation (initial charge on a crystal minus the charge transferred to the sphere by that crystal) were plotted on histograms. In all cases, individual charges were between −10 and +10 milli-statcoulombs[2]. When small potentials were applied, the charges concentrated around 0.1 msc, but when large potentials were applied, the charges were close to 10 msc. Positive and negative fields were applied and the charges observed carried both positive and negative values. The tallies, calculations and plots of the data were all made by IBM 7094 digital computer. Table 1 summarizes some of the experimental results.

It was impossible to plot this large range of data on an ordinary histogram with either a linear or logarithmic plot and still be able to compare data from different experiments. The linear scale tends to separate the data into a large group in one location with many individual events scattered throughout the scale, and a logarithmic scale does not allow both negative and positive values to be plotted. Thus, in order to plot all the experimental data on a single scale for comparison, the abscissa of the histogram plot was distorted as follows: The abscissa was divided into 56 equal divisions to cover the range −10 to +10 msc. Divisions on the positive side were labeled using the numeric pattern, 0, 1, 2, 3, . . . , 10, 20, 30 . . . 100, where the number 1 was given the unit 0.01 msc. The same pattern was used for the negative

[2] A milli-statcoulomb (msc) is defined as 10^{-3} esu.

side. Figs. 5, 6, 7 and 8 are shown with this abscissa. This scale is neither logarithmic nor linear but is logarithmic in decades and linear between decades.

5. Analysis

In experiments with a potential gradient present it is easy to see the high negative correlation between the charge transferred to the ice sphere and the charge carried off by the ice crystals after separation (CSD, see Table 1b). Similarily, the correlation between the charge given up to the ice sphere and the original charge (CRS) is relatively high with no potential, but it was very small otherwise. This means that when no field was applied most of the charge on the ice sphere was due to direct transfer with a small contribution from actual generation of charge on collision by fracture of the crystal surfaces, thermoelectric effects, etc. However,

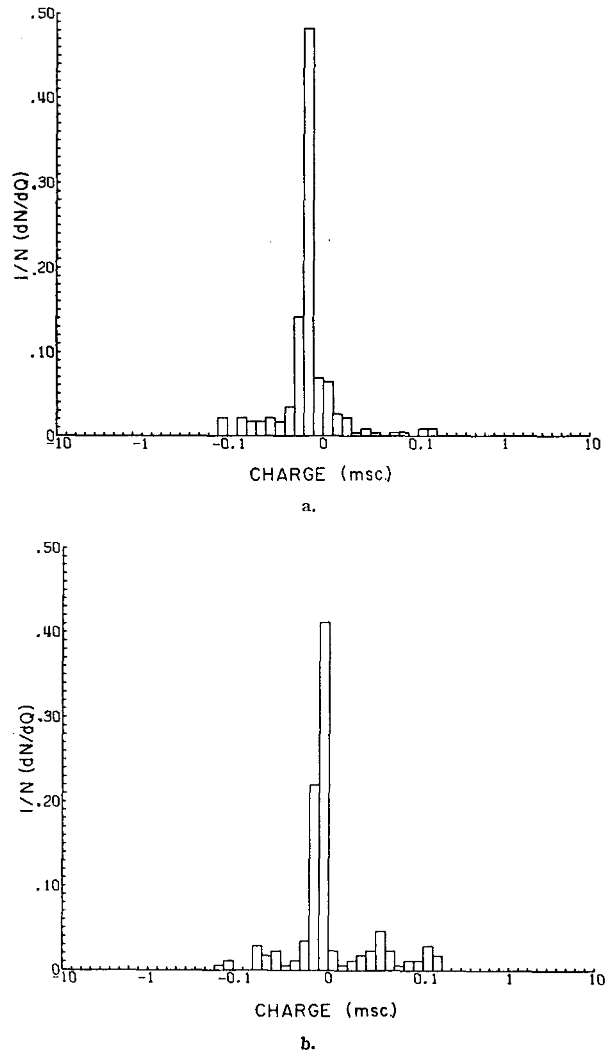

FIG. 5. Charges on the incoming snow crystals (Experiment 1), a., and those communicated to the ice sphere with no potential gradient (Experiment 1), b.

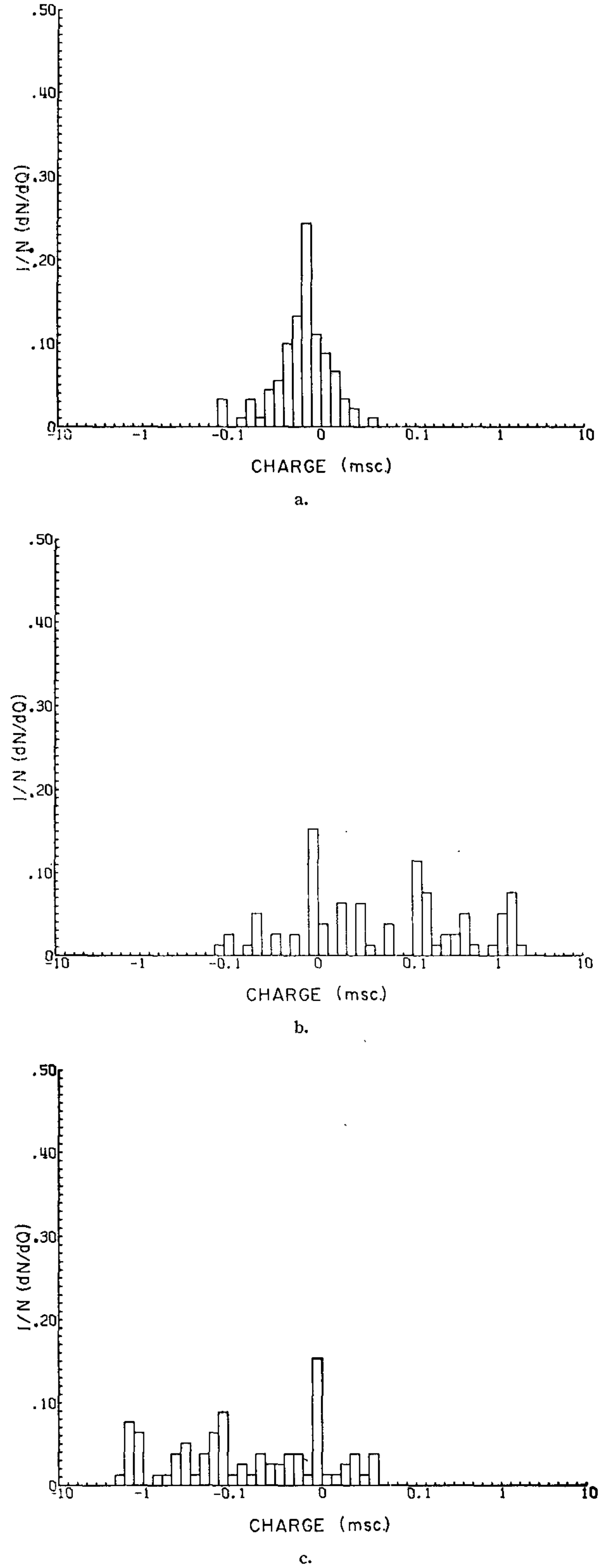

FIG. 6. Charges on incoming ice particles (Experiment 2), a., those communicated to the ice sphere when 58.7 V cm^{-1} were applied (Experiment 2), b., and net charges remaining on the rebounding ice crystals (Experiment 2), c.

when relatively high electric fields were applied, the portion of the original charge transferred appeared small compared to the charge separated due to polarization charging.

The correlation coefficient between the original charge and the charge carried off by the small ice crystals after separation (CRD) is relatively low for all experiments. This indicates again that when a potential gradient was applied, the charge carried off by the small ice crystals came mainly from the charge separation due to polarization. The fact that CRD was relatively small when no potential was present implies that under these conditions the charge carried off on the particles is mainly the charge actually generated by collision.

Direct charge transfer is evident in the similar appearance of Figs. 5a and b. The shape of the distribution in Fig. 5a is nearly as Gaussian as one would expect from random charging effects which occurred before the crystals entered the apparatus. The differences between Figs. 5a and b may be accounted for by charge generated (not separated by polarization) during the interactions. In this case, with no applied potential, the average charge communicated to the sphere was 0.018 msc.

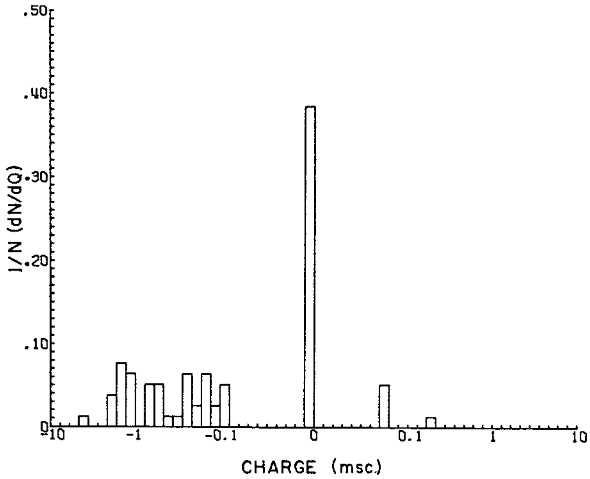

FIG. 8. Charges communicated to the ice sphere when -102 V cm^{-1} is present (Experiment 7).

Later, in the following experiment, a potential gradient of 58 V cm^{-1} was imposed and the average charge communicated increased to 0.38 msc (see Figs. 6a and b). The charge carried off by the rebounding ice crystals was almost exactly the negative of the charge left on the sphere (see Fig. 6c). As even higher voltages were applied, the distribution moved to even larger charges (see Figs. 7a and b) so that when 102 V cm^{-1} was applied, the average charge communicated to the sphere was 1.6 msc. When opposite electric fields were applied, exactly opposite charging occurred. Fig. 8 shows the distribution when -102 V cm^{-1} was applied; the average charge was -1.2 msc.

The forms of the distributions are noteworthy. The distributions show both normal and log-normal trends. To show this the data were plotted as cumulative distributions on linear-probability plots. Fig. 9 shows cumulative distributions for Experiment 9. The cumulative distribution of the original charges is represented by a nearly straight line in the center of the graph, indicating a normal distribution. However, the charges transferred to the sphere and the charges carried off after separation show exponential features as would be expected from log-normal distributions.

In all histograms many charges can be found near 0.01 msc. This is possibly due to collisions of the stellar crystals with their basal face. When the crystals are oriented so as to collide with their basal face, the probability of separation directly after the collision is reduced. This means that most of the charge recorded in such collisions is the result of direct transfer of the initial charge on the falling ice crystals.

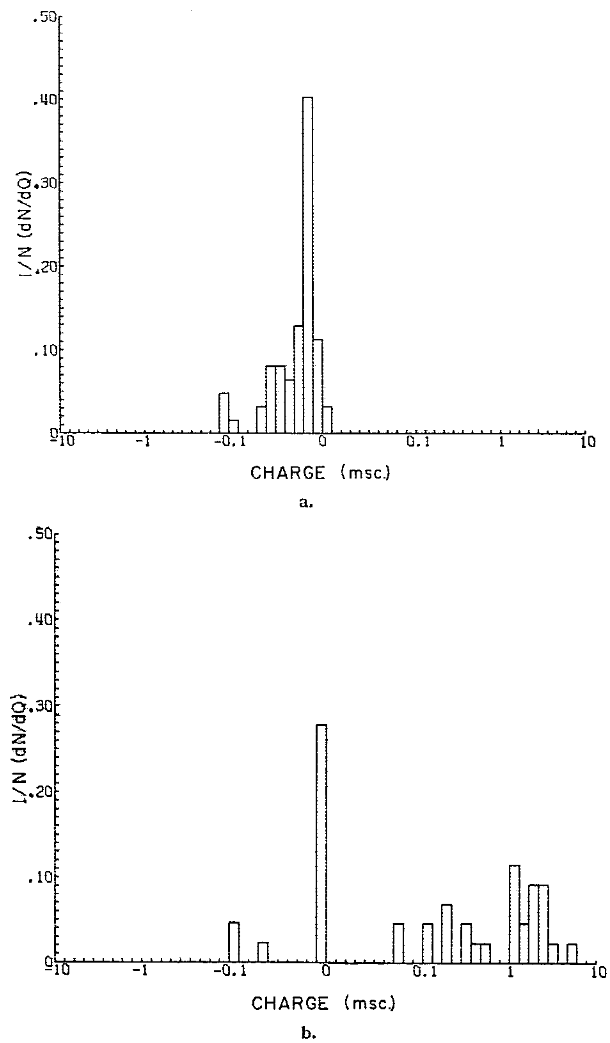

FIG. 7. Charges on the incoming ice particles (Experiment 6), a., and those communicated to the ice sphere when 102 V cm^{-1} were applied (Experiment 6), b.

The effect of potential gradient is summarized in Fig. 10, where the abscissa represents the applied potential gradient and the ordinate the average charge transferred to the ice sphere for all experiments listed in Table 1. The straight line represents Eq. (5) for particles of characteristic size (diameter) of 1 mm. Since the particles were stellar, $\frac{1}{4}$ of a millimeter was used as the effective radius for polarization charging. The data are very well described by the theoretical curve below potential gradients of 50 V cm^{-1}. At higher

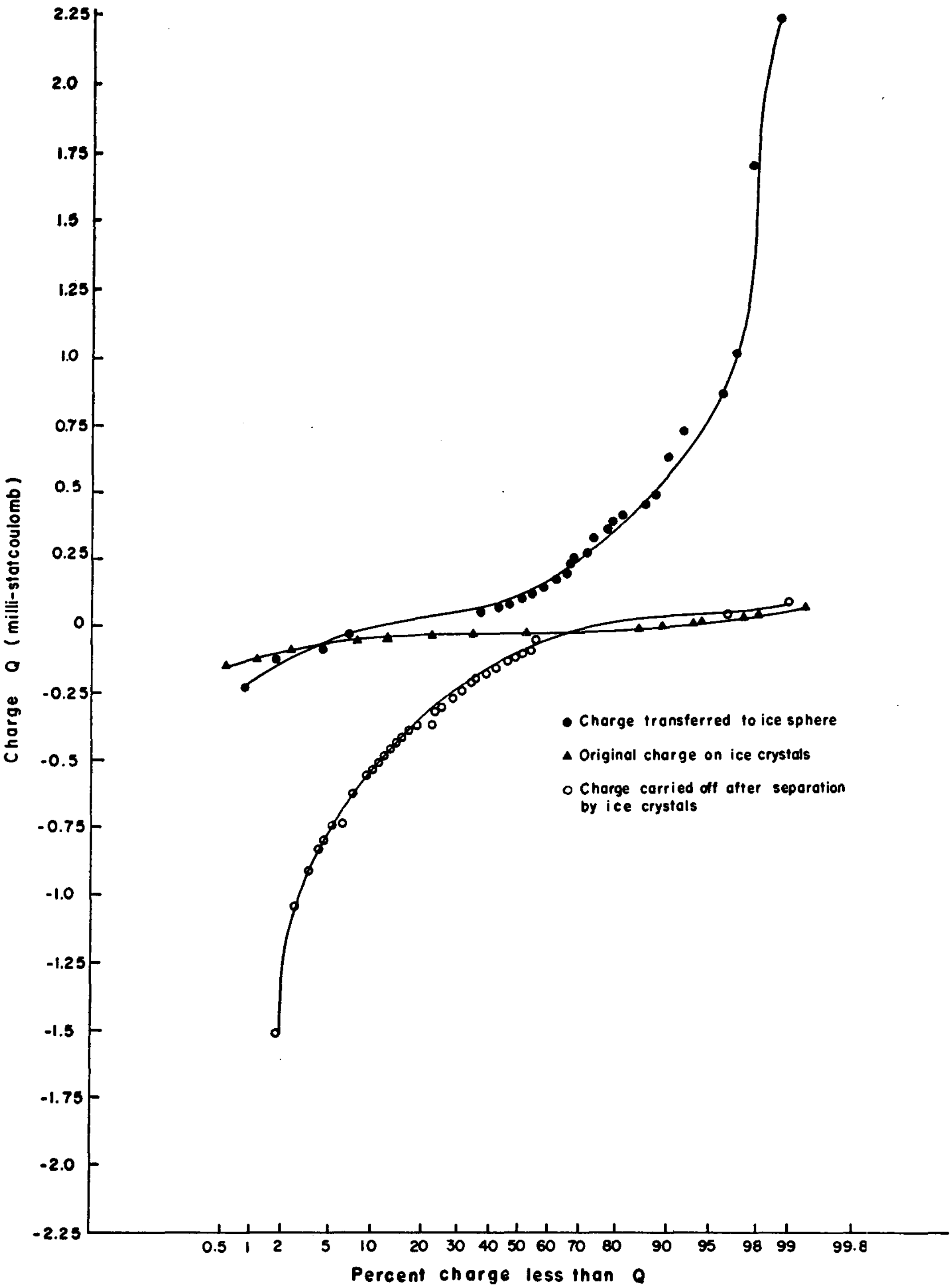

FIG. 9. Linear probability plot of charging events in Experiment 9.

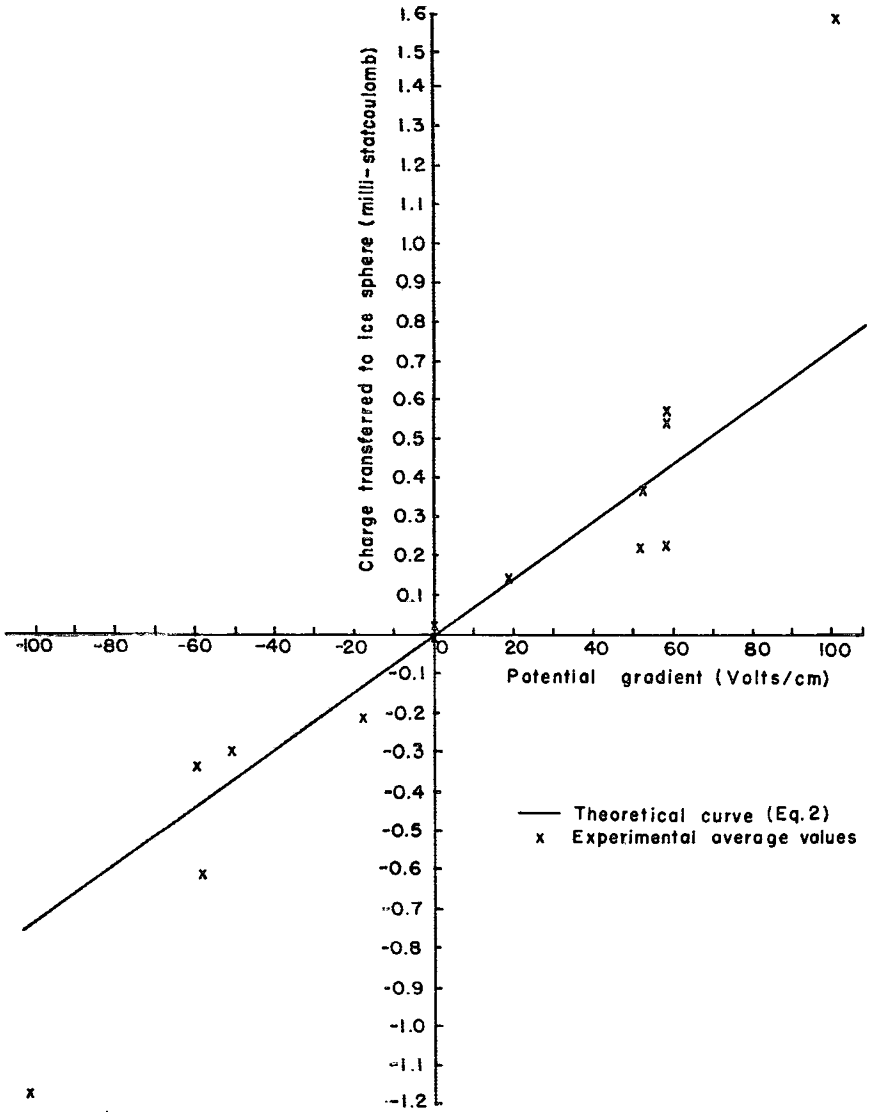

FIG. 10. Electric field vs average charge transferred to ice sphere.

gradients, however, more charge is separated than the theory predicts. This may be a result of several effects, including point discharge and an asymmetric charge distribution in the real snow crystals, as well as the omission of second-order terms in the mathematical solution.

6. Discussion

It is most significant that the potential gradient is such an effective charging agent. Polarization charging explains this effect satisfactorily. With no consideration for the physics of ice (thermoelectric effect, Workman-Reynolds effect, etc.) the electrification of thunderclouds can be explained. Of course, Sartor (Sartor, 1967; Sartor and Abbot, 1968) has shown theoretically and experimentally that polarization charging during collisions of water drops is an effective mechanism for charge generation in clouds. Also, Sartor (1954), Müller-Hillebrand (1954), and Latham and Mason (1962) have shown theoretically that the mechanism is effective during ice particle collisions. The present results demonstrate experimentally that polarization charging is indeed effective in the case of ice-ice interactions.

Polarization charging easily explains the charging that occurs in glaciated clouds without supercooled droplets (Hobbs and Burrows, 1966; Stow, 1969). It also explains the high correlation between particle charges and the potential gradient observed in real clouds in Arizona (Latham and Stow, 1969). Müller-Hillebrand (1954, 1955) predicted that such polarization charging in ice could be important in cloud electrification. His prediction was based on a theoretical analysis similar to the one leading to Eq. (5). However, our experimental results show that this equation underestimates the charging at high electric fields. In other words, this mechanism is much more efficient than predicted. Montgomery and Dawson (1969) have observed an analogous increase in charging on collisions of water drops.

According to the results shown in Fig. 10, in the early stages of the development of a thundercloud the fair weather positive potential gradient is sufficient to cause a substantial charge separation. A positive charge of 0.03 msc is transferred to a 1-mm particle when it collides with a larger particle. Separation of the larger particles from the smaller ones by gravity further enhances the positive potential gradient, resulting in a positive feedback, and more charge is separated. The only necessary condition for polarization charging is that there be particles or droplets which have sufficient size relative to their neighbors so that they have a large relative velocity. Water droplets, of course, undergo the same charging but the faster relative growth of ice in clouds (Wegener-Bergeron mechansim), and the higher separation efficiency may explain the causal relationship between the occurrence of ice and the concurrent charge build-up in thunderclouds in mid-latitudes.

It remains to explain the differences between the present experimental results and those of Latham and Mason (1962). There appear to be at least three ways in which our results differ from those of Latham and Mason. First, we experimented with natural snowflakes which, as a result of contamination in the atmosphere, should have an electrical conductivity at least one or two orders of magnitude greater than the pure ice used by Latham and Mason. The use of pure ice results in a greatly increased relaxation time and therefore less charge transfer. Second, in the laboratory experiments of Latham and Mason very small crystals were blown at relatively high velocities past a cylindrical probe. Sartor (1965) has shown that only a relatively small amount of charge build-up in clouds can result from the small hydrometers of the size used by Latham and Mason. The velocities were higher than the terminal velocities of the snow crystals used in our experiments and probably resulted in smaller contact times and, perhaps, less charge transfer. Finally, the natural ice particles in our experiments undoubtedly had rough surfaces so that there was more sticking and a larger contact time.

The fact that the distribution of the charge transferred to the sphere under a potential gradient is log-normal while the distribution of the original charge on the crystals is normal can be explained by assuming that the size of the crystals is log-normally distributed. In a potential gradient, then, the charge transferred should follow Eq. (5). If the initial charge on the ice crystal is small, the charge transferred will vary as the square of the particle radius. The particle size appears to be log-normally distributed (see Fig. 3). Any power function of a parameter which is log-normally distributed is also log-normal (see Herden, 1960). Therefore, the charge transferred should be log-normally distributed. The original charge on the particle is insignificant when potential gradients are applied so that the original charge distribution does not significantly affect the final distribution of the transferred charge.

7. Concluding remarks

This experiment demonstrates the effectiveness of charging by collisions of polarized ice particles. Following the ideas of Sartor (1961a, b), it appears that this mechanism could account for the large charging found in glaciated clouds and thunderclouds in general. Further experiments are required to see the effect of temperature, ice crystal shape and size, and impact velocity on the charge transferred in the presence of a potential gradient. Also, higher potentials should be used to follow the dramatic increase in charging at higher potentials observed in these field measurements.

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