Corona Charging of Frozen Precipitation

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ABSTRACT

Experiments are described in which ice samples resembling natural precipitation elements were exposed to an electric field of sufficient strength to produce corona at the extremities of the particles. Measurements were made of the residual charge Q_R left on the particles after the field had been turned off.

Values of Q_R lay typically in the range $\sim 0.1-0.5$ nC at 1000 mb, falling roughly linearly with pressure. Possible applications of this process in thunderclouds are discussed.

1. Introduction

A number of experimental studies have been performed to determine the magnitude of the uniform electric fields necessary to initiate corona from various types of precipitation particles, both solid and liquid, under conditions representative of those occurring in thunderclouds (Dawson, 1969; Richards and Dawson, 1971; Crabb and Latham, 1974; Griffiths and Latham, 1974a; Griffiths, 1975). Consideration of the possible role of this process in thunderclouds leads to two main lines of inquiry.

The first of these is concerned with the behavior of the electrical discharge in the gas once it has been produced by the precipitation particle, and deals with the propagation of corona (Phelps, 1971, 1974; Griffiths and Phelps, 1976a), the possible role of positive streamers in lightning initiation (Griffiths and Phelps, 1975, 1976b), and the effect of corona on the ionic conductivity within the cloud (Griffiths *et al.*, 1974).

The second line of inquiry focuses on the fate of the precipitation particles that have been in corona, whether or not they become charged, and if so whether they then play, by virtue of this residual charge, a significant role in the electrification process (generative or dissipative) occurring in the cloud. In addition, it has been suggested (Pierce, 1957) that the production of highly charged raindrops by corona might of itself constitute a mechanism for lightning initiation, independent of the subsequent behavior of the discharge in the gas. This aspect of corona was examined by Dawson and Duff (1970) and Richards and Dawson (1971) for the case in which the precipitation is in the form of large single raindrops. In the following sections we describe a parallel study dealing with the case in which the precipitation is frozen.

Before describing the experiments we will review the arguments that lead us to expect that a frozen precipitation particle that has been in corona will hold a residual charge, since the reasons for this are different from those applying to the liquid phase. This distinction arises because of the difference in electrical properties of ice and liquid water and because the liquid is deformable whereas the ice is rigid. A water drop undergoing corona of both polarities simultaneously from points diametrically opposed on its surface acquires a residual charge because the positive and negative corona occur at considerably different values of ambient electric field (Dawson, 1969). The situation is complicated if the drop is falling, because the corona onset and extinction criteria are modified by the effects of aerodynamic forces which influence the stability of the water surface so that the discharge may be restricted to one polarity only. In either case the drop becomes charged.

In the case of ice the positive and negative corona onsets for a given point are very nearly the same. This behavior has been attributed to the fact that ice is much more effective than liquid water as a secondary emitter (Bandel, 1951; Obolensky, 1912). For an ice particle exposed to a sufficiently high electric field it is found that both polarities of corona occur simultaneously from opposite ends (Griffiths and Latham, 1974a). Since it is most improbable that the two ends would display such a combination of surface geometry that the two onsets occurred at exactly the same value of ambient field, it follows that one polarity of corona will persist slightly longer than the other as the ambient field is reduced below the corona extinction level. Under these circumstances, when both polarities have been finally extinguished, the particle should carry a residual charge. [The corona extinction occurs at a value of ambient field some 10–20% lower than that required for onset (Griffiths and Latham, 1974a).] This effect should be most marked for precipitation particles displaying the greatest degree of surface geometry asymmetry, such as conical graupel. Precipitation particles subjected to corona-producing electric fields in a thundercloud would exhibit this behavior if they fell or were carried out of the high-field region, or if the field itself were to relax. Similarly, particles subjected to a transient high field in the vicinity of a lightning channel would be expected to acquire a charge by this process.

Considering the case where the difference in corona extinction fields is primarily due to surface geometry asymmetry, we would expect the more pointed end to continue in corona longer than the blunter end. On this basis, the polarity of the residual charge Q_R should be opposite in sign to the direction in which the sharper end points, where the positive direction of the field is that in which a positive charge would experience a force. However, since there *is* a small difference in the critical conditions applying to the two polarities of corona for a given ice point, we further expect that if the experiment is repeated with the field direction reversed then Q_R will be not only of opposite sign, but also somewhat different in magnitude.

In contrast, some particles will display very little surface geometry asymmetry, so that the corona polarity difference may be the dominant factor. For example, a given ice sample may have the lower extinction field at the negative end for both directions of ambient field, in which case we would expect Q_R to be positive irrespective of the field polarity.

In addition to the above considerations, Q_R should be affected by changes in gas pressure and temperature, since the processes underlying corona are functions of gas density. However, in view of the observed effect of the ice temperature in inhibiting the production of corona from pure samples colder than −18°C (Griffiths and Latham, 1974a, b), these experiments were all performed at −10°C so as to eliminate complications arising from temperature-dependent variations in the electrical properties of the ice.

2. Apparatus and method

The apparatus, shown in Fig. 1, is essentially the same as that employed by Griffiths and Latham (1974a) with the addition of a means of measuring Q_R. Ice crystals of various types having overall dimensions of a few millimeters were grown in vapor diffusion chambers. An ice crystal selected for study was removed from the chamber on a fine glass capillary and then attached to a thin nylon monofilament (radius 50 μm) by bringing it into contact with a tiny drop of distilled water that had been placed on the line and allowed to supercool. The line was arranged so that the ice was suspended between two circular parallel plate electrodes of about 10 cm diameter, between which a known electric field could be maintained by means of a variable 0–60 kV dc

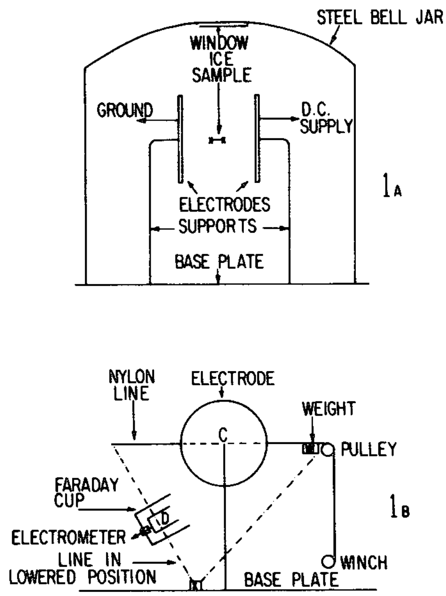

Fig. 1. Schematic sections of the apparatus in elevation perpendicular (a) and parallel (b) to the field direction. The solid and dash-dotted lines depict the raised and lowered positions of the nylon line as described in the text.

electric power supply of reversible polarity. The ice was positioned centrally between the electrodes, with the longest dimension of the sample parallel to the field. The electrode system was built onto a thick aluminum base plate, and could be covered with a steel bell jar fitted with observation windows and a pumping port, the whole apparatus being housed within a freezing cabinet in which the temperature was maintained at −10°C. The pressure in the chamber could be maintained at any desired value in the range 200–1000 mb. Once the sample had been attached to the line the electric field could be increased until the onset of corona occurred, detected visually with the dark-adapted eye. The field was then turned off so that the corona was extinguished.

The value of Q_R was determined by lowering the ice sample into a shielded Faraday cup connected to an electrometer and measuring the induced charge, care being taken that the ice did not contact the walls of the cup. This procedure was accomplished by having one end of the nylon line wound over a pulley and onto a winch operated by a reversible dc motor. When the line was unwound a small weight, located at W in Fig. 1b, was lowered to point X on the chamber floor, thereby also lowering the ice sample from point C between the electrodes to point D inside the Faraday cup, the walls of which were provided with narrow slots to accommodate the line. The ice could be withdrawn from the cup after Q_R had been measured, and wound back to its former position. By this means several determinations of Q_R could be made using the same piece of ice under a variety of experimental conditions. At each data point 10 measurements of Q_R were taken.

TABLE 1. The range of values of Q_R(nC) obtained from 10 readings at each data point for seven different ice samples classified according to type size and mass. All data are for a pressure of 1000 mb.

Sample	Description	Longest dimension (mm)	Mass (mg)	Q_R range Positive	Negative
A	Thick hexagonal plate	6	5	0.16–0.25	0.16–0.25
B	Dendritic aggregate	8	2	0.39–0.46	0.16–0.20
C	Hexagonal column	10	1	0.25–0.27	0.31–0.35
D	Thin hexagonal plate	8	0.3	—	0.30–0.40
E	Thin hexagonal plate	5	0.2	0.10–0.30	0.10–0.30
F	Irregular pellet	8	6	0.10–0.30	—
G	Irregular pellet	10	8	0.24–0.45	—

In addition to the experiments performed using ice crystals grown in the diffusion chambers, Q_R was also measured for some irregular pieces of ice made by freezing rain water that had been splashed onto a piece of crumpled aluminum foil, as well as for crystal aggregates grown in the diffusion chambers and then rimed by exposing them to a supercooled droplet cloud. In each case the mass of the ice sample was determined at the end of the experiment, when it was melted and weighed on an electrical microbalance. Before applying the electric field for the first time, each sample was lowered into the Faraday cup as soon as it was attached to the line to check that there was no significant initial charge.

3. Results

Table 1 shows the results obtained at 1000 mb for seven different ice samples. The range of values of Q_R (nC) obtained from 10 readings in each case is recorded in the right-hand column under the appropriate sign. Blank entries indicate runs that were terminated early because of failure, the commonest being that the sample broke free of the line as a result of electrically induced oscillations. For cases A, B and C it was found that reversal of the field caused Q_R to change sign as predicted. This was also observed for cases F and G, even though these data runs were incomplete. For these two latter samples, in which one end was markedly more pointed than the other, the expectation that Q_R would be opposite in sign to the field direction indicated by the sharper end was confirmed for both polarities, some negative readings being obtained before the run was terminated. Only one polarity of field was successfully examined for sample D. For sample E the sign of Q_R was not determined by the field polarity; in fact, both positive and negative values were obtained in roughly equal numbers for both directions of field. This behavior is most probably caused by small-scale changes in ice surface geometry over the duration of the experiment, due to evaporation. This same explanation would also account for some of the scatter in the data obtained for other samples, where the polarity of Q_R *was* consistently determined by the field direction.

In order to test this conjecture, measurements of Q_R were made for a sample consisting of a hardened steel needle 5 mm in length, having one end sharp and the other blunt. In this case, where the surface geometry would be constant over the run, the scatter in Q_R was very small compared to the corresponding data for ice.

The effect of pressure on Q_R for ice samples was investigated successfully in only two cases, E and G. The data obtained showed considerable scatter, but can be summarized in the statement that Q_R is linearly proportional to pressure in the range 200–1000 mb, with a spread of $\pm 50\%$ of the mean value of Q_R at any point. It appears again that this scatter is partly due to evaporative changes in ice geometry during the run. In support of this it was found that for the steel substitute needle described above, $Q_R \propto$ pressure describes the results within $\pm 10\%$ over the same pressure range.

In a few cases the field was increased well above the corona threshold so that a spark-over occurred. In such cases Q_R was always less than 5 pC.

4. Discussion

The process investigated in these experiments is capable of producing highly charged ice particles. The samples used are comparable in type, size and mass to those found in natural precipitation (Locatelli and Hobbs, 1974), and electric fields of sufficient magnitude to give corona from such particles are known to occur in thunderstorms (Winn *et al.*, 1974). We may therefore reasonably expect this process to occur in nature, and in the following paragraphs we examine the possible role of this phenomenon in the thunderstorm.

As mentioned earlier, mechanisms for lightning initiation by corona can be divided into two classes, one depending on the propagation of the discharge in the gas, and the other on the accumulation of residual charge on the precipitation.

The latter mechanism, suggested by Pierce (1957), was investigated quantitatively using a computer simulation technique by Dawson and Duff (1970). In this model it is proposed that the negative charges acquired by a column of raindrops in corona might produce a local field enhancement sufficient to cause neighboring drops to yield further corona. A chain reaction of such discharges could conceivably propagate a self-regenerating wave of local field enhancement sufficient to initiate the lightning stroke. However, Dawson and Duff found that the necessary residual charges were several hundred times larger than could reasonably be expected on the basis of the earlier work of Dawson (1969), and in some cases were in excess of the Rayleigh limit. For large drops present in number concentrations of 12, 4 and 1.2 m^{-3} the charges required were 38, 115 and 400 nC, respectively.

They proposed that in some circumatances this difficulty might be overcome if the charge were to be released from the drops in the form of highly charged

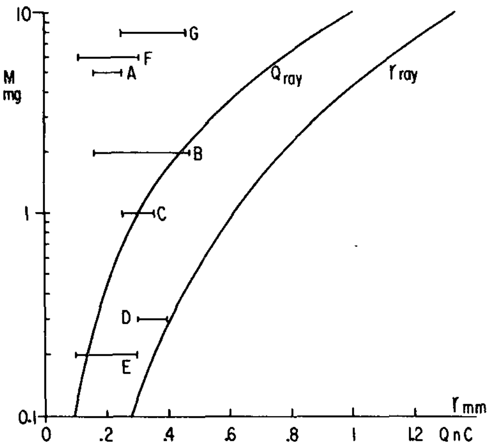

Fig. 2. The results from Table 1 superimposed on a graph of ice-sample mass versus the Rayleigh limit charge Q_{ray} and radius r_{ray} of the equivalent melted drop.

negative droplets, but Richards and Dawson (1971) showed experimentally that such a process did not occur in the case of drops falling at terminal velocity, because of aerodynamic stabilization of the lower surface of the drop in the airstream. Values of Q_R measured for large drops in their experiment were typically ~0.5 nC. In the experiments reported here the values of Q_R for ice are of the same order, so that we may conclude that the residual charge mechanism of lightning initiation cannot work for either liquid or frozen precipitation, since the magnitude of Q_R is insufficient in either case.

Considering next the effect of these particles on the electric field that produced them, we note that a typical corona onset field for an ice particle a few millimeters in length at an altitude of a few kilometers is $\sim 4\times 10^5$ V m^{-1} (Griffiths and Latham, 1974a). For a crystal having a mass of 1 mg, and taking 0.3 nC as a representative value of Q_R, the electrical force on the particle in this field is about 10 times that due to gravity. With the electrical force thus predominant we can expect the resultant movement of the particle to have a dissipative effect on the electric field. This tendency could be counteracted or assisted by air motions, but in view of the large size and small number densities of such particles, the overall effect will most probably be dissipative of the pre-existing field. The terminal velocities of the charged particles will be greatly affected by the electrical forces, and we would expect a significant modification in the interaction rate with other cloud and precipitation elements.

One of the more interesting aspects lies in the fact that in some cases Q_R exceeds the Rayleigh limit of the drop that would be produced if the ice crystal were to melt before significant charge loss occurred. This is illustrated in Fig. 2, which shows the results from Table 1 superimposed on a graph of the particle mass plotted against the Rayleigh limit charge Q_{ray} and the radius r_{ray} of the equivalent drop, the two latter variables both on the abscissa. Where $Q_R \geqslant Q_{ray}$ disruption would occur immediately on melting, leading to an increase in the small charged droplet population. Additionally, some larger charged drops would be produced as a result of the melting of particles carrying charges less than the Rayleigh limit. In suitable conditions members of either or both of these groups may evaporate to the point where further Rayleigh disruptions would occur; for droplets that become supercooled prior to undergoing these subsequent disruptions we would expect the process to yield frozen daughter products, contributing to the small ice crystal population. Further experiments are required in order to establish whether or not such a chain of events could take place in a thundercloud.

5. Conclusions

Ice crystals may acquire considerable residual charge as a result of undergoing corona in a strong electric field, the magnitude of Q_R being sufficient to significantly affect the subsequent history of the particles. As in the case of liquid drops, Q_R is not large enough for the process to be viable as a means of lightning initiation by the charged precipitation mechanism proposed by Pierce.

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