A Critical Examination of Theories of Charge Generation in Thunderstorms

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Abstract

A concise review is presented of the more important features of the meteorological and electrical behaviour of thunderstorms from which the main conditions to be fulfilled by any satisfactory theory of charge generation, are enumerated. The various theories are then examined, as far as possible from a quantitative point of view, in the light of these requirements. None is found to be entirely satisfactory. It is concluded that the mechanism which most accords with the observed facts is the charge generation and separation which, according to the results of laboratory experiments, will be associated with the growth of graupel pellets in the super-cooled region of the thundercloud.

1. Introduction

During the last forty years, at least eight different mechanisms for the generation of electricity in thunderclouds have achieved prominence in the literature. Too often theories have been formulated without sufficient regard to all the available experimental data on the behaviour of thunderstorms, and rarely have they been examined for *quantitative* agreement with these data. Any satisfactory theory must show quantitatively how charge can be created and separated at the rate required by the measurements of the electric field-change and the frequency of lightning discharges and must conform with known facts about the meteorological and electrical structure of the cloud, its life-history and the nature and time-scale of the precipitation processes.

2. The Electrical and Meteorological Behaviour of a Thunderstorm

(a) *The Life Cycle of a Thunderstorm*

The investigations made during the Thunderstorm Project (see BYERS and BRAHAM, 1950), indicate that a thunderstorm consists of one or more identifiable units or *cells* which are localized regions of pronounced convective, microphysical and electrical activity. The life of an individual cell can be divided into three stages, depending on the direction and magnitude of the vertical air currents. The cumulus, or growing stage is characterized by the existence of an updraught throughout the cell; the mature stage by the presence of both updraughts and downdraughts, at least in the lower part of the cell, the onset of lightning activity and the appearance of precipitation below cloud base; the dissipating stage by weak downdraughts prevailing throughout the cell with marked reduction in the intensity of precipitation and electrical activity.

The duration of the cumulus stage reckoned from the time of initial detection of the radar echo, which appears soon after the visible cloud top extends above the 0° C level, is between 10 and 15 minutes. The mature stage, during which most of the precipitation is released, lasts for 15 to 30 minutes. The duration of the dissipating stage, measured to the time when vertical motions inside the cloud become insignificant, is of the order 30 minutes. Thus the life of one cell occupies about one hour, but the duration of the radar echo and its associated electrical activity may be confined to a period of less than 30 minutes. The larger, more persistent thunderstorms which may last for several hours probably result from the activation of a group of cells. Successive centres develop in turn and more than one may be active simultaneously.

(b) *The Meteorological Structure of a Thunderstorm*

Most of our information on the structure of the thunderstorm again comes from the data of the Thunderstorm Project and from the observations made at the Observatory on the Zugspitze (altitude 10,000 feet) and reported by KUETTNER (1950).

In the early stages, the incipient thundercloud grows rapidly in the vertical and is characterized throughout its volume by updraughts whose magnitude was 7 m/sec. on average in the storms investigated by the Thunderstorm Project, but values of 15 m/sec. are not uncommon and may be appreciably exceeded. The horizontal dimensions of the cell, as first detected by radar, may be only 0.5 km with the top extending only about 1 km above the 0° C level. Thereafter, the visible cloud top may grow rapidly towards the − 30° C isotherm, or even higher. Byers and Braham report observations which indicated that within the updraught region of a single cell there was more than one locality of strong vertical ascent; that these regions were separated in space or time, or both; and that they resulted in the development of individual cloud columns appearing as turrets at the summit of the visible cloud. Kuettner also quotes evidence for this sub-division of a cell, the smaller units having horizontal dimensions of 100 m to 1 km, i.e. about one-tenth those of the cell. They often occur at different positions relative to the centre of the cloud and successive turrets often penetrate to greater heights than their predecessors. These sub-cells may perhaps be identified with the "bubbles" which are regarded by SCORER and LUDLAM (1953) as the fundamental units in the structure of cumulus; a succession of rising bubbles would confer on the updraught something of the pulsating nature mentioned by BYERS and BRAHAM and by WORKMAN and HOLZER (1942).

The last-mentioned authors state that, in the early stages of cloud development, the water particles are small but their size continually increases with time. Later, as the cloud top reaches colder regions, larger particles of snow, graupel and rain appear but continue to be carried upwards by the updraught which may now be typically 1.5 km in diameter. The greatest concentration of hydrometeors occurs at and above the 0° C level. The size and concentration of the precipitation elements continue to increase until they can no longer be supported by the existing updraught and they then begin to fall relative to the earth. At about the same time, strong downdraughts appear in the lower part of the cell, particularly in the region where precipitation is falling. This marks the onset of the mature stage of the cell during which it attains its maximum height and may reach the tropopause; the horizontal dimensions of the radar echo may now lie between 5 and 14 km at the base, tapering off towards the top. There may still be strong local updraughts particularly in the upper parts of the cloud where the average velocities are about 10 m/sec., but on occasions may exceed 30 m/sec. Precipitation elements consist mainly of raindrops below, and snow or graupel particles above, but hail may occur in some cells, particularly those containing exceptionally strong updraughts. The mature stage is gradually transformed into the final dissipating stage in which the whole cell contains air moving downwards or almost at rest. Precipitation continues to fall for some time but gradually diminishes in intensity and ceases.

Kuettner presents some very valuable information on the nature of hydrometeors found in thunderstorms; his observations being made on a mountain top immersed in the cloud are more reliable and clear-cut than those made from aircraft. He reports that solid precipitation elements were predominant in the greater part of the thundercloud, being found on 93 % of the occasions, while raindrops were present in only 21 % of the clouds. Kuettner states that graupel (including snow pellets and soft hail) was the most frequent form of hydrometeor, being present on 75 % of occasions; large hail was relatively rare and was, by no means, a necessary event in thunderclouds. Snow crystals prevailed during the later periods of a storm when the precipitation became more steady and moderate in character and the lightning activity diminished.

Both Kuettner and WORKMAN and REYNOLDS (1950 a) state that a necessary condition for the development of thunderstorms on the Zugspitze and in New Mexico respectively, is that the cloud base should be warmer than 0° C. Furthermore, Workman and Reynolds state that the first lightning flash occurs only when the top of radar echo approaches the − 30° C level; Byers and Braham say that the top of the echo must be colder than − 20° C. WORKMAN and HOLZER (1942) report no lightning from clouds of depth less than 5 km.

(c) *The Electrical Structure of a Thunderstorm*

From his measurements on the change of the electric field at the ground during lightning activity and the variation in the sign of the field-change with distance from the storm, WILSON (1920) deduced that the thundercloud has a bipolar structure with a positive charge situated above a negative charge. Wilson's conclusions have been amply confirmed by similar measurements by WORKMAN, HOLZER and PELSOR (1942) in New Mexico, who found some evidence which pointed to the upper charge-centre being displaced in the direction of motion relative to the lower negative centre (this is to be expected in the presence of a wind-shear). The positive and negative charge centres were, on average, 2.5 km and 4 km respectively, above cloud base, but probably only in the early stages; WORKMAN and REYNOLDS (1950 a) report that as the storm progresses, the positive centre moves upwards while the negative centre appears to remain fixed in the zone of heavy precipitation.

MALAN and SCHONLAND (1951 a, b), from a study of the electric-field changes in the intervals between successive strokes of lightning flashes to earth, conclude that the negative charge which is involved in such a flash is contained in a nearly vertical column, which, on occasion, may be 6 km long, the temperature at its base being not much below 0° C and its top frequently reaching the − 40° C level. Their techniques allow determination of the heights of the charges involved in separate strokes; the results obtained from five different methods agree in indicating that successive strokes tap progressively higher and higher regions of the negative column, the average increase in height per stroke being about 0.7 km. The first stroke appears to originate from near the − 5° C level, while later strokes may extend upwards by more than another 5 km. Malan and Schonland also report that, in their South African thunderstorms, 65 % of the first strokes of flashes to earth have type β leaders indicating that there is a positive space-charge below the base of the main negative column. The discharge of the negative column to earth may therefore, in many cases, be triggered off by the strong field between the positive pocket and the bottom of the negative column.

WORMELL (1953) has made similar investigations but finds that on 75 % of occasions there is no appreciable change of field during the *j* portion of the stroke, i.e. although there is a transport of charge, the electric moment is not changing. This indicates that in 75 % of the multi-stroke flashes to earth around Cambridge, England, the negatively charged regions in the cloud which are discharged by successive strokes, are all sensibly at the same height. In the remaining 25 % of cases the form of the field change indicates that the heights of these regions increases for successive strokes as found by Malan and Schonland.

The most direct information on the electrical structure of a cumulonimbus comes from measurements of the electric field made from balloons and aircraft. The pioneer work was carried out at Kew by SIMPSON and SCRASE (1937) and SIMPSON and ROBINSON (1941), who used the altielectrograph on a balloon to determine the sign of the vertical component of the electric field as a function of height and also to obtain an estimate of its magnitude. The records established beyond reasonable doubt that the upper part of a thundercloud is positively charged and most of the lower part negatively charged. In 7 of 13 different storms there was also evidence of one or more localised regions in the base of the cloud containing positive charge. The upper positive charge was usually associated with temperatures below − 20° C, and always below − 10° C. The temperature at the negative charge centre was below 0° C in 13 out of 15 cases while the lower positive charge, in 5 cases out of 7, was at temperatures above 0° C. Simpson and Robinson stated that their results could be represented schematically by a thunderstorm model with an upper charge of + 24 coulombs distributed in a spherical volume of 2 km radius centred at a height of 6 km (– 30° C), a negative charge of – 20 C in a sphere of radius 1 km centered at a height of 3 km (– 8° C) and a charge of + 4 C in a sphere of radius 0.5 km centred at 1.5 km (+ 1.5° C). Thus, the upper positive charge and the bulk of the negative charge were in regions where the temperature was below 0° C. Similar results regarding the charge distribution have been reported by CHAPMAN (1950) who used a radiosonde device, the observations being telemetered to the ground. The negative charge centres for 7 storms were reported to lie with 0.5° C of the 0° C isotherm.

The results of these balloon investigations, while of great value in establishing the general features of the charge distribution, cannot be regarded as very reliable for giving the temperatures of the charge centres and the actual magnitudes of the electric field, because it seems probable that on the majority of occasions, the balloon missed the electrical centre of the storm; in fact 15 % of Simpson's useful ascents came to a violent end in a rapidly increasing field. The fields reported by Simpson et al, barely exceeded 100 V/cm while the largest field recorded by Chapman was 210 V/cm; these are to be compared with values of 1,300 V/cm, and on one occasion, 3,400 V/cm measured by GUNN (1948) from an aircraft. The last named author encountered the most intense fields near the 0° C level.

KUETTNER (1950), from his observations on the Zugspitze, finds that the lower positive charge has a horizontal extent generally less than 1 km and is accurately centred at the 0° C level. The more extensive negative charge is centred, on average, near the – 8° C level, while the main upper positive charge is still higher and even more diffuse. The negative charge centre is apparently the starting point of the lightning flashes.

It is of some importance to reconcile the deductions of Malan and Schonland and of Wormell concerning the distribution of the negative charge in a thundercloud. In most of the South African storms it appears that the negative charge is distributed in a nearly vertical column which is tapped at progressively higher and higher levels by outwardly-directed positive streamers during successive strokes of a flash to earth. This charge configuration might be expected in a cell containing only one region of strong updraught and one column of precipitation and electric charge. However, if there are more than one such regions separated in space and time throughout the cell, it is possible that a particular centre may become discharged by positive streamers directed outwards from a neighbouring centre which has already passed its charge to earth. Thus, the total charge dissipated in a lightning flash may be drawn from several charge centres of smaller dimensions than the thunderstorm cell and the discharge of a new centre by the next stroke might involve very little change in electric moment or electric field as measured at the ground. Such a mechanism may be responsible for the 75 % of Wormell's records.

(d) *Correlation between Electrical Activity and Meteorological Processes*

Kuettner states that a high precipitation is an indispensable requirement for electrical activity in a cumulonimbus, the central lightning area usually being coincident with the area of highest precipitation intensity. The onset of lightning activity coincides with the appearance of heavy solid precipitation within the cloud.

WORKMAN and REYNOLDS (1950 a) assert that separation of electric charge within the cloud is closely associated with the precipitation mechanisms and does not take place until precipitation processes are well under way; it takes place at temperatures between 0° C and – 15° C, most probably between – 5° C an – 10° C. The first internal flash occurs about 12 minutes after the initial radar echo, which by this time has approached the – 30° C level and started to descend; at the same time precipitation appears at the cloud base. Cloud-to-ground discharges follow within a few minutes. These authors also report that the lightning activity has a periodicity of 25 to 40 minutes corresponding to the active life of a cell.

WORKMAN and HOLZER (1942) report that clouds of greatest vertical depth display the greatest electrical activity. The vertical motion often appeared to be pulse-like in character, each new surge (or turret) being associated with increasing electric fields at the ground and a new series of lightning flashes.

Measurements of field strength from aircraft made in conjunction with ground radar observations during the Thunderstorm Project showed that, during growth of the cell, the positive field (positive charge above, negative below), became strong in the precipitation area. In the dissipating stage the positive field was replaced by a negative one. A positive charge was often found in the rain core of the cloud near the cloud base. The maximum frequency of lightning preceded the onset of maximum intensity of rainfall at the ground.

(e) *The Electric Moment Destroyed in a Lightning Flash—Rate of Charge Dissipation*

From measurements of the change in the vertical component of the electric field at the ground during a distant lightning flash, one can calculate the electric moment $\delta M = 2H\delta Q$ destroyed, where δQ is the charge neutralised and H is the vertical separation of the main positive and negative charge centres for an internal flash, or the height or the involved charge above ground for a discharge to earth. WORMELL (1939, 1953) gives 110 C-km and 130 C-km as the most frequent values for the moments destroyed during internal and cloud-to-ground flashes respectively, in storms investigated at Cambridge. WILSON (1920) gave an earlier mean value of 100 C-km, while SCHONLAND (1928) quotes 90 C-km as the appropriate mean value for South African thunderstorms. Taking a mean value of 110 C-km for all types of flashes, values of H varying from 2 to 3.5 km for cloud-to-ground discharges and up to 5 km for internal flashes, the charges neutralised are calculated to be of the order 10 to 30 coulombs. WORKMAN and HOLZER (1942) report that the magnitude of the charge involved in New Mexico storms varies between 10 C and 190 C, the most frequent values lying between 20 C and 50 C. HOLZER (1950) states that a multiple-stroke flash which may neutralise about 20 C, very often originates from several charge centres, each of which may contribute from about 3 to 8 coulombs. He gives the average interval between strokes of a cloud-to-ground flash as 0.05 sec.; Wormell gives 0.07 sec. and Schonland 0.03 sec. Taking ALLIBONE and MEEK's (1938) mean value for the positive streamer velocity as 2.4×10^6 cm/sec., and the average duration of a stroke as 0.05 sec., we arrive at 1.2 km for the average separation of the charge centres; this is a very reasonable value for the separation of the sub-cells or bubbles in the cloud.

Lightning flashes from a given cell occur on average at intervals of about 20 sec., so that the current dissipated by lightning is of the order 1 amp.

(f) *Recovery of the Electric Field after a Flash; Rate of Charge Generation*

The recovery of the field after the passage of a lightning flash which corresponds to the regeneration of the electric moment in the cloud, is approximately exponential in form and according to WILSON (1929) and WORMELL (1939) has, on average, a time constant of about 7 sec. The initial rate of recovery represents the rate at which the electric moment grows when the internal field is small; the slowing down which follows is due to the increased electrical forces on the charged elements tending to oppose their separations as the internal field grows, and by the increased rate of dissipation by charges on the precipitation elements, by point discharge currents and ionic leakage to the upper atmosphere. If we take the charge neutralised in an average flash to be 20 C and the *initial* rate of regeneration as $1/7$ sec.$^{-1}$, the vertical current in the cloud immediately after the discharge turns out to be 3 amps; however, the various leakage factors mentioned above, subsequently restrict the average net charging current to about 1 amp.

The rebuilding of the electric moment, however, implies not only a generation of charge but a vertical separation of charges of opposite sign. If, as is assumed in most theories, charge of one sign is attached to the precipitation particles and that of opposite sign carried upwards on ions or cloud droplets, their rate of vertical separation cannot exceed the rate of fall of the precipitation elements in still air. Now, the initial rate of regeneration of moment, would if it remained constant, replace the whole moment destroyed by the discharge, 110 C-km, in 7 sec. Taking 8 m/sec. as the fall velocity of the particles, the maximum vertical separation of the charges in this time would be 56 m; this implies that the magnitude of the charges which are separating immediately after discharge is about 1,000 C.

Wilson first suggested that these charges would be distributed through a considerable volume which is in the main electrically neutral, but as separation proceeds through the volume, a positively charged region appears near the top and a negatively charged region near the base. As WORMELL (1953) points out, such a bulk charge of about 1,000 C would be sufficient without replenishment, to supply the charges removed in a considerable number of lightning flashes, so that the primary charging mechanism need not necessarily supply new charge to the region as rapidly as it is being dissipated by a brief spell of lightning activity.

(g) *Summary—The Requirements of a Satisfactory Theory*

The main features of the thunderstorm which have been described in the foregoing paragraphs and with which any theory of charge generation must be consistent are:

(i) The average duration of precipitation and electrical activity from a single cell is about 30 minutes.

(ii) The average electric moment destroyed in a lightning flash is about 110 C-km, the corresponding charge being 20 to 30 C.

(iii) The magnitude of the charge which is being separated immediately after a flash, by virtue of the fall-speed v of the precipitation elements, is of order $8{,}000/v$ coulombs where v is in metres/sec.

(iv) In a large, extensive cumulonimbus this charge is generated and separated in a volume bounded by the $-5°$ C and the $-40°$ C levels and having a typical radius of say, 2 km.

(v) The negative charge is centred near the $-5°$ C isotherm while the main positive charge is situated some kilometres higher up; a subsidiary positive charge may also exist near the cloud base, centred at or below the $0°$ C level.

(vi) The charge generation and separation processes are closely associated with the development of precipitation, particularly in the solid form (graupel); the precipitation particles must be capable of falling through updraughts of several metres/sec.

(vii) Sufficient charge must be generated and separated to supply the first lightning flash within about 12 to 20 minutes of the appearance of precipitation particles of radar detectable size.

3. The Theories of Charge Generation and Separation

Having reviewed briefly our present knowledge concerning the electrical and meteorological behaviour of a thunderstorm, the two, of course, being intimately related, we are now in a position to examine the various theories of charge generation and separation and determine how far they are consistent with the observed facts.

(a) *Influence Theories*

(i) ELSTER and GEITEL (1913) considered the effects associated with a raindrop falling through a vertical electric field and colliding with smaller cloud droplets lying in its fall-path. The raindrop will be electrically polarised; in a downwardly directed field such as exists in the atmosphere under fine-weather conditions, the lower half of the drop will carry a positive charge and the upper half a negative charge. Elster and Geitel assumed that on collision, the cloud particles would *rebound* from the raindrop and carry away some of the charge from its lower half. Thus, with a positive field, the raindrops would acquire a net negative charge, while further gravitational separation would enhance the original field. Nowadays, this theory appears untenable; the *coalescence* of drops possessing differential rates of fall plays an important part in modern precipitation theory, and there is direct experimental evidence that it takes place with high efficiency when drops of raindrop-size fall through a cloud of droplets of radius about 10 μ (GUNN and HITSCHFELD, 1951).

(ii) *Wilson's Process of Charging by Selective Ion Capture*

WILSON (1929) pointed out that under certain conditions, an electrically polarised raindrop in falling through a cloud of ions or charged cloud droplets, could by a process of selective ion *capture*, acquire a net charge. If the drop falls more rapidly through a downwardly-directed field than the downwardly-moving positive ions, the latter are repelled from the lower half of the drop and deviated to one side, while the negative ions are attracted to it. Hence the drop acquires a net negative charge which tends to augment the pre-existing field. The mathematical theory of the process has been worked out by WHIPPLE and CHALMERS (1944) who showed that, if the fall velocity of the raindrop is large compared with the drift velocity of the ions under the existing vertical field, (this will generally be the case if the ions are charged cloud droplets), (α) the final charge acquired by a drop of radius a, independent of its initial charge, in a vertical field of intensity X, is

$$Q_{\max} = -3\,(3-2\sqrt{2})\,Xa^2 = -0.52Xa^2 \quad (1)$$

(β) if its initial charge is zero, the initial (i.e. maximum) rate of charging of a drop is

$$\left(\frac{dQ}{dt}\right)_{\max} = -3\pi Xa^2\lambda_- \quad (2)$$

where λ_- is the polar conductivity for the large negative ions,
(γ) the time required for the drop to acquire half of its final charge is

$$\tau = 0{,}04/\lambda_- \text{ sec.} \quad (3)$$

As the above mechanism proceeds, the field increases, so that the equilibrium charge towards which the drops are tending is increasing with time. However, we can estimate the magnitude of the maximum charge which can be generated by this process, and the rate of charging.

Let us suppose that the precipitation process has developed to a stage at which the precipitation rate in the active part of the cloud reaches 2.5 cm/hr with a corresponding mean volume drop radius of 1.5 mm and precipitation-water content of 1 g/m^3; the concentration of drops under these conditions will be 70/m^3. Taking the average intensity of the vertical field to be 1,000 V/cm, the maximum charge that can be developed per km^3 by the Wilson process is then 0.9 C. But, we now have to consider whether the drops could approach their equilibrium charge during the life of a thunderstorm cell. There appears to have been no reliable determination of polar conductivity in cloudy air, but if we substitute a conservative value of 4×10^{-6} e.s.u. for λ_- in (3), we find that it would take 10^4 sec. for the drop to acquire half of its maximum charge. Hence, the value of 0.9 C/km^3 is a considerable overestimate of the charge which could be built up by the Wilson process during the life of an active cell, and even so, is much smaller than the value of about 16 C/km^3 required by conditions (iii) and (iv) of Section 2 (g).

As WORMELL (1953) points out, the maximum possible rate at which the charging process can proceed, cannot exceed the rate at which ions are being produced in the lower atmosphere, i.e. 10 ions cm^{-3} sec.$^{-1}$, or 6 C-km^{-3}hr^{-1}. But the raindrops sweep out only a fraction of the space in which ions are being produced; in the above example the fraction would be only 3.5×10^{-3}, so that if the raindrops catch all the cloud particles encountered in their fall-paths, the charging rate would be only 2×10^{-2} C-km^{-3} hr^{-1}. This is to be compared with the average rate of 1,000 C in 20 minutes generated in a volume of about 60 km^3, i.e. 50 C-km^{-3}hr^{-1} required by conditions (iii), (iv), (vii).

It therefore appears impossible that the Wilson process can of itself separate the observed charges during the life time of a typical cell. It may well play a minor role in the charge separation process during the later stages when copious ionisation and strong fields have been produced by the primary process. It is almost certainly of importance in determining the magnitude and sign of the charge on precipitation elements reaching the ground after they have fallen through the space-charge blanket existing between cloud base and ground.

(iii) *Wall's Theory*

WALL (1948) does not accept the view that the direction in which the electric field builds up can be controlled by the normal fine-weather field—a fundamental assumption of

Wilson's theory. He also attempts to account for the fact that charge separation occurs mainly at temperatures below 0° C, by suggesting that ice crystals, rather than raindrops, are involved in selective ion capture. The initial polarising field is now attributed to the polar properties of the hexagonal plate-like crystals which, in falling with their principal axes vertical, are assumed to become dipoles, *presumably* with their undersides positively charged. These crystals, originating at temperatures below −10° C and having become polarised by their own internal field, are then assumed to separate the charge in much the same way as proposed by Wilson.

This theory rests on the assumption that ice is polar; it should therefore exhibit piezo- and pyro-electricity; Wall deduced its polar nature, not from direct experimental tests, but from observations of asymmetrical development along the *c* axis of crystals grown from the melt. Experimental tests on crystals from the melt have all failed to detect piezo- and pyro-electricity. Recently, MASON and OWSTON (1952) using very sensitive tests, have failed to detect these effects in asymmetric crystals grown from the vapour; indeed the molecular structure of ice and the randomised motion of the dipoles militates against the lattice possessing a resultant dipole moment. These are serious objections to Wall's theory which, in any case, is subject to the quantitative limitations of the Wilson theory. It appears to have few, if any, redeeming features.

(iv) *Frenkel's Theory*

FRENKEL (1944, 1946, 1947) considers that the electrification of clouds arises primarily from the orientation of the molecular dipoles at the surface of a water drop or ice crystal, giving rise to an electric double-layer with the negative ends of the dipoles directed outwards. By virtue of this surface configuration the drop (or crystal) is supposed to capture negative ions preferentially from an ionised atmosphere. In a state of statistical equilibrium, the drops are assumed to acquire a net negative charge q and a corresponding potential ξ equal to the potential difference across the electric double-layer; thus $q = a\xi$, where a is the droplet radius and $\xi = -0.25$ volt. The corresponding positive charge is left in the air in the form of large ions surrounding the drop. Gravitational separation of the positive ions and negative drops then produces a positive field, the growth of which is opposed by the migration of ions under the field setting up a depolarising current. Frenkel considers that these two effects eventually become balanced to produce a steady electric field, the total current density through the cloud then being zero. The intensity of the equilibrium field can be written

$$X = g \Big/ \frac{q}{m} + \frac{\lambda g}{Nqv} = g \Big/ \frac{3\xi}{4\pi a^2} + \frac{\lambda g}{Na\xi v} \qquad (4)$$

where m, a and v are respectively the mass, radius and fall velocity relative to the air, of the drop, g the acceleration due to gravity, N the number of drops per unit volume (assumed all of the same size), and λ the total conductivity of cloudy air.

If we take the liquid-water content of the cloud to be 2 g.m^{-3}, $\lambda = 4 \times 10^{-6}$ e.s.u., $\xi = 0.25$ V $\simeq 10^{-3}$ e.s.u. we have that, when $a = 10\,\mu$, $X = 1{,}200$ V/cm. This value is not seriously affected by assuming a higher value of λ, e.g. 3×10^{-5} e.s.u., the average value for the lower *dry* atmosphere at Kew.

The time constant of the field is approximately $3/4\pi\lambda$, i.e. 6×10^4 sec. or 8×10^3 sec. depending on which of the above values of λ is adopted. These figures suggest that Frenkel's mechanism, if it occurs, could produce a positive field of several volts/cm in the early, non-precipitating stages of the cloud; measurements by GUNN (1952) suggest that these fields are always less than 10 V/cm.

However, as Frenkel points out, for large drops in strong fields, the capture of ions due to the polarisation charges on the drop is a more important phenomenon. He attributes the acquisition of charge by this latter mechanism merely to the difference between the polar conductivities due to positive and negative ions, the equilibrium charge then being *positive* and of magnitude

$$q^1 = \frac{\lambda_+ - \lambda_-}{\lambda_+ + \lambda_-} \cdot Xa^2 = 0.13\ Xa^2, \left(\frac{\lambda_+}{\lambda_-} = 1.3\right) \qquad (5)$$

This positive-charging mechanism therefore predominates over the negative charging process described above if $Xa > 6.4 \times 10^{-3}$. Thus, a drop of radius 100 μ would eventually acquire a positive rather than a negative charge in a field of 200 V/cm, while the corresponding field for a droplet of 10 μ radius would be 2,000 V/cm. It then appears that while sedimentation of cloud droplets might, perhaps, set up an initial positive field by the Frenkel process, precipitation particles would become positively charged in the fields which exist in thunderclouds and that these, in settling out, would tend to destroy the original field.

Frenkel argues that this influence mechanism does not affect materially his primary charge separation process but may explain the fact that rain from thunderstorms is predominantly positive in sign. Nevertheless, one would expect that, on his picture, the build up of the positive field would reach a maximum in the Cu-congestus stage, before an appreciable fraction of the liquid water becomes transformed into precipitation elements which will, according to *his* influence mechanism, oppose its growth. This is inconsistent with the observation that the development of precipitation is essential to the onset of lightning activity. Moreover, as the fall velocities of cloud particles are so small, the charge which must be separated in order to produce a lightning flash must be correspondingly large. For droplets of $a = 10\,\mu$, for which $v \simeq 1$ cm.sec.$^{-1}$, generation of an electric moment of 110 C-km in 7 sec. would require separation of 8×10^5 C of charge. The maximum negative charge which a 10 μ droplet will acquire by Frenkel's process is 10^{-6} e.s.u.; assuming a concentration of 500 droplets/cm^3, we find that is a volume of 60 km^3 the maximum possible charge would be 10^4 C, but the actual charge built up during the life of the cell will be an order of magnitude less. Thus, quantitatively, Frenkel's theory is incapable of accounting for the rate of charge separation required in a thundercloud. With regard to separation of charge leading to a positive field, the maximum charge predicted by Wilson's theory exceeds that given by Frenkel for drops of $a > 50\,\mu$ in a field of 100 V/cm.

(b) *The Drop-Breaking Theory*

The electrification associated with the rupture of water drops on colliding with a solid surface was first investigated in detail by LENARD (1892). SIMPSON (1909), in a series of careful experiments in which he largely eliminated this "splashing" or "Lenard" effect, established that breaking of a drop in a strong vertical air jet could also produce a considerable electrification. The results were found to be sensitive to traces of impurity in the water, but, for distilled water the large fragments of the broken drops carried positive charges, while the surrounding air contained ions of both signs with an excess of negative charge. Ruptured drops of diameter about 8 mm produced, on average, a charge of 5.5×10^{-3} e.s.u., i.e. about 2.3×10^{-2} e.s.u./cm^3; with less violent shattering in conditions approximating more closely to those under which a raindrop might break-up in a thundercloud, the charge produced was slightly less – 1.5×10^{-2} e.s.u./cm^3.

ZELENY (1933), using highly purified water, found that the rupture of drops in a 20 m.sec.$^{-1}$ horizontal air jet was accompanied by charges of about 2×10^{-2} e.s.u./cm^3. The negative charge communicated to the air increased quite rapidly with increasing velocity of the jet.

CHAPMAN (1952) allowed drops of distilled water of diameter 4 mm to fall into a vertical jet of speed 17.3 m.sec.$^{-1}$. The violent disruptions were accompanied by separation of charge amounting on average to about 0.3 e.s.u. per drop, i.e. 10 e.s.u./cm^3. However, when he allowed two drops to coalesce and the resultant unstable mass to break-up into *large* fragments in a steady upcurrent of 8 m.sec.$^{-1}$, the charge generated was less than one-thousandth of the previous figure, i.e. of the same order of magnitude found by Simpson and by Zeleny.

It then appears, that the charge separated by breaking drops depends markedly on the violence with which they are shattered, i.e. the number of fragments which result. According to Simpson and Zeleny, the more pure the water the higher the charge generated; Chapman, however, found evidence for a slight increase in the charge when solutions of concentration 5×10^{-4} N. were used.

It is generally accepted that falling raindrops cannot exceed a diameter of about 5.5 mm. At this size they become distorted from the spherical, become unstable and break up into several large, and probably many more small fragments. These conclusions are based on the studies of LENARD (1904) who balanced drops of various sizes on vertical air jets of appropriate velocities. Some recent work by BLANCHARD (1950) has shown that the size at which drops rupture depends largely on the scale and intensity of the microturbulence in the jet, and that the maximum stable diameter may be greater, or less than 5.5 mm, depending on these factors.

It is likely that a raindrop in falling through an updraught region of a cumulus will encounter small-scale eddies and be subjected to appreciable accelerations, but probably not as violent as those obtaining in Chapman's experiments with the high-speed jet. Even the accelerations in the experiments of Simpson and Zeleny appear severe compared with those which might be experienced by a raindrop in a thundercloud, where, according to the Thunderstorm Project, velocities of sharp-edged gusts rarely exceed 8 m.sec.$^{-1}$.

We shall therefore assume the values quoted by Simpson and by Zeleny of about 2×10^{-2} e.s.u./cm^3 as an upper limit for the charge separated by the rupture of water drops in a cumulonimbus, and enquire whether this could be a significant factor in the generation of thunderstorm electricity.

It is clear that if a positive charge resides on the large fragments of the broken drops and a corresponding negative charge is communicated to the air by ions (which may soon become captured by cloud droplets), gravitational separation will tend to confer a negative polarity on the cloud, i.e. of opposite sign to the observed polarity. It is of interest, however, to determine whether the charges generated by drop-breaking are significant in magnitude compared with those involved in lightning discharges.

We may take 4 gm^{-3} as an average value for the liquid-water content of a large cumulus, and if this is all involved at least once in drop breaking, the charge generated would be 3×10^{-2} C/km^3, assuming Simpson's value of 2.3×10^{-2} e.s u./gm. It is clear, then, that for the process of drop-breaking to be significant in the electrical budget of the thunderstorm, repeated rupture of the same mass of water would be necessary. Now, if one traces the growth of a raindrop by the coalescence process in a cumulus cloud having a base temperature of 10° C, a steady updraught of 8 m.sec.$^{-1}$ and containing the theoretical maximum liquid-water content, one finds that it is theoretically possible for it to reach a diameter of 5 mm before reaching cloud base. If, at this stage, the drop is assumed to break into fragments of radius 1 mm, the *minimum* time taken for each of these to grow again to break-up size by coalescence, is about 4 minutes. This can be seen from the following simplified and approximate calculation. The growth rate of a drop by coalescence is given by

$$da/dt = Ewv/4\varrho \qquad (6)$$

where a, ϱ, E are respectively the radius, density, and collection efficiency of the drop, v its fall-speed relative to the cloud droplets, and w the liquid-water content. Thus assuming E and w to be constant during the growth from $a = 0.1$ cm to 0.25 cm, we have

$$a - a_0 = \frac{Ew}{4\varrho} \int_0^t v dt \simeq \frac{Ew}{4\varrho} \bar{v} \cdot t \qquad (7)$$

where t is the time required for growth to break-up size. Putting $E = 0.9$, $w = 4 \times 10^{-6}$ g.cm^{-3}, $\varrho = 1$, and v the average fall speed during growth = 700 cm.sec^{-1}, t turns out to be 239 sec. Actually, this is an underestimate of the time required, because when there are a considerable number of growing rain-drops all competing for the available cloud droplets, the effective value of w will be less than that assumed here.

We have seen that only about 12 minutes elapses between the appearance of the initial radar echo from a thunderstorm and the first lightning flash, so that there is time for about only three successive ruptures of the same mass of water during this interval. The maximum possible charge which will be generated in 1 km^3 is therefore 9×10^{-2} C, which is two orders of magnitude smaller than that required by (iii) and (iv) of Section 2 (g)[1].

It has been suggested by Simpson and others that the drop-breaking mechanism might account for the appearance of the pocket of positive charge in the base of some thunderclouds, generally in the region of heaviest precipitation. Simpson describes the positive charge as having magnitude about 4 C dis-

[1] It must be pointed out, however, that no experiments have been reported which provide information on the charges liberated by drops breaking in the presence of a strong electric field. In these circumstances the separated charges might be considerably larger than those measured by Simpson and by Zeleny in view of the polarisation charges $3\ Xa^2/4$.

tributed throughout a volume of about 0.5 km^3, i.e. 8 C/km^3. This again is about 100 times larger than we should expect to be generated by the drop-breaking process, so that it appears necessary to find another mechanism to explain the origin of the lower positive charge centre. It may well arise by capture of positive ions by the drops from the upwardly-directed point-discharge current which prevails beneath thunderclouds.

(c) *Simpson's Theory of Charging by Collision of Ice Crystals*

SIMPSON and SCRASE (1937), SIMPSON (1942) suggested that the main charge structure of a thundercloud could be accounted for by the production of frictional electricity during the collision of ice crystals which were assumed to receive a negative charge, the compensating positive charge being carried upwards on the cloud droplets.

Unfortunately, there is practically no direct information as to the sign and magnitude of the charge released by colliding ice crystals. PEARCE and CURRIE (1949) have eroded a block of snow with an air blast and found the large eroded fragments to carry a negative charge, the air receiving a positive charge. CHALMERS (1952) has rubbed two handfuls of snow together and allowed the fragments so produced to fall into a collector. On every occasion a negative charge was recorded, the generation of which he attributed to friction. The results of these experiments, cannot however, be applied quantitatively to the atmospheric problem, and since we can make no reliable estimate of the frequency of collisions between ice particles in a turbulent cloud mass, it is not possible to demonstrate that such a mechanism could generate and separate charge at the required rate.

There is, however, some laboratory evidence to show that when air currents of a few cm/sec. are allowed to flow past a deposit of frost grown by sublimation, small splinters are broken off the delicate dendritic crystals and carry away charges predominantly of one sign, leaving those of opposite sign on the parent crystal. Such a splintering process might well occur in clouds when snowflakes composed of delicately branded crystals collide or, they may be torn off by frictional drag with the air. FINDEISEN (1940, 1943) found the splinters from a growing deposit to be predominantly negatively charged and the deposit positively charged; with an air stream of 35 $cm.sec.^{-1}$ the rate of charging of the deposit was 4×10^{-16} C/cm^2 sec. KRAMER (1948) found a charging rate of the same magnitude and sign in the early stages of a growing frost layer but found that later, the polarity became reversed. KUMM (1951) measured the charges on individual splinters and found positive splinters to be about 7 times as numerous as negative ones, so that the frost deposit acquired a negative charge. The average charge carried per splinter was much the same as found by Findeisen, i.e. about 10^{-15} C.

Let us take Findeisen's value of 4×10^{-16} C cm^{-2} $sec.^{-1}$ for the rate of charging and make a crude estimate of the rate of charge production by splintering in a cloud. We shall assume a frozen-water content af 1 gm^{-3} composed of snowflakes of average mass 1 mg and effective area 1 cm^2, (a high value). The charge generated per second in a volume of 1 km^3 would then be 4×10^{-4} C, i.e. about 0.5 C would be produced over a period of 20 minutes. If the fall-velocity of the flakes is assumed to be 1 $m.sec.^{-1}$, generation of an electric moment of 110 C.km in 7 sec. would require separation of 8,000 C of charge, or about 130 C per km^3. Thus, unless the splintering of ice crystals in the atmosphere is more efficient than in the above laboratory experiments, by at least two orders of magnitude, it cannot play a significant role in the generation of thunderstorm electricity. Furthermore, it is doubtful whether dendritic snow crystals form a major part of the frozen-water content during the active growth stage of the thundercloud, when falling crystals collect large numbers of supercooled droplets which freeze on contact to form pellets of graupel or hail.

(d) *The Dinger-Gunn Effect*

DINGER and GUNN (1946) have shown that when ice containing air melts the air bubbles are released, and upon breaking the surface they transfer to the adjacent air a negative charge, while the melted water retains an equal and opposite positive charge of magnitude 1.25 e.s.u./gm. This process may have relevance during the melting of graupel pellets and snowflakes. It is of the wrong sign, however, to account for the observed polarity of thunderclouds, but may be partly responsible for the predominance of positive charge associated with steady rain and may, perhaps, contribute to the local positive charge found in the bases of warm thunderclouds. In a cloud where solid precipitation elements in a concentration of 2 gm^{-3} are approaching the 0° C level, a charge of 0.8 $C.km^{-3}$ would be developed according to the results of Dinger and Gunn.

(e) *The Workman-Reynolds Theory*

WORKMAN and REYNOLDS (1948, 1950 b) have made extensive investigations of the electrical effects associated with the freezing of water and dilute aqueous solutions. They discovered that, during freezing, a potential difference developed across the ice-liquid interface, the sign and magnitude of which depended on the nature and concentration of the solute. For the majority of solutions tested the ice became negative with respect to the liquid, with important exceptions in the case of ammonium salts. The largest potential difference, −232 V, (potential of liquid with respect to ice), was obtained with a 5×10^{-5} N solution of ammonium hydroxide. Sodium chloride and calcium carbonate solutions of concentration 10^{-4} N produced potential differences of +30 V and +20 V respectively, while doubly-distilled water carefully freed of traces of ammonia showed practically no electrical effects. It appears that, during the freezing process, solute ions of one sign are preferentially incorporated into the ice, those of opposite sign being left in excess in the liquid.

Workman and Reynolds have attempted to erect a theory of charge generation and separation in thunderstorms on the basis of these laboratory experiments. The kernel of their arguments is the wet hailstone—an ice pellet which, on reaching a critical size and fall velocity determined by the temperature and liquid-water content of the cloud, commences to collect supercooled cloud droplets at a rate faster than these can freeze, and so acquires a liquid coat. The limiting factor is the rate at which the latent heat of fusion can be dispersed to the environment, the theory of which has been worked out by LUDLAM (1950). Workman and Reynolds assume that hailstone will first become wet at temperatures between −10° C and −15° C and that, thereafter, only a fraction of the impinging water will become frozen, the rest being flung off in the form of *small* drops. It is further assumed that at the ice-water interface, negative ions will be preferentially incorporated into the ice, (as in the laboratory experiments with solutions of NaCl and $CaCO_3$), so that the water drops flung-off will carry away a positive charge leaving the hailstone with a net negative charge. Gravitational separation of the negative hailstones and small positive drops will then lead to a charge distribution of the observed polarity. In the non-supercooled region of the cloud, the water shed by the hailstone will carry away its excess negative charge and the authors suggest that these negative drops may be carried up to levels where they may be captured by negative hailstones, whose charge is thereby enhanced. The build up of the electric field thus becomes a cumulative process.

The two main advantages which the authors claim for their theory is that it affords a natural explanation for the centre of the negative charge being located around the −10° C level and that the charges transferred across the ice liquid interface during the laboratory freezing experiments (a maximum value of 9×10^4 e.s.u. per cm^3 of frozen NaCl solution) are of sufficient magnitude to account for the charges appearing in thunderstorms.

The assumption that hailstones will not become wet until they approach the −10° C level may be challenged. For a cloud of given temperature and liquid water content, the temperature at which an ice particle becomes wet depends largely on the density with which it is assumed to grow. Calculation shows that in a cloud with base temperature 10° C, the maximum theoretical water content and a steady updraught of 10 $m.sec.^{-1}$, an ice pellet originating at −5° C and growing with a density of 0.3 will first become wet at −25° C − i.e. 10 $^1/_2$ minutes later.

Whether the Workman—Reynolds effect has relevance to thunderstorm electrification will depend upon the contaminants present in the precipitation elements being able to give a positive water-negative ice charge distribution during freezing. WORKMAN and REYNOLDS (1951) collected small hail pellets from near the 0° C level in an active thunderstorm and found them to contain $CaCO_3$

and NaCl, the concentrations of which were not, however, determined. The electrical effects associated with the re-freezing of the melted particles were erratic. When stored at room temperature, the water became *negative* as freezing began and assumed zero potential at the end of the freezing period. When stored at 0° C before freezing, the water again assumed a *negative* potential when freezing began, but became positive after about 20 sec.; thereafter the potential fell to zero at the end of the freezing period. These erratic effects were attributed to the absorption of CO_2 and its reaction with the calcium carbonate to produce soluble calcium bicarbonate. Certainly the electrical effects obtained with solutions of $CaCO_3$ and $Ca(OH)_2$ were very sensitive to the amounts of dissolved CO_2. For NaCl solutions the charging phenomena were very sensitive to the concentration of salt; while maximum charge separation was obtained with a 10^{-4} N solution, no effect at all was produced when the concentration was increased to 5×10^{-4} N. With doubly-distilled water the water became *negative* with respect to the ice during freezing, an effect which has been confirmed by GILL and ALFREY (1952) Workmann and Reynolds attribute this to the presence of small traces of ammonia.

The fact that the Workman—Reynolds effect appears to be so sensitive to the concentrations of salts and carbon dioxide and to traces of ammonia in the cloud water makes it unattractive as the main mechanism of charge generation in thunderstorms. Also, an ice particle becomes wet only when it has attained a radius of several millimetres; it then acquires a clear coat of ice to form a true hailstone and takes longer to melt than the low-density graupel. This leads us to suppose that if the Workman—Reynolds effect were the most important charge generating mechanism, thunderstorms would generally be accompanied by hail. The observational evidence, although admittedly not well documented, does not show this to be the case.

The cumulative build-up of the electric field in the manner visualised by the authors also seems open to doubt. It seems likely that most of the water accumulated by a wet hailstone will be flung off from the top-side, in the form of large drops rather than as small ones; thus their velocity of separation from the hailstones and the probability of their capture by hailstones at higher levels will be correspondingly reduced. Furthermore, in the presence of a positive field, the separation of liquid water from the negatively polarised upper half of the hailstone will tend to *diminish* the field.

(f) *Charge Separation Associated with the Formation of Rime*

A number of experimenters have, in recent years, reported that when supercooled droplets are allowed to impinge and freeze on an ice surface, the latter acquires a substantial charge. This effect is to be distinguished from that which obtains when non-supercooled water splashes off an ice surface. In the latter case it was shown early on by Faraday and later by Sohncke that the ice becomes positively charged, the rebounding water drops acquiring a negative charge; the same result has been obtained recently by GILL and ALFREY (1952).

FINDEISEN (1940, 1943) formed a rime layer by spraying water droplets onto a cold metal surface and found that it acquired a positive charge of order 3×10^{-13} C.cm^{-2} sec.$^{-1}$. The charging ceased if the surface became smooth and glassy, or if it became wet.

A very careful re-investigation of these phenomena has been made by KRAMER (1948) who found the ice deposit acquired a *negative* charge which varied as the impact velocity of the drops; for a speed of 0.5 m.sec.$^{-1}$ the charging rate was 2×10^{-14} C.cm^{-2} sec.$^{-1}$ Findeisen assumed that the compensating charge was carried away on splinters in much the same way as for his frost deposits, (see Section 3 (c)), and some evidence for the production of charged splinters during riming was obtained by Kramer.

LUEDER (1951) made experiments in natural supercooled clouds on a mountain top in order that the contaminants present in the water should be those occurring in nature. The rime was deposited on a slowly rotating metal rod which was enclosed for a part of each revolution by a Faraday cage. Its charge caused a periodic variation in the potential of an electrode. Lueder states that the growing deposit of rime acquired a very strong negative charge, an equal positive charge being communicated to the air, probably on the parts of the drops which were flung off without freezing. The charge generation was more pronounced at lower temperatures, i.e. the more efficient and rapid the freezing process. It is not, however, easy to deduce the actual magnitude of the rate of charging from these experiments.

MEINHOLD (1951) measured the electric field strength at the surface of the fuselage of an aircraft flying at 80 m.sec.$^{-1}$ through a supercooled Cu-congestus. The deposition of rime was accompanied by a rapid rise in the field strength from about 200 V/m to 5,500 V/m in a sense which showed that the aircraft skin was acquiring a strong negative charge. From the rate of increase of the field intensity Meinhold calculated the rate of charging to be 5×10^{-12} C.cm^{-2} sec.$^{-1}$ and attributed this high rate to the high speed of impact and the rapid freezing of the droplets.

The balance of the evidence from these experiments points to the acquisition of a *negative* charge by a growing layer of rime, the rate of charging being higher the velocity of impact of the drops and the more efficient the freezing process. The outstanding contradiction is provided by Findeisen's experiment in which he claimed the rime deposit acquired a positive charge. Some difficulty may arise in the interpretation of the experimental results because of the complications connected with the rebound of some of the droplets from the ice—a process which appears to communicate a *positive* charge to the ice. It seems important, therefore, to separate the electrical effects associated with the freezing and with the rebound of droplets in these investigations.

In this respect the most satisfactory and conclusive experiments have been carried out by WEICKMANN and aufm KAMPE (1950 and private communication). Their cold body was a metal rod of diameter 5 mm placed in a cold room kept either at $-5°$ C or $-12°$ C. Water droplets of diameters 5 μ to 100 μ were sprayed on to the rod at velocities varying from 5 to 15 m.sec.$^{-1}$ The droplets in the immediate vicinity to the rod were slightly supercooled and the water content of the cloud in this region was about 4 g.m^{-3}. Thus, conditions relevant to graupel pellets or small hailstones falling in a cumulonimbus were fairly well simulated. Singly-distilled water, tap water, weak NaCl solutions and strong solutions of ammonium hydroxide and sodium fluoride were used in different experiments, but in each case the rate of charging of the rod was the same, for a given air velocity. The charge generation increased with the velocity of the air-stream, i.e. the rate of accretion of the rime, and for a velocity of 15 m.sec.$^{-1}$ attained a value of 5×10^{-12} C. cm^{-2}sec.$^{-1}$ The ice deposit on the rod showed the clear and opaque layers characteristic of hailstones, but charging stopped when the ice became wet. When water at temperatures slightly above freezing was sprayed on the rod it acquired a slight *positive* charge.

4. Conclusions

We have seen that all the theories of charge generation and separation which have been advanced during the last forty years, and which have been discussed above, are open to objection on quantitative grounds and/or because they do not fit the known facts about the meteorological and electrical behaviour of thunderstorms as listed in Section 2 (g). The only other mechanism suggested by laboratory experiments and which appears to fit, in a qualitative manner, the observed facts, is the charge generation associated with riming. The onset of lightning activity appears to coincide with the appearance of heavy solid precipitation, especially in the form of graupel. We recall that Malan and Schonland gave evidence for the negatively charged column extending up to, but not beyond the $-40°$ C level; this is consistent with the theory of charge generation accompanying the growth of graupel particles because supercooled droplets may be found at temperatures down to, but not below $-40°$ C. The fact that laboratory experiments show that during the formation of a rime layer, a negative charge is acquired by the ice and presumably an equal positive charge by the air, indicates that the growth and fall-motion of graupel pellets would bring about a charge distribution of the observed polarity.

It remains to be shown, quantitatively, that this process is capable of generating and separating the required quantity of charge in the time suggested by the electric field-change and radar data. This will form the subject of a future paper.[2]

[2] See Mason, B. T. "On The Generation of Charge Associated with Graufel Formation is Thunderstorm. Q. J. Roy. Met. Soc. 79 p. 501. 1953.

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