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An experimental investigation of the inductive mechanism of thunderstorm electrification

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A laboratory study of the inductive charging mechanism has been carried out, in which conducting spheres are allowed to fall through a region of high uniform field in a cloud of supercooled water droplets. The mean charge transfer was measured and found to be of the same order as the theoretical value for the same conditions.

1. INTRODUCTION

The inductive theory of thunderstorm electrification, first proposed by *Elster and Geitel* [1913], is perhaps the simplest and most elegant of the many proposed thundercloud charging mechanisms. It is based upon fundamental and well understood physics, but in spite of its underlying simplicity its importance as a charging mechanism is still the subject of debate after 80 years.

The essence of the theory, in its current form, is that a graupel pellet may be considered as a conducting sphere; falling in a uniform electric field directed vertically downward, it will become polarized with its upper half negatively charged and its lower half positively charged (Figure 1). Cloud droplets impacting on the underside of the graupel may rebound from it and carry away some of the positive polarization charge, leaving the graupel with a net negative charge. The precise nature of such collisions is not well known, and the term rebound, while convenient, may be misleading; the droplets do not rebound in the manner of a billiard ball collision but appear to first stick to the graupel and then tear away from it, leaving part of their mass behind [*Aufdermaur and Johnson*, 1972].

Gravitational separation of the particles, along with their net charges, results in the reinforcement of the electric field. This positive feedback leads to a rapidly increasing rate of charge separation and field growth, until finally a breakdown field is reached. The resultant lightning flash reduces the separated charges and the electric field within the cloud. The field may then recover by the same process, which can continue for as long as sufficient precipitation intensity and updraughts within the cloud are maintained.

The original theory concerned the interaction of raindrops with cloud droplets. It was proposed that as the cloud droplets collided with the underside of a falling raindrop, they might bounce off again, a cushion of air preventing coalescence. The rebounding droplets might then carry away some of the polarization charge from the bottom of the raindrop. An experimental investigation by *Schumann* [1925] showed that the mechanism would not work as suggested, since the behavior of colliding droplets was somewhat different to that assumed by Elster and Geitel. Small droplets tend to coalesce with the raindrop, while larger droplets have sufficient inertia to break away after coalescence, effectively passing straight through the rain drop, and so carry off some of the induced charge from the upper surface of the drop. *Müller-Hillebrand* [1954] applied the mechanism to the interaction of ice crystals and soft, rimed hail pellets. He proposed that the ice crystals "slipped" off the graupel pellet shortly after impacting, having remained in contact long enough for charge to flow between the two particles. *Latham and Mason* [1962] also demonstrated the theoretical viability of the theory as applied to graupel and ice crystals, providing that the contact times were longer than the relaxation time for charge transfer. However, in an experimental study they found no detectable effects on the charge separation with applied fields of up to 1000 V cm^{-1}, apparently because contact times were too short. Further theoretical work was presented by *Mason* [1968, 1972], showing that the restrictions imposed by the short contact time would not apply to water droplets rebounding from a graupel particle, since water has a much higher conductivity than ice. Experimental confirmation that significant charge was separated by rebounding water droplets, in reasonable quantitative agreement with the theory, was provided by *Aufdermaur and Johnson* [1972]. They allowed individual droplets to impact on an ice-coated target connected to a sensitive charge amplifier while a field of up to 1500 V cm^{-1} was applied at the surface of the target. Their results suggested that only droplets making grazing collisions separate and so carry off charge, and that these droplets partially coalesced with the target before separating again, leaving part of their mass behind. *Moore* [1975] pointed out that the angular dependence of the rebound probability found by Aufdermaur and Johnson severely limited the mechanism's effectiveness. He reasoned that as charge was removed from the graupel, the region of zero surface field near its equator would migrate downwards. When the electrical equator moved down to the region corresponding to the mean contact angle of rebounding droplets, charge separation would cease. This resulted in a reduction of the maximum charge that could be acquired by a graupel pellet, to less than 20% of the value obtained when a uniform rebound probability was assumed, as in all previous studies.

Gaskell [1981] made a similar study to that of Aufdermaur and Johnson, with similar results; charge was separated in agreement with the theory, but the fact that droplets only separated when glancing off the target near its equator, where the surface charge density is low, meant that the charge transferred in each interaction was small. Gaskell concluded that the mechanism was unlikely to be able to account for cloud electrification.

Measurements made within developing thunderclouds [*Gaskell et al.*, 1978; *Christian et al.*, 1980; *Marshall and Winn*, 1982] have detected small graupel pellets with charges much larger than can be accounted for by the inductive mechanism, given the

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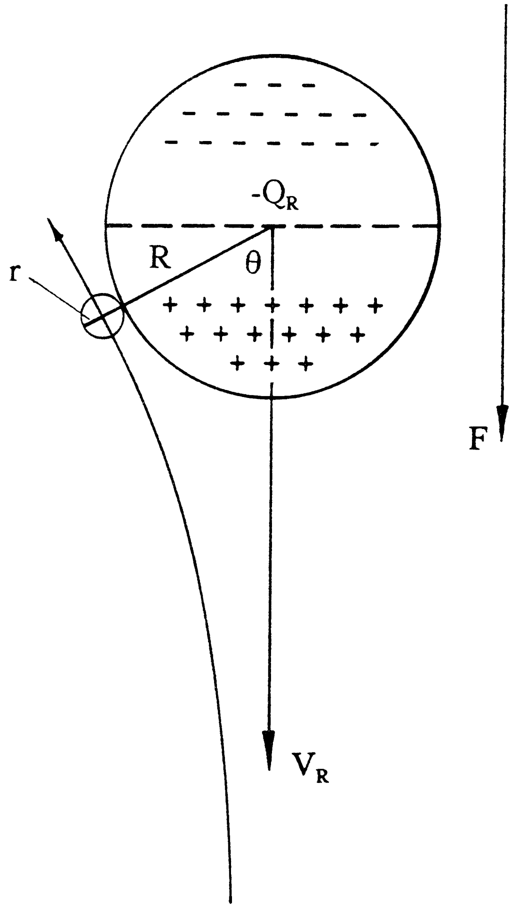

Fig. 1. Basic inductive charging mechanism: a cloud droplet rebounds after a grazing collision with a spherical graupel pellet.

prevailing electric field in the early stages of electrification. This suggests that the mechanism can, at best, be significant only in the later stages of thunderstorm development, where it may act as a bootstrapping process, increasing the rate of charge separation and field growth. Many thunderstorm models have included the inductive mechanism in such a capacity but with conflicting results. *Helsdon and Farley* [1987] obtained good agreement with observation of a cloud from the 1981 CCOPE project when the mechanism operated in tandem with a noninductive ice-ice charging process. *Dye et al.* [1986], modeling the same cloud, found no significant contribution from the inductive process; when the inductive process alone was included in the model, minimal electrification took place. *Ziegler et al.* [1991] actually found the mechanism to act dissipatively when included in a noninductive model of a New Mexico mountain thunderstorm.

The inductive mechanism as applied to droplet-graupel interactions is also unable to explain the observation of significant charges (>5 pC) of both signs coexisting in the same regions of electrified clouds [*Dye et al.*, 1986], or the fact that such charges appear to be carried by a relatively small fraction (<10%) of the ice particles in the cloud.

Although it appears unable to explain all the observational evidence, a recent paper by *Mason* [1988] has revived the inductive theory, as applied to droplet-graupel interactions, as a primary charging mechanism for thunderclouds. A detailed theoretical treatment is presented, showing that low-density, millimeter-sized hail pellets, falling through a cloud of supercooled droplets are able to separate sufficient charge to create large-scale fields of 4000 V cm^{-1} within 10 min, providing that within this time the precipitation intensity builds from zero to 20 mm h^{-1}.

The present study aims to test the theory by comparing the theoretical and experimental charge transfers for the same conditions, which are arranged to be as realistic as possible in a laboratory situation. In particular, care has been taken to ensure a uniform field. The studies of both Gaskell and Aufdermaur and Johnson suffered from the difficulties of obtaining a uniform field around a fixed target in the confined space of a wind tunnel, and they obtained their most reliable results with more or less radial fields; even then they could only give an estimation of the field strength at the surface of the target. The present study takes a very different approach to previous experiments, allowing a free-falling target to pass through a region of high field in a cloud of supercooled water drops, its charge being measured before and after the field region.

2. THEORY

The rate of charging of a spherical hail pellet of radius R, falling at a velocity V_R with respect to cloud droplets of radius r, in a uniform, vertical field F is given by *Mason* [1988] in the reduced form of (1). (N.B., following Mason, equations are presented in cgs units and F is positive when due to a positively charged region above a negative region.)

$$\frac{dQ_R}{dt} + \frac{Q_R}{\tau} = -\frac{3FR^2\cos\theta}{\tau} \qquad (1)$$

where θ is the angle of impact with respect to the vertical and τ is the time constant associated with the rate of charging, given by

$$\tau = \left(\frac{1}{6}\pi^3 E V_R n_r \alpha r^2\right)^{-1}$$

where $-3FR^2\cos\theta$ is the maximum charge that may be acquired by the hydrometeor via the inductive mechanism. E is the collision efficiency of the target for droplets of radius r; n_r is the number concentration of the droplets; and α is the fraction of impacting droplets that rebound. Values of E and $\cos\theta$, and hence α, are derived from the potential flow solutions of *Fonda and Herne* [1957] for spherical collectors, via a dimensionless parameter which is a measure of the inertia of the droplets; *Mason* [1988] provides a graph of these values, valid for droplet-graupel size ratios in the range $0.005 \leq r/R \leq 0.02$, which has been used for the theoretical calculations presented here. Note that E, θ, α, and τ all depend upon the drop radius r. Integrating (1) with $Q_R = 0$, when $t = 0$, gives

$$Q_R = -\frac{3\cos\theta}{\tau e^{t/\tau}} \int_0^t R^2(t) F(t) e^{t/\tau}\, dt \qquad (2)$$

In the laboratory, F and R can be kept constant and so taken out of the integral which may then be completed to give

$$Q_R = -3FR^2\cos\theta\left(1 - e^{-t/\tau}\right) \qquad (3)$$

Q_R being the total charge on the hydrometeor after a time t. It should be noted that this equation gives the charge transfer due to a single droplet size only. To determine the charging in a real cloud, the charge separation due to droplets in each interval of the spectrum may be summed to give an approximate total charge separation. The situation is complicated by the fact that the electrical equator moves downward as the charge on the pellet increases. Droplets of different radii have different values of θ;

it would thus be possible for some of them to rebound from above the electrical equator as it moves down, and so remove the opposite sign of charge. A simple summation could thus result in large errors in the calculated charge transfer; however, for the small charges involved in the work presented here, the approximation is valid, with an error of much less than 1%.

In order for this continuum approach to inductive charging to be usefully applied, two conditions should be met. (1) The time between collisions must be short compared to τ; this is readily seen to be so by comparing the passage time through the system of < 0.02 s, during which many collisions take place, to typical values of τ from Table 1. (2) The value of τ should be short compared to the total time over which charging takes place; this condition is evidently not satisfied; however, the final results are averaged over a large number of measurements, with a total charging time of a similar order to τ.

3. EXPERIMENTAL ARRANGEMENT

The experimental arrangement is shown schematically in Figure 2 and is situated inside a large cloud chamber in a cold room. It consists of two parallel, circular plate electrodes, of diameter 42 cm separated by 15.5 cm; the upper plate is grounded and the lower one connected to a 10-kV power supply. Induction tubes connected to sensitive charge amplifiers situated above and below the plates are coaxial with 2-cm-diameter holes through the plate centers to permit the passage of falling spheres. A cloud is formed in the chamber by admitting water vapor from a boiler beneath one corner of the chamber. The cloud may pass freely between the field plates, and its temperature in the region of the plates is maintained at -19 ± 2°C. The liquid water content, measured by means of a Gerber Instruments particle volume monitor (PVM), is approximately 3 g m^{-3} with a variability of about 0.5 g m^{-3} over the course of an experiment. Conducting spheres (steel ball bearings), 4.76 mm in diameter and cooled to ambient cloud temperature, are allowed to fall freely through the cloud, passing through the region of high field between the plates at a mean velocity of 8.4 m s^{-1}. The charge on the spheres is measured by induction tubes immediately before and after they pass through the interaction zone. The outputs from the charge amplifiers (Figure 3) are digitized and processed by computer, information about the induced voltage peaks being saved for detailed analysis at a later date. The enclosed region below the high-voltage plate is kept free of cloud by maintaining it at a slight positive pressure with respect to the rest of the cloud chamber, thus ensuring that no reverse charge transfers take place in the field between the lower plate and the grounded floor of the cloud chamber.

Individual measurements of charge transfer are highly variable, due to both the natural variability in the charge transferred, because of the stochastic nature of the interactions, and the effects of amplifier noise on the signal. To determine the mean charge transfer, several thousand individual charge measurements were made and the results averaged. It was inevitable that charge leakage would occur from the tips of ice crystals growing in the high field around the edges of the field plates, leading to a net charge on the cloud droplets. In order to account for the charge transfer to the spheres due to the collection of charged droplets, a separate measurement was made of the mean droplet charge by drawing the cloud through a tube plugged with steel wool which was connected to a charge amplifier. The total charge deposited was measured and the collected rime weighed. The mass of rime collected by a falling sphere was calculated and hence the charge collected by the spheres from cloud droplets was determined. The cloud droplet spectrum was determined with a forward scattering spectrometer probe (FSSP) (figure 4).

4. RESULTS

The theoretical charge transfers due to interactions with droplets from each interval in the measured spectrum were calculated from equation [3]; these were summed and gave a total theoretical transfer of 4.0 ± 0.8 fC, the sign being the same as that of the applied potential on the bottom plate. The error in this calculation arises from the uncertainty in the cloud liquid water content. The distortion of the electric field in the immediate vicinity of the central holes in the plates has two effects, the vertical component of the field is reduced, dropping to zero in the plane of the plate, and a horizontal field component will be present off axis. The former is accounted for in the calculation of the theoretical charge transfer, the latter will tilt the electrical equator of the falling sphere and so enhance or reduce individual charge transfers depending upon where a droplet rebounds, increasing the variability in individual measurements; the resultant

TABLE 1. Contribution to the Total Theoretical Charge Transfer From Each Interval in the Droplet Spectrum Along With Values of E, $\cos\theta$, α, and τ

r, μm	No/cm^3	E	$\cos\theta$	α	τ, s	Q, fC
1.75	17.1	0.01	0.80	0.004	9823829	0.000
3.25	35.8	0.33	0.58	0.005	35194	0.029
4.75	68.5	0.52	0.32	0.006	5149	0.112
6.25	135.5	0.66	0.20	0.006	1029	0.342
7.75	211.3	0.77	0.13	0.007	316	0.765
9.25	224.6	0.86	0.10	0.009	162	1.096
10.75	146.7	0.90	0.08	0.010	154	0.886
12.25	62.8	0.92	0.06	0.011	242	0.450
13.75	20.6	0.94	0.05	0.012	518	0.172
15.25	7.3	0.96	0.04	0.013	1068	0.070
16.75	2.9	0.97	0.04	0.015	2013	0.031
18.25	1.0	0.99	0.03	0.016	4650	0.012
19.75	0.3	1.00	0.03	0.017	14122	0.003
21.25	0.1	1.00	0.02	0.018	51687	0.001

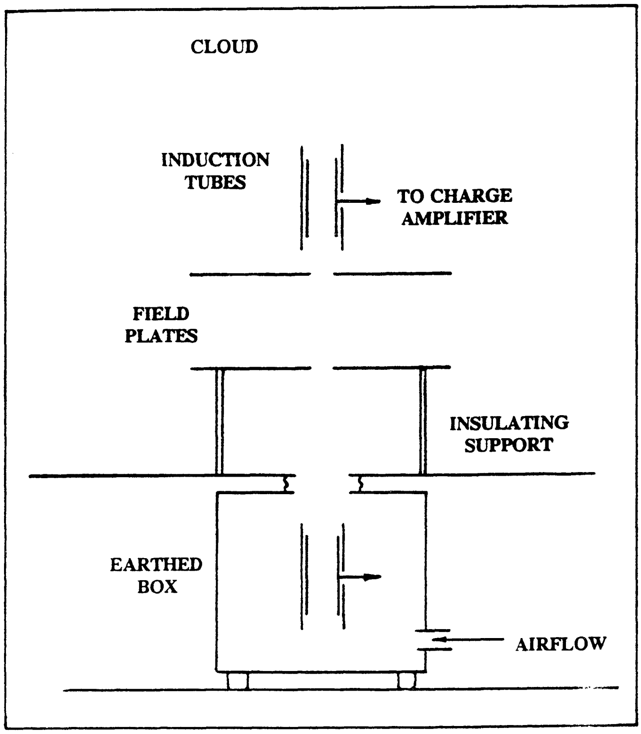

Fig. 2. The expeimental arrangement.

error in the averaged results should, however, be small and is included in the analysis of the error arising from variations in individual charge measurements.

Table 1 shows a breakdown of the theoretical charge transfers with droplet size for the laboratory conditions, along with values of E, cos θ, α, and τ. The effect of increasing velocity is to increase E and cosθ and decrease α, resulting in a net increase in the rate of charging; however, in the limited laboratory system, the shorter time spent in the interaction area results in a net decrease in the charge transferred. The calculated charge transfer assumes that the initial charge on the spheres is zero, initial charges of the same sign as the expected charge transfer should reduce the charge separation, those of the opposite sign should increase it. In practice the initial charge on the spheres varied randomly in sign and magnitude, having a mean magnitude of approximately 200 fC. It is estimated that this would lead to a change in the theoretical charge transfer of only 2% and may thus be neglected. The initial charge that would be required to reduce the net charge transfer to zero is of the order of 11000 fC.

The data were split into three sets according to the direction of the field and the initial charge on the droplets, which were analyzed separately; the first two sets had the lower electrode at a positive potential, with positive and negative initial charges, while the third set had a negative lower electrode and negative initial charges only (positive initial charges were also found, but the statistics were too poor for these results to be of use). Figure 5 shows the individual charge transfer measurements for one data set, plotted against the initial charge on the rimer, the other two sets being very similar. Problems with the calibration of the charge amplifiers results in a slight apparent increase in the charge transfer with initial charge. A straight line is fitted to the data, and the intercept with the ordinate, where initial charge is zero, is taken as the value of mean charge difference between the two induction tubes. The mean inductive charge transfer is then obtained by subtracting from this charge, the charge collected directly from droplets swept out of the cloud, estimated to be 1.5 ± 1 fC. Table 2 gives the values of the intercepts, mean charge transfers, and associated errors for all three data sets.

There are a small number of charges evident in Figure 3 and in the other data sets, which are very much larger than the majority. An examination of the recorded signals for these events revealed that their passage times and shapes were normal, however, such large transfers of charge seem highly unlikely via the inductive mechanism but may be due to collisions with ice crystals growing on the equipment in the cloud. The analysis was repeated with all apparent transfers greater than 60 fC deleted from the data sets; a breakdown of the results from the reduced data sets is given in Table 3. It is not thought that any significant errors will result from collisions with the plates or the sides of the induction tubes, as it was observed that after such collisions the signal was invariably rejected by the logging program.

5. DISCUSSIONS

The measured mean charge transfers are less than or do not significantly exceed the ± 4 fC predicted by the inductive theory for the conditions used. The results are broadly in line with the theory at the level of individual interactions. Small discrepancies between the experimental and theoretical values of the charge transfer have two possible explanations: the individual droplet rimer interactions may separate less charge than predicted or the fraction, α, of impacting droplets that rebound may be less than assumed in the theoretical treatment. The theoretical calculations assume that both target and droplet are perfect spheres and that droplets rebound whole and undeformed by the collision; in practice this is not so; the droplet partially coalesces with the rimer and then tears away from it. *Aufdermaur and Johnson* [1972] made careful observations of droplets collected after interacting with a riming target and deduced that the droplet leaves part of its mass behind, thus the separating droplet is slightly smaller than assumed and might carry less charge. The exact quantity of charge transferred to the droplet depends on its shape and hence the strength of the local electric field, as it tears away from the rimer, and also on the detailed structure of the surface at its point of impact, neither of which are known. Both Aufdermaur and Johnson's and Gaskell's experiments showed charge separation in rough agreement with the theory, so individual charge transfers are not expected to depart greatly from the predicted values. The value of α may be expected to depart

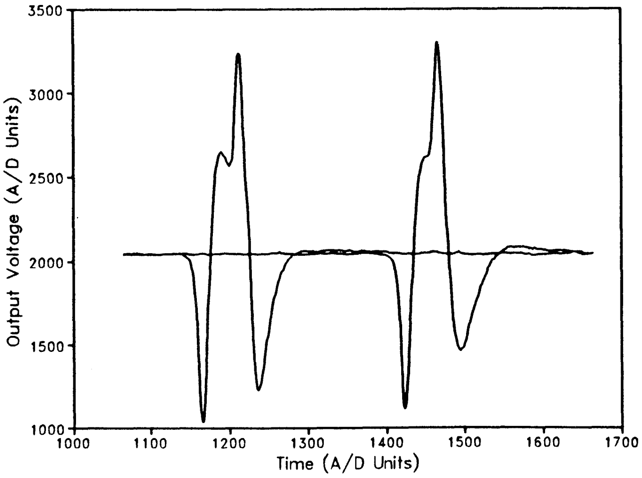

Fig. 3. Example of the induced voltage pulses on the induction tubes.

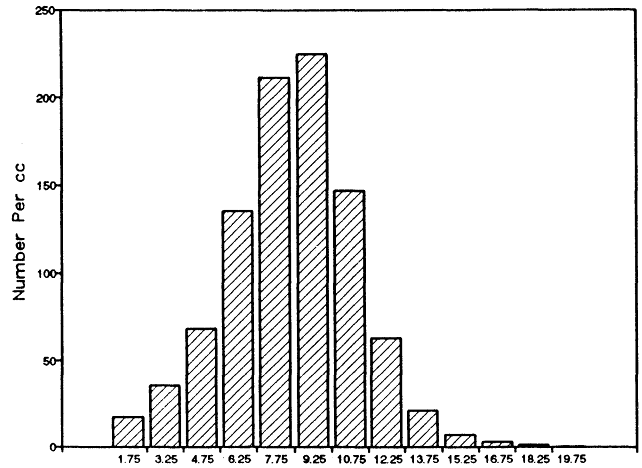

Fig. 4. The laboratory cloud droplet spectrum, averaged over a period of 11 min.

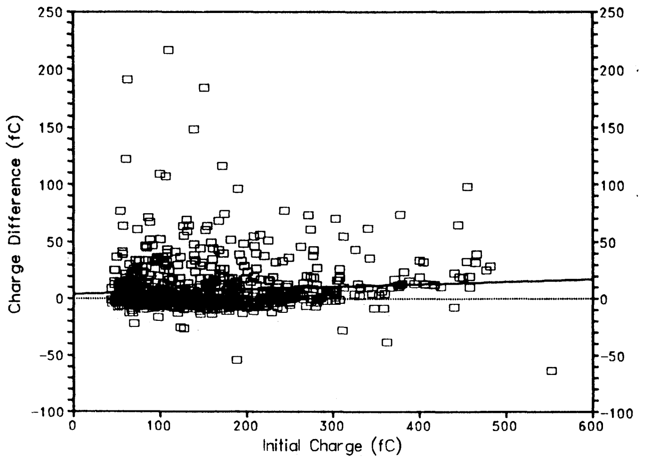

Fig. 5. Individual measurements of the apparent difference in charge measured by the two induction tubes, plotted against the initial charge as determined from the upper induction tube. (positive initial charges, +10 kV on the bottom field plate.)

rather more from that assumed in the calculations, since the nature and conditions of the collisions differ markedly from the idealized theory. The range of values observed in experimental studies shows a strong dependence on the surface structure of the target. Aufdermaur and Johnson, using droplets between 20 and 100 μm, and a riming target, obtained values between 0.1% and 1%, while Gaskell, with a smooth surfaced target and 100-μm droplets under otherwise similar conditions, obtained values as high as 10%. The calculated values of α for the work presented here are shown in Table 1 and range from 0.4% to 2%. It is noted that while the theory allows only those droplets making a grazing collision to rebound, thus confining charge transfers to the region of low surface charge density near the equator of the rimer, it assumes that all droplets making such a collision rebound. Given the observed variation in α with surface conditions, this is unlikely to be the case. In the present experiments the spheres were partially rimed before entering the field region and so had a slightly roughened surface; it thus seems likely that the discrepancy between the theoretical and experimental charge transfers is due to a smaller fraction of impacting droplets rebounding than is assumed in Mason's theory.

The results presented here have implications for thundercloud models which include the inductive mechanism; it is suggested that the charge separation rates might be reduced below those suggested by Mason by a factor of about 2, possibly more since it seems likely that the number of droplets rebounding from a natural graupel pellet may be lower than that from the sphere in these experiments. Unfortunately the errors associated with the current work preclude a more accurate determination of the charge separation rates. Also of relevance to modeling studies is the choice of a single representative droplet radius, where a full cloud spectrum is not being used. Calculations based on the droplet spectrum in Figure 4 show that the mean, mean volume, and modal radii overestimate the theoretical charge transfer by 26%, 12%, and 11%, respectively, while the effective radius, defined as $r_{\text{eff}} = \Sigma nr^3/\Sigma nr^2$, gives the best value, overestimating Q_R by just 1.5%. Careful consideration must also be given to the effects of graupel radius, density, and velocity on E, cos θ, and α and hence on the rate of charge separation. All studies to date have assumed the rimer to be a perfect sphere, in practice this is not so, many graupel particles having a conical shape; in order to more accurately determine the effectiveness of the inductive mechanism, the airflow and electric field about such particles and the interaction of droplets with them should be investigated.

6. CONCLUSIONS

The experimental results are broadly in line with the predictions of the inductive theory, as presented by *Mason* [1988], although it seems likely that he may have overestimated the number of droplets that rebound from the rimer. The significance of the mechanism to thunderstorm electrification is still open to question. There are strong doubts about its ability to act as the primary thunderstorm charging mechanism since it is unable to account for the observed charges in the early stages of thunderstorms [*Gaskell et al.*, 1978]. It seems more likely that it acts as a contributory mechanism in the later stages of electrification, although there is disagreement between thundercloud models which include it in this capacity [*Dye et al.*, 1986; *Helsdon and Farley*, 1987; *Ziegler et al.*, 1991]. A better

TABLE 2. Measured Charge Transfers From the Three Data Sets

Data Set (Initial Q)	Intercept	Calibration Error	Charge Transfer
1 (+ve)	4.3 ± 1.5	± 3	2.8 ± 3.2
1 (-ve)	0.5 ± 1.7	± 0.7	-1.0 ± 2
2 (-ve)	-5.7 ± 1.7	± 2.3	-4.2 ± 2.5

Column 1 indicates the sign of the initial charge on the spheres, column 2 the intercept on the graphed data, column 3 the error due to the calibration of the amplifiers, and column 4 the resultant experimental charge transfers (all values in femtocoulombs).

TABLE 3. Results for the Reduced Data Sets (All Values in femtocoulombs)

Reduced Data Set	Intercept	Calibration Error	Charge Transfer
1 (+ve)	2.3 ± 0.9	± 2.1	0.8 ± 2.3
1 (-ve)	3.5 ± 0.9	± 0.6	2.0 ± 1.3
2 (-ve)	-8.0 ± 1.2	± 2.3	-6.5 ± 2.5

understanding of the detailed nature of droplet-graupel interactions in clouds is required in order to assess properly the contribution of the inductive mechanism to cloud electrification.

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