Electrification produced by the growth of soft hail in thunderclouds

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ABSTRACT

Detailed studies of the electrification associated with the growth of an artificial pellet of soft hail have been made by REYNOLDS, BROOK & GOURLEY (1957), LATHAM & MASON (1961*a*) and MAGONO & TAKAHASHI (1963*a*, *b*). The apparent contradictions between the results of these separate studies are shown to be merely the consequence of the different conditions under which they were performed and it is demonstrated that the temperature gradient theory affords a qualitative explanation for all the results obtained. Strong negative charging of the growing pellet is produced by two processes, both manifestations of the theory: (1) Collision between the pellet and supercooled droplets which freeze onto its surface and shatter to eject positively charged ice splinters. (2) Momentary contact between ice crystals and a rimed pellet of irregular surface structure; the charge transfer resulting from this process depends markedly upon the violence of the impact.

Calculations show that appreciable negative charging of the growing pellet will occur in a thundercloud over ranges of droplet diameter $0 < d < 120\ \mu$, pellet radius $0.25 < r < 2.5$ mm and environmental temperature $-35° < T < -4°$C. The combined rate of charging inside a thunderstorm by means of these two processes is estimated to be at least 3 C km^{-3} min^{-1}, which can easily account for the electrification of a moderate thunderstorm; this riming process may also be able to generate sufficient charge to explain the electrification of extremely severe thunderstorms.

Introduction

When a pellet of soft hail grows by the accretion of supercooled water droplets which freeze onto its surface it becomes electrically charged. This phenomenon has been studied in natural clouds and in the laboratory by many workers (FINDEISEN, 1940, 1943; KRAMER, 1948; WEICKMANN and aufm. KAMPE 1950; LUEDER, 1951; MEINHOLD, 1951; KUETTNER & LAVOIE, 1958). In general the hail pellet was found to acquire negative charge, but the origin of the electrification was not established in this early work although Findeisen suggested that temperature differences in the growing surface may be of fundamental importance. Three recent series of experiments, discussed below, confirm Findeisen's suggestion but provide contradictory assessments of the other factors important in the electrification of soft hail.

REYNOLDS, BROOK & GOURLEY (1957) measured the charge acquired by an artificial hail pellet as it grew in a cloud of supercooled droplets and ice crystals. They found that the temperature difference between the pellet and the impacting ice crystals played a decisive role in determining the magnitude and sign of the electrification. They concluded that charge transfer resulted from glancing contact between ice crystals and the warmer hail pellet; the function of the supercooled droplets was merely to raise the temperature of the hail pellet by giving up their latent heat of fusion on freezing on to it. Reynolds *et al.* at first attributed the charging observed in their experiments to the Workman-Reynolds effect but later BROOK (1958) suggested that the electrification was a consequence of the preferential migration of positive ions down temperature gradients in ice.

This temperature-gradient mechanism of charge transfer was expressed in a rigorous form by LATHAM & MASON (1961*b*) who derived and verified experimentally equations for the charge transfer produced when temperature gradients exist in ice. They showed that when a uniform temperature gradient $\Delta T/\Delta X$ is applied along a uniform ice specimen of cross-sectional area A the colder end acquires a positive charge of

$$Q = 5 \times 10^{-5}. \quad \frac{\Delta T}{\Delta X} A \text{ e.s.u.} \qquad (1)$$

and the warmer end acquires an equal negative charge. When two pieces of ice of different temperature are brought into momentary contact the warmer piece acquires a negative charge which has a maximum value of

$$Q_{max} = 3.10^{-3} \quad \Delta T.A. \text{ e.s.u.} \qquad (2)$$

for a contact time of 10^{-2} sec. LATHAM & MASON (1961*a*) showed that the temperature gradient mechanism affords a quantitative explanation for the negative charging of an artificial hail pellet when it collides with colder ice crystals and when supercooled droplets freeze onto its surface and eject positive ice splinters. However, in contradiction to Reynolds, Brook and Gourley they concluded that only the latter process can be of major importance in thunderstorm electrification.

In an attempt to resolve these differences MAGONO & TAKAHASHI (1963*a*, *b*) studied the electrification of an ice-coated rod growing in both natural and artificial clouds of supercooled droplets and ice crystals. In agreement with the work of Reynolds *et al.* and in contradiction to that of Latham and Mason they found that appreciable electrification occurs only when crystals and droplets coexist inside the cloud; however, the sign of the charging found in their work was often different from that of the previous two studies. Magono and Takahashi concluded that the riming rate and the structure of the rimed surface were important factors in determining the sign of the electrification. They offered no explanation for the mechanism involved in the observed charge transfer.

It is seen, therefore, that each one of these three exhaustive studies of the electrification produced by riming yielded results which were self-consistent and reproducible but which were significantly different from those of the other two studies. The only conclusive common observation was that temperature differences between the hailstone and the cloud in which it was growing is a controlling factor in determining the sign and magnitude of the charge transfer.

It seems possible therefore that the following results may emerge from a detailed analysis of these riming experiments:

(1) The differences between the results of the three studies may not, in fact, be contradictory but may be attributed to different experimental conditions.
(2) The temperature gradient effect may have been responsible for the electrification observed in each study.
(3) It may be possible to define rigorously the conditions for negative or positive charging of a growing pellet of soft hail.
(4) A reassessment may be made of the importance of soft-hail growth in the generation of electric charge inside thunderstorms.

The following analysis constitutes an attempt to clarify these four points.

The riming experiments

In the experiments of REYNOLDS, BROOK & GOURLEY (1957) an ice-coated metal sphere (the rimer) was rotated in a supercooled cloud of water droplets and ice crystals and measurement was made of the charge acquired by this artificial hailstone as it grew by collecting cloud particles. Systematic observations were made of the charging associated with the growth of the rime deposit as a function of the supercooled droplet and ice crystal concentration, the temperature difference between the growing hailstone and the impacting particles and contamination of the droplets with sodium chloride. They found that when the rimer was operated in a cloud composed entirely of supercooled droplets, or entirely of ice crystals, small charging effects were produced when compared with the very large values (about 400 e.s.u./g of rime) obtained when both were present. In general, the sign of the charge on the hailstone was positive when the crystals were numerous in relation to the droplets, and negative when the cloud in which the hailstone was growing was composed mainly of droplets. Reynolds *et al.* found that when the cloud conditions were adjusted for positive charging of the rime (i.e. numerous crystals and very few droplets) strong negative charging promptly resulted if the rimer was heated, which reverted to its initial sign as soon as the lamp producing the heat was switched off. The effect of 10^{-4} molar sodium chloride contamination of the droplets (but not the ice crystals, which grew from the vapour) was to produce negative charging of the hailstone, regardless of the relative amounts of water droplets and ice crystals in the cloud. Reynolds *et al.* estimated that the charge transfer produced by the collision between an ice crystal of radius 50 μ and the artificial hailstone was of order 5×10^{-4} e.s.u. The experiments were made at temperatures down to $-25°C$ and the average diameter of the droplets in the cloud was about 10 μ.

LATHAM & MASON (1961*a*) exposed an ice sphere to a stream of ice crystals and found that it acquired a positive charge which became negative if the sphere was heated relative to the ice crystals. It was found that for a temperature difference of 5°C between the crystal-stream and the ice sphere the average charge transfer per crystal-hailstone collision was 5×10^{-9} e.s.u. for crystals of diameter 20 μ. If the hailstone was contaminated with sodium chloride or hydrogen fluoride it acquired a negative charge on collision with the ice crystals. Latham and Mason found that when an ice sphere was exposed to a stream of supercooled droplets it became negatively charged if the droplet diameter lay between 30 and 120 μ, the air-stream velocity was in the range 2 to 25 m/sec and the temperature was below about $-3°C$. Under these conditions the supercooled droplets shattered as they froze onto the hailstone to produce a number of positively charged splinters; the average charge per droplet-hailstone collision was 4×10^{-6} e.s.u. Irradiation of the hailstone by means of a lamp during its exposure to the droplet stream, and contamination of the droplets with sodium chloride both produced a slight reduction of the negative charging. For higher values of wind velocity and droplet diameter splashing conferred a positive charge on the hail pellet.

MAGONO & TAKAHASHI (1963*a*, *b*) measured the charge acquired by a cylindrical ice specimen exposed to a stream of natural or artificial ice crystals or supercooled droplets. In agreement with Reynolds, Brook and Gourley, they found that appreciable charge was separated only when ice crystals and droplets were present in the cloud at the same time. For temperatures close to 0°C and low riming rates $R \lesssim 10^{-4}$ g cm^{-2} sec^{-1}, determined by weighing the ice cylinder before and after exposure to the cloud particles, the cylinder acquired a slight positive charge and the rimed surface was extremely smooth. At lower temperatures and higher riming rates the cylinder acquired a considerable negative charge and had a delicate surface structure. Heating the ice cylinder while it was exposed to the particle stream caused its negative charge to be greatly enhanced or its positive charge to be reduced or even changed to negative. Magono and Takahashi observed that when ice crystals collided with an already-rimed cylinder it acquired positive charge if it was smooth and negative charge if it had an irregular surface. Collision of droplets only with the artificial hailstone produced no perceptible charging. A smooth ice cylinder exposed to a stream of ice crystals acquired positive charge if formed from 2.10^{-5} N ammonium hydroxide solution and negative charge if formed from 10^{-2} N or 10^{-4} N sodium chloride solution. Magono and Takahashi offered no explanation for the physical mechanism responsible for the observed charge transfer and gave no values for the charge per collision between crystals or droplets and the ice cylinder; however, it can be estimated from their results that if the surface of the cylinder is irregular the average charge per collision is several orders of magnitude greater than that measured by Latham and Mason for a smooth ice surface. The diameter of the supercooled droplets was less than 5 μ; the average ice crystal diameter was several millimetres.

These experiments show that the electrification of a growing rime surface is a sensitive function of riming rate, droplet diameter, relative proportions of impinging droplets and crystals, surface structure of the rime, impact velocity, chemical constitution of the ice from which the artificial hailstone is formed, temperature and temperature difference between the growing rime surface and the particle stream to which it is exposed. Reynolds *et al.* consider that ice crystal-hailstone collisions are responsible for the bulk of charge transfer produced during the riming process while Latham and Mason consider that the splintering of supercooled droplets is the dominant mechanism of electrification; in contradiction to these workers Magono and Takahashi conclude that the rate of riming and the surface structure of the rime are factors of prime importance in producing the observed charge transfer.

Discussion of the riming experiments

There appear to be two ways in which the temperature-gradient mechanism can produce appreciable charging of a soft hail pellet growing in a cloud of ice crystals and supercooled water droplets. Electrification can be caused by the fragmentation of droplets as they impinge and freeze onto the hailstone and by the asymmetric rubbing between ice crystals and the hailstone.

MASON & MAYBANK (1960) found that during the early stages of freezing of a supercooled droplet a shell of ice is formed on the outside of the droplet, the interior remaining liquid. The expansion which accompanies any subsequent freezing sets up stresses in the ice shell which usually disintegrates to produce a number of ice splinters. However, during the freezing of the droplet interior a radial temperature gradient is established across the ice shell with the inner surface held at 0°C and the outer surface cooling towards the air temperature. According to the temperature-gradient theory protons migrate preferentially down this temperature gradient and produce a net positive charge in the outer layers of the ice. Splinters ejected from these layers during the freezing process will therefore tend to carry away a positive charge and leave the droplet residue negatively charged. This was confirmed by Latham and Mason over the ranges of droplet diameter, air temperature and wind velocity mentioned previously; the average charge per droplet-hailstone collision, 4×10^{-6} e.s.u., is consistent with Equation (1).

HENRY (1953) showed that if two identical specimens of an insulator are rubbed together asymmetrically, i.e. so that the area of rubbing of one specimen is different from that of the other, then charge is separated. The specimen of smaller contact area will be heated relative to the other one, thus producing a temperature gradient across the interface. If the concentration of mobile charge carriers in the specimens is a function of temperature, then flow will occur down the concentration gradients set up, and the specimens will acquire equal and opposite charges. In the case of ice the temperature-gradient theory predicts that the specimen of smaller rubbing area will become heated relative to the other one and will thus acquire negative charge. This effect was demonstrated qualitatively by Reynolds *et al.* for large ice rods and Latham and Mason for small ice crystals rubbing against an ice coated rod. LATHAM (1963) showed that the charge transfer produced by the asymmetric rubbing of two smooth ice specimens was explicable in terms of Equation (1). Therefore, when an ice crystal slides over a smooth ice surface it will become heated relative to the surface which will therefore acquire positive charge. Conversely, if the surface is rimed and highly irregular, consisting of a multitude of delicate ice branches, then collision between it and ice crystals of diameter between 100 μ (REYNOLDS *et al.*) and several millimetres (MAGONO and TAKAHASHI) will cause the rimed surface to become warmer at the points of contact than the impacting crystals and therefore to acquire a negative charge. Stow (private communication) has observed that the charge transfer produced on contact between two ice specimens of different temperature increases markedly as the violence of the impact increases. Therefore, the negative charge acquired by a complex rimed surface exposed to a stream of ice crystals will be numerically much greater than the positive charge acquired by a smooth ice surface exposed to the same crystal stream.

It is possible, therefore, to predict the charge transfer resulting from the three processes involving interactions between the cloud particles and the rimed surface which are likely to be of major importance in the electrification of a growing pellet of soft hail:

(1) Glancing collision between ice crystals and a smooth ice surface confers a small positive charge on the surface; if the surface is several degrees warmer than the crystals it will acquire a small negative charge.
(2) Collision between ice crystals and a complicated, heavily-rimed surface confers a large negative charge on the surface.
(3) Collision between an artificial hailstone and supercooled droplets of diameter $30 < d < 120\ \mu$, velocity $2 < U < 25$ m sec^{-1} at temperatures below -3°C causes the hailstone to acquire a negative charge.

In a thundercloud the temperature difference that exists between a growing pellet of soft hail and its environment, produced by the evolution of latent heat by the freezing supercooled droplets, will reduce the electrification produced by Process (1) and accentuate that produced by Process (2).

It is now possible to interpret all the results of the three riming studies described in the previous section in terms of the temperature gradient theory.

Since the diameter of the largest droplets used in the experiments of Magono and Takahashi was about 5 μ Process (3) would not occur in their work which is explicable entirely in terms of the asymmetric rubbing effect. The ice cylinder became warmer than the crystals and negatively charged if its surface was irregular (Process (2)) and cooler (positive) if its surface was smooth (Process (1)); the cylinder was smooth at high temperatures and low riming rates and irregular at low temperatures and high riming rates. If the rime surface was irregular heating the ice cylinder increased the temperature difference between the cylinder and the crystals and therefore increased the negative charge; if the surface was smooth heating the cylinder reduced or even reversed the temperature difference with a consequent reduction or reversal of the positive charging of the cylinder. The observation that the ice cylinder became highly charged only when crystals and droplets were present in the air stream at the same time is also consistent with the theory; when droplets only were present they were too small for Process (3) to operate, and when crystals only were present the cylinder remained smooth in which case the only charging mechanism operative was Process (1) which confers a small positive charge on the ice cylinder. However, if the cylinder had an irregular surface before exposure to the crystal stream then Process (2) operates with the resultant high negative charging of the cylinder, as observed by Magono and Takahashi. The theory predicts that if the ice cylinder is formed from solutions of molarity greater than about 10^{-4} M whose positive ions are more mobile than the negative ones then contact between pure ice crystals and the cylinder causes it to acquire negative charge; if the mobility of the negative ions is greater than that of the positive ions the cylinder will acquire positive charge. This explains the observation that when the cylinder was formed from NaCl solution it became negatively charged and when it was formed from NH_4OH solution it became positively charged; the Na^+ ion is more mobile in ice than the Cl^- ion, but the NH_4^+ ion is less mobile than the OH^- ion. All the results of Magono and Takahashi are therefore explicable in terms of the temperature gradient effect.

Latham and Mason deliberately separated the effects of crystal-hailstone collision from those of droplet-hailstone collision. When the airstream contained crystals only Process (1) was operative since the artificial hailstone was smooth and thus acquired positive charge. When the airstream contained supercooled droplets only Process (3) was operative and ice splinters were ejected as the droplets froze onto the hailstone, which became negatively charged. Latham and Mason showed that all their results were explicable in terms of the temperature gradient theory and that their measurements of $q_c = 5 \times 10^{-9}$ e.s.u. for the average charge transfer per crystal-hailstone collision and $q_d = 4 \times 10^{-6}$ e.s.u. for the average charge transfer per droplet-hailstone collision are consistent with Equation (2) and Equation (1) respectively. The effect of heating the hailstone was to reduce the temperature difference across the ice shell—and therefore the negative charging—in the droplet experiments and to reduce or reverse the temperature gradient—and therefore the positive charging—in the ice crystal experiments.

The experiments of Reynolds, Brook and Gourley are also consistent with the temperature-gradient theory. These workers do not specify the size of the supercooled droplets used in their experiments but Brook (private communication) reports that there was no evidence of splintering as the droplets froze onto the artificial hailstone. The droplets must therefore have been less than about 20 μ diameter in which case Process (3) would not operate and the asymmetric rubbing effect will be dominant. The observation that appreciable charging resulted only when droplets and ice crystals were present together in the cloud in which the hailstone was growing is identical with that of Magono and Takahashi and is therefore explicable in terms of the theory; when droplets only are present they are too small for Process (3) to be effective, when crystals only are present the hailstone surface is smooth and only Process

(1) is operative, and when both crystals and droplets are present in the cloud strong negative charging of the hailstone results from the collision between the ice crystals and its irregular surface. The effects of contamination and heating the growing hailstone are similar to those observed by Latham and Mason and by Magono and Takahashi and are thus explicable in terms of the theory. Reynolds *et al.* estimated that the average charge produced on collision between an ice crystal of side about 100 μ and the hailstone is roughly 5×10^{-4} e.s.u. Assuming a cubical crystal then even if the area of contact is equal to the area of one side of the cube and the time of contact is 10^{-3} sec, the theoretical time for maximum charge transfer, Equation (2) predicts a charge transfer of only 1.5×10^{-6} e.s.u. if the temperature difference produced by asymmetric rubbing is 5°C. There is, therefore, an apparent discrepancy of at least two orders of magnitude between theory and observation. However, Reynolds *et al.* estimate that their value may be in error by as much as a factor of ten and since the charge transfer produced on contact is much greater than that predicted by Equation (2) if the violence of contact is great the discrepancy may possibly be eliminated. The experiments of Reynolds, Brook and Gourley therefore are explicable, qualitatively at least in terms of the temperature-gradient theory; further experiments are required to measure more accurate values of the charge per crystal-hailstone collision.

The riming experiments of Magono and Takahashi, Latham and Mason, and Reynolds, Brook and Gourley are therefore all explicable, qualitatively at least, in terms of the temperature-gradient effect and the apparent contradictions between the three studies have been removed. They have been shown to result from the fact that although there was a large degree of overlap in the studies they were quite different at certain points. Where overlap existed the experiments gave identical results; the results conflicted with those of the other studies only when the conditions were different.

Application of the results to thunderstorm electrification

It is possible to deduce from these riming studies approximate values for the conditions under which a pellet of soft hail growing inside a thundercloud in the presence of ice crystals and supercooled water droplets will acquire appreciable negative charge. Strong negative charging of the pellet can be produced by Process (2) and by Process (3)

Process (2), the collision between ice crystals and a heavily rimed pellet of soft hail was shown by Magono and Takahashi to occur only when the riming rate exceeded about $R = 10^{-6}$ g cm^{-2} sec^{-1}. The riming rate can be expressed approximately by the equation $R = \pi r^2 VL/4\pi r^2$ where r is the radius of the pellet, V its velocity relative to the cloud particles and L is the liquid water content of the cloud. Latham and Mason (1962) showed that for pellets ranging in radius from $R = 10^{-2}$ to 10^{-1} cm the relative velocity of a falling pellet is related to its radius by the relation $V = 8500\ r$, and putting $L = 2 \times 10^{-6}$ gm cm^{-3} the critical pellet radius below which appreciable charge transfer does not occur is seen to be about $r = 0.025$ cm. Above this value of r the pellet surface becomes sufficiently irregular for impact with ice crystals to produce appreciable charging. However, Kuettner (1950) has reported that significant quantities of soft hail pellets of radius greater than 0.25 cm are not normally found inside thunderstorms so this value represents an upper limit beyond which strong negative charging does not usually occur. There appear to be no serious restrictions on the size of supercooled droplets which can produce a delicate riming structure; for very small droplets the collection efficiency is low under field-free conditions but is probably about unity in the intense electric fields present inside a thunderstorm. However, significant negative charging of the pellet by Process (2) is unlikely to occur at temperatures above about -4°C as Latham and Mason showed that at these warmer temperatures aggregation of crystals occurs instead of rebounding; the negative charging will probably be insignificant at temperatures below about -35°C since supercooled droplets freeze spontaneously at -40°C.

Process (3), the collision between a growing pellet of soft hail and supercooled droplets which freeze onto its surface, splinter, and produce strong negative charging of the pellet was shown by Latham and Mason, as mentioned previously, to occur at temperatures below about -3°C, for droplets in the diameter range $30 < d < 120\ \mu$ when the velocity of impact lay be-

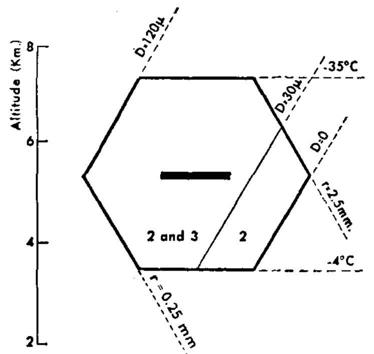

FIG. 1. The ranges of pellet radius r, supercooled droplet diameter d, and temperature T over which a growing pellet of soft hail acquires appreciable negative charge by means of Processes (2) and (3).

tween 2 and 25 m sec^{-1}. The lower velocity limit corresponds to a pellet of diameter about 2.5×10^{-2} cm but the upper limit of 25 m sec^{-1} is of no importance in a consideration of a normal thunderstorm as Kuettner's upper radius limit of 0.25 cm corresponds to a pellet of lower fall-velocity.

Fig. 1 indicates roughly the ranges of temperature T, pellet radius r, and droplet diameter d, for which a pellet of soft hail growing inside a thunderstorm will acquire a large negative charge. The charge is generated by Process (2) and Process (3). The boundaries marking the transition between appreciable and insignificant negative charging of the pellet are uncertain as the controlling variables are to some extent interdependent and the limiting values of one consequently affect those of another. Some negative charging of the pellet will occur outside the limits indicated but the great bulk of the charge will be produced within them. The diagram shows that although the activity of Processes (2) and (3) is confined to approximately the same ranges of r and T Process (2) operates over a wider range of d, the supercooled droplet diameter.

It appears unlikely that appreciable *positive* charging of a pellet of soft hail will be produced by riming inside a thundercloud. Process (1), the collision between ice crystals and a smooth pellet of the same temperature was shown by Magono and Takahashi to produce weak positive electrification, but this process is likely to occur only at the edges of thunderclouds near to their summits. Additional positive charging by splashing was shown by Latham and Mason to occur for large values of supercooled droplet diameter ($d > 130\ \mu$) and impact velocity ($V > 25$ m sec^{-1}). This process may contribute towards the positive charge region located near the freezing level in thunderclouds, particularly if large hail is present in the cloud.

Having established the conditions for strong negative charging of a soft hail pellet it is possible to calculate the rate at which charge may be separated within a thundercloud by the riming process. Electrification will be produced by Processes (2) and (3).

Latham and Mason showed that the rate of charge production in unit volume of the thunderstorm by collisions between ice crystals and soft hail pellets of mean radius $\bar{r}$ and density $\bar{\varrho}$ can be expressed by

$$\frac{dQ}{dt} = \frac{3}{4} E \frac{p}{r\varrho} n_c q_c \qquad (3)$$

where $p = 5/3600$ cm sec^{-1} is the contribution of the soft hail to the precipitation intensity in a thunderstorm and $E = 1$ is the collision efficiency. A reasonable value for the concentration of ice crystals of all sizes is $n_c = 0.5$ cm^{-3}, and a conservative value for the charge transfer per crystal-hailstone collision produced by Process (2) is $q_c = 2 \times 10^{-5}$ e.s.u. This value falls within the experimental uncertainty of Reynolds *et al.* when allowance is made for the fact that the diameter of the ice crystals used in their experiments (100 μ) is considerably higher than the median diameter of all the crystals producing charge inside a thundercloud by means of Process (2); this value for q_c can possibly also be reconciled with the temperature-gradient theory when allowance is made for the enhanced charge transfer associated with increased violence of impact. Substitution of these values into Equation (3) yields a charging rate of

$$(dQ/dt_2 = 2\mathrm{C}\ \mathrm{km}^{-3}\ \mathrm{min}^{-1}$$

for the contribution made by Process (2) towards the generation of charge in thunderstorms.

Using a similar equation Latham and Mason showed that the contribution made by Process (3) is

$$(dQ/dt)_3 = 1\ \mathrm{C}\ \mathrm{km}^{-3}\ \mathrm{min}^{-1}.$$

More refined computations on the rate of charge production by the splintering process have been made by BROWNING & MASON (1963) and have confirmed this value for the contribution made by Process (3) towards the generation of charge in thunderstorms.

The total rate of charge generation by these two processes, both of which are manifestations of the temperature-gradient effect, is therefore at least 3 C km^{-3} min^{-1}. This is three times the value of 1 C km^{-3} min^{-1} calculated by MASON (1953) as an essential minimum requirement for a satisfactory theory of thunderstorm electrification. Latham and Mason, basing their value for q_c on the collision between an ice crystal and a *smooth* ice surface concluded that only Process (3) is important in thunderstorm electrification and thus computed a value of 1 C km^{-3} min^{-1} for the rate of charge generation. The additional contribution, a consequence of the operation of Process (2) within the cloud, enhances the possibility that the riming process is the major source of thunderstorm electrification for the following reasons:

(1) The two processes in conjunction may explain the production of electrification in extremely severe storms where the charging rate is considerably greater than 1 C km^{-3} min^{-1}, particularly since the value of q_c used in computing the electrification produced by Process (2) is a conservative value.

(2) Browning and Mason could explain thunderstorm charge generation in terms of Process (3) only by assuming that the bulk of the charge is generated in regions of the cloud where a strong inclined updraught lies above a region of strong downdraught. The simultaneous operation of Process (2) within the cloud reduces the contribution required from Process (3) and produces electrification over a much larger volume of the cloud.

It has been established, therefore, that no contradiction exists between the results of the riming studies of Magono and Takahashi, Latham and Mason, and Reynolds, Brook and Gourley and that they are all explicable, qualitatively at least, in terms of the temperature-gradient theory. Appreciable negative charging of a soft hail pellet growing within a thundercloud occurs over certain ranges of temperature and pellet and supercooled droplet diameter by means of two processes, both of which are manifestations of the temperature-gradient effect; collision between soft hail pellets and supercooled droplets which freeze onto the pellets and splinter, and collision between ice crystals and the irregular surface of the rimed pellets. These two processes combine to generate charge inside a thunderstorm at a rate which easily produces the electrification of normal thunderstorms and which may also be sufficient to account for the electrification of severe thunderstorms.

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