The scavenging of particles by electrified drops: radar echo intensification following lightning

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SUMMARY

A series of laboratory experiments were performed in an effort to improve our understanding of the physics of the echo-intensification phenomenon, in which the radar reflectivity of a region of a thundercloud increases rapidly immediately following the occurrence of lightning within it. Measurements were made of the charges, \( q \), deposited on falling water droplets when they engage in direct interactions with positive corona streamers in a uniform electric field, \( E \), just above the limit for propagation, \( E_0 \). As the drop radius increased from 12 to 950 \( \mu \text{m} \), \( q \) increased from about \( 10^{-13} \) to about \( 10^{-10} \) \( \text{C} \); and \( q \) increased as \( E \) was raised above \( E_0 \). These measurements yielded an estimate of \( 30 \mu \text{m} \) and \( 10^9 \), respectively, for the radius of, and the number of elementary charges contained in, the tip of a propagating streamer at a pressure of one atmosphere.

The collection efficiencies of drops in the radius range 40 to 120 \( \mu \text{m} \) carrying charges appropriate to the direct interaction process, for uncharged droplets of radius around 12 \( \mu \text{m} \), were found to be about four times the non-electrical values. It was concluded that this enhancement in collection resulted largely from dipole rather than coulomb forces. A simple analysis indicates that reported echo-intensification observations cannot be explained in terms of these enhanced collection efficiencies, but could possibly be a consequence of the greatly enhanced velocities (and hence growth rates) of drops of radius \( \sim 100 \mu \text{m} \) highly charged by direct interaction with corona streamers in the intense electric fields of a thundercloud.

1. INTRODUCTION

Moore, Vonnegut and collaborators have reported, in several papers on their radar studies of thunderclouds (1962, 1964), that following a lightning stroke a sudden intensification of reflected signal sometimes occurs in the vicinity of the lightning channel. They attribute this to the rapid formation of rain, resulting from the increased collection rates of drops highly charged by interaction with corona streamers. More recent evidence of such an event was obtained during radar studies of lightning channels by Szymanski et al. (1980). A lightning echo from a region of low precipitation was followed by a discernible increase in the precipitation echo within three seconds of the discharge. This echo intensified at 24 dB min\(^{-1}\), descending rapidly as it did so to merge with the main precipitation of the cloud within little more than a minute.

The role of positive streamer systems in the rapid movement of charge within a thundercloud, suggested by Loeb (1966), is reasonably well established. UHF noise occurring during thunderstorms, just before stepped leader and dart leader formation, and also in the interstroke periods, has been attributed to intense generation of positive streamers inside the cloud (Brook and Kitagawa 1964). Griffiths and Phelps (1976) have developed a quantitative model showing how this rapid charge transport, which in some conditions can lead to the development of breakdown fields, can take place. Kreibiel, Brook and McCrory (1979) find evidence of charge movement in the pre-breakdown and interstroke periods of the flash, which is consistent with the development of such streamers over distances of several hundred metres or more.

There are thus many parts in the complete flash process in which streamer systems form the link between the relatively immobilized, widespread and tenuous charges residing on hydrometeors in the body of the cloud, and the rapid, intense phenomena of the discharge and the lightning channel. During any of these charge movements, interactions between streamers, ions and droplets occur. We attempt a quantitative assessment of some of these interactions, which may contribute to an understanding of the role of electrical forces in the formation of thunderstorm precipitation.

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A streamer system can charge the cloud drops by two distinct mechanisms. It is possible for a direct encounter to occur between a streamer tip and a cloud particle, resulting in a relatively large positive charge being deposited on the particle. The role of these directly charged drops was considered unimportant by Phelps (1972) because of the small number of drops involved, and because the mechanism was thought to operate only for droplets above 50 μm in radius; while Sartor (1970) considered the charges deposited on smaller droplets to be more influential in the rapid formation of rain. However, Sartor's small droplet category extended up to radii of 100 μm and we find (section 2) that direct charging can occur down to radii of 12 μm. In a typical cumulonimbus cloud (data from Weickmann and auflm Kampe 1953) 98% of the total direct interaction cross-section for collisions between streamer tips and droplets comes from droplets in the radius range 30–100 μm, and 85% of the charge lost by the streamer system in direct interactions would be deposited on droplets in this important category.

Drops become indirectly charged by the diffusion of ionic debris in the wake of the positive streamers onto nearby cloud particles. This process operates on particles of any size and can produce charges of either polarity, depending on whether the system is growing or dying (Phelps 1974). The magnitude of the charge produced depends on the local electric field existing at the time, but has been found to be about an order of magnitude lower than the charges produced by direct interactions (Phelps and Vonnegut 1970). We are not concerned with indirectly charged drops in this paper.

In section 2 we describe measurements of the charges acquired by water drops, of radius 12 μm to 1 mm, which engage in direct interactions with positive corona streamers. In section 3 we describe experiments designed to measure the collection efficiencies for cloud droplets of drops, of radius 40 to 120 μm, carrying charges appropriate to the direct interaction process. In section 4 we discuss the capture mechanism and in section 5 we endeavour to examine the role of electrified drops in the reported echo-intensification phenomenon.

2. DIRECT CHARGING OF WATER DROPS BY CORONA STREAMERS

The objective of the experiments described in this section was to determine values of the charge, \( q \), deposited on water drops by direct contact with positive corona streamers, over as wide a range of drop radius, \( r \), and uniform electric field, \( E \), as could be achieved.

The radius range 12–950 μm was covered by using three separate techniques of drop production: a spinning top (May 1949) for 12–30 μm; the generator designed by Abbott and Cannon (1972) for 35–85 μm; and the arrangement developed by Atkinson and Miller (1965) for 200–950 μm. The cloud or stream of drops so produced entered a region in which they were exposed to positive corona streamers. The electrode arrangement used to produce positive streamers and a uniform field through which they could propagate is illustrated in Fig. 1. A pair of circular, smooth copper electrodes, of diameter 8-4 cm, were mounted coaxially, with their planes vertical. Their separation was adjustable but generally around 7 cm. One, the collector electrode, was earthed; the other contained a central hole, of diameter 2-4 cm, housing a snug-fitting P.T.F.E. stud, through which passed a metallic needle which served as the corona point. This plate and the needle were connected electrically so that the application to them of a high voltage pulse (variable between 10 and 30 kV), of duration about 0-1 ms, produced positive corona streamers and a horizontal electric field through which they could propagate. Drops of all sizes examined were found to acquire charges as a consequence of their interaction with streamers.

In the case of the smallest drops (12 < \( r < 30 \mu m \)), \( q \) was measured by applying a sweeping field \( E_s (\leq E_r) \), of duration 8 ms, between the electrodes, immediately following the expiration of the 0-1 ms pulse. This drove the positively charged drops to the collector electrode, where their charges flowed to earth through the charge amplifier shown in Fig. 1. The individual charge pulses were recorded on magnetic tape for subsequent analysis. This method of charge measurement was optimized by using a voltage-ring to convey a
small negative charge to the drops as they were produced by the atomizer. As a consequence, the sweeping field drove only those droplets positively charged by interaction with streamers to the collector electrode. The charges acquired by the larger drops were measured by collecting them in a shielded metallic cup connected to an electrometer and recorder. The rate of production of these drops was adjusted so that only one drop would be in the vicinity of the streamer system during each discharge. In all cases, the measured initial charges on the drop ($<10^{-16}$ C) were much smaller than those ($10^{-13}$ to $10^{-10}$ C) deposited by interactions with streamers.

In a subsidiary experiment, the electrode configuration was roughly simulated and associated equipotentials plotted, using conducting paper. It was found that the electric field was uniform to better than 10% at distances greater than 2 cm beyond the tip of the corona electrode. This was considered satisfactory.

It was estimated that for the smallest drops $q$ could be measured to an accuracy of $\pm 15\%$. The dispersion of droplet sizes produced by the spinning top was around 15% and the values of $r$ quoted below for drops within this size band are averages. For drops of intermediate ($35 < r < 85 \mu m$) and large ($200 < r < 950 \mu m$) size, $q$ was measured to an accuracy of $\pm 10\%$, the estimated errors in $r$ being $\pm 5\%$ and $\pm 2\%$ respectively. These uncertainties are small compared with the observed variations in $q$ associated with the statistical nature of the processes of streamer propagation and charge deposition. This argument is illustrated in Fig. 2 which presents the measured distributions, for two radii, of the charge deposited when streamers intercepted drops produced by the spinning-top device.

Figure 3 presents results obtained for all three size bands, for $E = 4.1 \text{kV cm}^{-1}$, just above the critical value for propagation. The deposited charge is seen to increase rapidly with drop radius. The values of $q$ for precipitation-sized drops agree reasonably well with those obtained (with copper spheres) and discussed by Phelps and Vonnegut (1970) and Phelps (1972), but for the smallest droplets ($r \sim 15 \mu m$) our values of $q$ exceed those of the latter workers by an order of magnitude. Similar results were obtained for other values of $E > E_0$. 

![Diagram of apparatus](image-url)
Figure 2. Characteristic distribution of charge $q$ deposited on water drops by direct interactions with positive corona streamers. A, $r = 14 \, \mu m$; B, $r = 20 \, \mu m$.

Figure 3. The measured charge $q$ deposited upon drops of radius $r$ by direct interaction with positive corona streamers in a uniform electric field of magnitude $E = 4.1 \, kV \, cm^{-1}$, slightly above the threshold value for propagation, $E_0$.

Our results are strongly indicative of a single mechanism – direct charging – operating over the complete size range ($12-950 \, \mu m$) examined. They cannot be reconciled, for the smallest sizes, with those of Phelps, who employed an ingenious and complex technique – droplet oscillation in a highly divergent a.c. field – to measure $q$. It appears possible that in the latter experiments some charging events took place in regions where $E < E_0$.

Figure 4 presents the measured relationship between deposited charge and the electric field applied between the electrodes as it increases above the critical value for propa-
Figure 4. The measured variation with field strength $E(>E_0)$ of the charge $q$ deposited on water drops by direct interactions with positive corona streamers. $r = 560 \mu m$.

...
a transfer of the tip-charge, \( q = N_0 e \), to the drop. Drops of this size are large enough to ensure complete transfer of the tip-charge, but normally small enough to preclude the possibility of two streamers striking the same hydrometeor. In our experiments, as mentioned earlier, the drop-production rate was adjusted to ensure that throughout the duration of a pulse only one drop was falling between the electrodes.

For a single streamer tip, of charge \( q_s \) and internal energy \( u \), growing in a field \( E \), a simple energy balance suggests

\[
du/dx = q_s (E - E_0),
\]

(1)

where \( E_0 \) is the critical field in which a streamer has zero growth; the energy losses due to excitation and ionization being just balanced by the gain from the ambient field. Electrostatic arguments give \( u = kq^2 \), and \( k = 3/20 \pi \varepsilon_0 A \), where \( \varepsilon_0 \) is the permittivity of free space; \( k \) is constant provided \( A \) is unchanged, an assumption justified by the work of Bastien and Marode (1979). Substituting for \( du/dx = 2kq_s dq_s/dx \) in Eq. (1) and integrating, we obtain \( q_s - q_0 = (E - E_0) x/2k \). Here, \( q_0 \) is the charge which contains the minimum number of ions required for streamer onset and \( x \) is the distance travelled in the ambient field. Thus \( q_s \) is a linear function of \( E \) with a slope depending upon the tip radius, \( A \), and an intercept of \( q_0 \) for \( E = E_0 \). For the values shown in Fig. 4, obtained using a droplet of radius \( 560 \mu m \) and a voltage pulse amplitude of \( 30 \text{kV} \) and taking \( x \) to be the distance between the point electrode and the droplet, a least squares fit yields \( A = 30 \mu m \) and \( N_0 = 1.0 \times 10^8 \). The value of \( E_0 \) was taken to be \( 4.0 \text{kV cm}^{-1} \) (Phelps 1974). Bearing in mind the statistical nature of the streamer process and the complex and little understood nature of the branching mechanism, the close agreement with Dawson and Winn’s prediction is clearly somewhat fortuitous. However, further experiments, in which ice crystals were exposed to corona streamers, provided confirmation of these estimated values of \( A \) and \( N_0 \). Crystals of dimension >500 \( \mu m \) were grown from the vapour and mounted on a rigid rod within a deep-freeze cabinet which also housed a corona-pulse/electrode arrangement similar to that utilized in the experiments with falling drops (Fig. 1). In a typical experiment, a crystal was exposed to positive corona streamers in a specified electric field, \( E \), and then lowered into an induction can connected to a vibrating reed electrometer, in order to measure the charge, \( q \), deposited upon it. It was then discharged, and the procedure was repeated for a different value of \( E \). In this way many measurements could be taken to reveal the relationship between \( q \) and \( E \) for an individual crystal. Results for four different ice crystals are presented in Fig. 5. They are seen to be very similar to those (Fig. 4) found for water drops; \( q \) increases rapidly with \( E > E_0 \). Table 1 shows that the estimates of \( A \) and \( N_0 \) obtained in four separate cases (ice and water) agreed within a factor of about two.

A more detailed account of these experiments has been presented by Verma (1980).

<table>
<thead>
<tr>
<th>Target</th>
<th>( A (\mu m) )</th>
<th>( N_0 (\times 10^8) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice crystal-sector plate</td>
<td>43</td>
<td>0.44</td>
</tr>
<tr>
<td>Ice crystal-column</td>
<td>47</td>
<td>0.56</td>
</tr>
<tr>
<td>Water droplet, radius 560 ( \mu m )</td>
<td>30</td>
<td>1.00</td>
</tr>
<tr>
<td>Water droplet, radius 560 ( \mu m )</td>
<td>20</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Value of radius, \( A \), and number of elementary charges, \( N_0 \), in the tip of a propagating positive corona streamer, estimated from the \( q/E \) relationships obtained for water drops and ice crystals, as described in section 2.

3. COLLECTION EFFICIENCY MEASUREMENTS

The experimental arrangement is shown schematically in Fig. 6. A stream of uniformly sized and charged collector drops, doped with \( \text{Co}^{++} \) ions in the form of hydrated
Figure 5. The measured variation with field strength $E (> E_0)$ of the charge $q$ deposited on ice crystals by direct interactions with positive corona streamers. $X$ is the longest dimension and $m$ the mass.

- $\bigcirc$, sector plate: $X = 3.0\, \text{mm}, m = 2.6\, \text{mg}$;
- $\bullet$, column: $X = 2.5\, \text{mm}, m = 1.0\, \text{mg}$;
- $\ast$, plate: $X = 2.5\, \text{mm}, m = 1.0\, \text{mg}$;
- $\times$, plate: $X = 2.0\, \text{mm}, m = 1.0\, \text{mg}$.

Cobaltous sulphate and coloured with lissamine rhodamine dye was generated by the device developed by Abbott and Cannon (1972). Drop radii $R$ were measured by impaction on a magnesium slide (May 1950) and were varied between 120 $\mu$m and 40 $\mu$m. Their charges, $Q$, fixed at 0.6 or 3 pC throughout the size range, were measured by the current to an electrometer sampling-electrode placed in their path. A small sample of the liquid, volume $s_x$ suitably diluted, was analysed to determine the concentration of dope in the drops. All chemical analyses were performed using an atomic absorption spectrometer with a flameless atomizer. This was capable of detecting 2 parts of dope-ion per $10^9$.

The drop stream was injected into a horizontal wind tunnel containing a monodisperse cloud of droplets of mean radius 12 $\mu$m generated by a spinning top device (May 1949) and doped with Mn$^{++}$ ions in the form of hydrated manganous sulphate.

The radii of the cloud droplets, $r$, were measured by impaction on a magnesium oxide coated slide inserted through a cloud-sampling porthole. The airborne dope concentration of the cloudy air, $L_{11}$, was also measured at this point by inserting a clean microscope slide of dimensions $b \times c$ for a measured time, $t$, and measuring the quantity
of accumulated dope. The airborne concentration of dope in the zone of interaction between drops and droplets, \( L_2 \), is then given by

\[
L_2 = L_1 (1 - f)(v/U)(W/H),
\]

where \( v \) is the sedimentation velocity of the droplets; \( U \) is the tunnel wind speed; \( W \) is the width of the cloud entry port into the tunnel; \( H \) is the height of the tunnel; and \( f \) is the fraction of drops lost to the tunnel floor and walls before the interaction zone is reached. An estimate of \( f \) was made for each experimental run by exposing a clean surface inside the tunnel and measuring the quantity of dope collected during the exposure.

After passing through the cloud the collector drops were recovered and washed into a sample bottle. Care was taken to minimize the contamination of this sample by cloud droplets that had not been captured by a collector drop. The collector drops passed through a small movable aperture in the floor of the tunnel, which was curtained by a jet of dry air directed across it. The drops fell into a region of high horizontal electric field and were captured on a clean cellulose acetate film covering the vertical high-tension electrode. The charge-to-mass ratio of the collector drops was typically two orders of magnitude higher than that of the cloud droplets, and in order still further to inhibit the cloud droplets from landing on the recovery electrode the spinning top generator was provided with a 9-volt charging ring which ensured that the cloud droplets all had a small negative charge. This charge (of the order of \( 10^{-16} \) C) was too small to affect the drop-droplet interaction (which was dominated in the conditions of the experiment by dipole forces) but was sufficient to provide a small force away from the high-tension electrode on which the collector drops landed.

The area of plastic film containing most of the collector drops (usually about 1 cm²), cut out and placed in a measured volume of dilute HCl, formed a primary sample for spectrometer analysis of both Mn⁺⁺ and Co⁺⁺, while a strip about 5 mm wide cut all round this area provided a sample used to estimate the degree of residual contamination by stray cloud droplets.

Samples prepared for analysis were acidified, stored in polythene and frozen until required, to prevent loss of ions by adsorption to the wall of the container. An advantage of the method of double-doping used was that it was unnecessary either to standardize the atomic absorption spectrometer or to count the number of droplets collected. The fact that the airborne dope concentration in the cloud and dope concentration in the collector
drops had been measured using the same instrument made the collection efficiency a simple function of the ratios of spectrometer readings and the volumes used for the dilution of samples. The collection efficiency is given by

\[ E_c = \frac{4}{3} \frac{R^3}{(R + r)^2} \frac{1}{W(1 - f)} \frac{U_{cbt} V_R}{s_r} \frac{\theta_R \phi_R}{V_r} \frac{\theta_r \phi_r}{V_r} \]

(2)

where \( V_R \) and \( V_r \) are the volumes used for the dilution of the collector-drop and airborne dope samples respectively, while the spectrometer readings for those two samples are \( \theta_R \) and \( \theta_r \), \( \phi_R \) and \( \phi_r \) are corrected spectrometer readings for Co\(^{++}\) and Mn\(^{++}\) present in the sample from the recovery box.

A full discussion of errors is contained in Barker (1978). The expression for \( E_c \) is long, and one of the main obstacles to precision in the measurement is the accumulation of a large number of random errors, even if individual error margins are kept reasonably low. The errors which are largest and which dominate the total error for \( E_c \) are in the spectrometer readings (estimated at \( \pm 10\% \)) and in the droplet radius \( r \) (typical dispersion value between 0.1 and 0.2). In addition to the measured quantities which occur in the equations for \( E_c \), the error in the setting of \( Q \) will also affect the precision of the corresponding measured value of \( E_c \).

The total probable random error was estimated at 25%. This does not take into account the effects of scatter in the values of \( Q \) and \( r \). There are insufficient data to make an estimate of these but it is likely that \( E_c \) is quite a sensitive function of \( r \).

In order to check for the presence of serious systematic error two runs were performed with \( Q \) about \( 2 \times 10^{-16} \) C, some three orders of magnitude lower than those used in the experiment. The collision efficiencies given by Mason (1971) for the drops used in these two experiments were 0.76 and 0.77, respectively. The experimental results obtained were 0.68 and 0.67 respectively. This is well within the margin of random error, so it was concluded that serious systematic errors were absent.

Results are presented in Fig. 7. An error bar, representing the 25% random error, has been drawn on one point only, to avoid cluttering the graph. The solid line represents the collision efficiencies of uncharged drops, taken from Mason (1971). This line is seen to fall well below the measured collection efficiencies for charged drops.

![Figure 7](image)

Figure 7. Measured collection efficiencies, \( E_c \), as a function of the radius, \( R \), of the collector drops, which carry a charge \( Q \). A specimen estimated uncertainty in \( E_c \) is shown. The solid line, for \( Q = 0 \), is from Mason (1971) for \( r = 13 \) μm.

- ●, \( Q = 0.6 \) pC;
- ▲, \( Q = 3 \) pC;
- ■, \( Q = 0 \)
4. COULOMB AND DIPOLE FORCES: THE CAPTURE MECHANISM

The enhanced growth rate of a highly charged drop is terminated by neutralization by cloud droplets of opposite polarity, and the effectiveness of the mechanism depends on how many cloud droplets can be captured before neutralization takes place.

Interactions between the drop and nearby cloud droplets consist of a coulomb component, $F_c$, due to the two charges $Q$ and $q$ and a dipole component, $F_d$, which results from the charges induced by $Q$ in the smaller drop. The dipole force is short-range and acts on all cloud droplets. The coulomb force has a longer range and, if it is an important component in the interaction, will tend to attract selectively the very particles which lead to a rapid neutralization of the drop.

If the ratio $Q/q$ is large enough, the distance at which coulomb forces dominate the dipole force is so great that the effect of these forces within the time available for the interaction is very small. By the time the droplet has approached the drop sufficiently for the electrical force to have a significant effect on its trajectory, the dipole interaction is the dominant force. Thus in the size range investigated the collection efficiency is enhanced for both positive and negative droplets.

In order to compare the effect of electrical forces on the trajectories of drops of opposite polarity we made a simplified trajectory calculation for a few representative

![Figure 8. Calculated trajectories of droplets of radius $r = 13\mu m$ and charge $q$ moving towards a drop of radius $R = 44\mu m$ and charge $Q = +0.6\ pC$ for various impact parameters $\sigma$. The circle is of radius $R + r$.](image)

A: $\sigma = 78\mu m, q = -1\ fC$
B: $\sigma = 78\mu m, q = 1\ fC$
C: $\sigma = 88\mu m, q = -1\ fC$
D: $\sigma = 92\mu m, q = 1\ fC$
cases. Our calculation included a Stokesian drag term for the motion of the smaller drop, but ignored the effects of air flow around the larger drop; its effect would be similar for similar droplet trajectories, and our response was to make a preliminary investigation of the effect of droplet polarity rather than to model the collision process precisely.

Following the method of Smith (1976) we took

\[
\begin{align*}
F_c &= \frac{Qq}{(4\pi \varepsilon_0 l)^2} \\
F_d &= \left(\frac{Q^2}{4\pi \varepsilon_0 \sigma}\right) \frac{(l - a)^2}{(r/l) - 1} \\
\end{align*}
\]

(3)

where \( l \) is the separation of drop centres and \( a = r^2/l \).

The expression for \( F_d \) underestimates the force at close range, when the gap between their surfaces is less than \( r \). We used the values of \( Q \) found for direct charging in our experiment, values of \( Q \) for indirect charging found by Phelps and Vonnegut (1970) and values of \( q \) taken by Takahashi (1973).

The results for representative directly charged drops are shown in Fig. 8. The impact parameter was initially chosen to be the value corresponding to the collection efficiency determined for this drop–droplet pair in our experiment. The effects of polarity are not negligible, but they are not large. As a rough indication it can be seen that a negative droplet approaching at an impact parameter of a little over 88 \( \mu \)m will follow a trajectory in the vicinity of the drop similar to that of a positive droplet approaching at an impact parameter of 78 \( \mu \)m. This represents a reduction of only 20–25% in collection efficiency for the positive droplets.

Figure 9 shows the same pair of droplets, but the charge on the larger drop corresponds to that acquired by indirect charging. It is striking how little the droplet path is affected by electrical forces in this case. When the charge on the droplet is positive the effects of the attractive dipole forces at close range balance roughly those of the coulomb repulsion it experiences further out.

We conclude that in the case of indirectly charged drops coulomb forces will play a more significant role in the initial stages of the collection process. In contrast, the greater value of \( Q \) on directly charged drops leads to a greater range of conditions in which dipole effects dominate those due to coulomb forces. It follows that a drop charged by direct collision can capture many unaffected cloud droplets without inhibiting its ability to capture more, and thus substantial growth is possible.

5. DISCUSSION

In this section we examine, by means of rudimentary calculations, the possibility that the rapid intensification of radar reflectivity which has been observed immediately following a lightning flash may be a consequence of enhanced coalescence rates associated with electrical forces. We select for consideration the observations of Szymanski et al. (1980), since these are the most detailed. They reported an intensification from less than 0.1 mm\(^6\) m\(^{-3}\) to about 25 mm\(^6\) m\(^{-3}\) in the first 25 s. At the end of this period the echo was moving downwards at about 12 m s\(^{-1}\). The initial echo was very weak, indicating that large particles were absent from this region of the cloud.

In the absence of electrical forces the rate of growth of a drop of original radius \( r \) falling with a velocity \( V = Kr \) (Chisnell and Latham 1974) through a cloud of liquid water content \( L \) is given roughly by \( r/r_0 = \exp \gamma t \), where \( \gamma = 0.5 KE_c(L/p_w) \); \( K \) is a constant, \( E_c \) the collection efficiency and \( p_w \) the density of water. The corresponding rate of increase of radar reflectivity is given by \( Z/Z_0 = \exp 6\gamma t \). If we take \( K = 8000 \) s\(^{-1}\), \( L = 1 \) g m\(^{-3}\), \( E_c \approx 0.7 \) and \( p_w = 10^3 \) g m\(^{-3}\) we find that after 25 s \( Z/Z_0 \approx 1.2 \), which is negligible compared with the 250-fold increase reported by Szymanski et al. at the end of this period.

If we take the same parameter values except for \( E_c \), which we now assume to be 3, as a consequence of the enhanced capture due to charges deposited on the drops by corona streamers, as described earlier, and if we assume additionally that the fraction, \( F \), of drops
in the volume of interest which are charged is equal to one, we find that at $t = 25$ s $Z/Z_0 \sim 2.5$, which is again negligible.

In the absence of enhanced electrostatic capture, no realistic parameter values can give an intensification which approaches that reported by Szymanski et al. Enhanced capture may be just about adequate if the liquid water content is very high ($\sim 8$ g m$^{-3}$), but such a value of $L$ is in direct conflict with the field evidence. Also, the reported rapid descent of the echo is not explained. The collection efficiency values reported in section 3 are clearly far too low to provide an explanation for the observed intensification.

An alternative possibility is the enhanced growth rate of charged drops, resulting from their increased velocities in the intense electric fields of thunderstorms at the time of breakdown. It can readily be shown, from the treatment of Gay et al. (1974), that a drop of radius 100 $\mu$m, carrying a charge of the magnitude obtained in the experiments described in section 2, will have a terminal velocity, $V$, of around 25 m s$^{-1}$ in a field of 4 kV cm$^{-1}$; a directly charged drop of radius 50 $\mu$m will have a terminal velocity of around 15 m s$^{-1}$. Gay et al. found that when the electrostatic forces greatly exceed the
gravitational forces the product $Vr$ is roughly constant; so if $F = 1$, and a directly charged drop grows by a factor $(250)^{1/6}, \sim 2.5$, without changing its charge, thus increasing its radar reflectivity by a factor of 250, its terminal velocity will have decreased by about the same factor. Thus a directly charged drop of original diameter $r_0 = 100 \mu m$ will reduce its speed from about 25 to 10 m s$^{-1}$ during its period of growth, while for $r_0 = 50 \mu m$ the reduction is from about 15 to 6 m s$^{-1}$. If $F < 1$ the factor is increased, but not greatly. Thus it appears possible that the rapidly descending echo observed by Szymanski et al. could have resulted from enhancement of the velocity of directly charged drops of original radius 50 to 100 \mu m. We now endeavor to determine, through a crude calculation, whether this mechanism can explain the observed rate of intensification of the radar signal.

We assume that a lightning stroke occurs at time $t = 0$ when (following Szymanski et al.) the radar reflectivity, $Z_0$, in its vicinity is 0.1 mm$^3$ m$^{-3}$. If $Z_0$ is more or less entirely a consequence of scattering from drops of radius $r_0 = 100 \mu m$, the largest particles in the spectrum, we find that the concentration, $N$, of such particles is about 1600 m$^{-3}$; the associated liquid water content is around $7 \times 10^{-3}$ g m$^{-3}$, which is small compared with the total value of $L$. If these large drops are charged at $t = 0$ by direct interaction with positive corona streamers, to a value given by the experiments described in section 2, they will be driven by the field ($E \sim 4$ kV cm$^{-1}$) at a velocity $V$ of about 25 m s$^{-1}$ and start to grow by collecting smaller drops, which we assume to be uncharged, on average. As mentioned earlier, $Vr \sim K'$, where $K'$ is a constant (equal to 25 cm$^2$ s$^{-1}$ for the particular case under discussion). Thus the rate of growth of these drops is given by

$$4\pi r^2 \rho_w dr/dt = \pi r^2 VE_c L = \pi r K'E_c L,$$

from which it follows that $(r/r_0)^2 = 1 + \beta t$, where $\beta = (K'E_c/2r_0^2)(L/\rho_w)$. If $F$ is the fraction of these larger drops which are charged by interaction with streamers, the associated rate of growth of radar reflectivity is given by $Z/Z_0 = F(1 + \beta t)^2$. Taking $\rho_w = 10^6$ g m$^{-3}$, $r_0 = 100 \mu m$ and $K = 25$ cm$^2$ s$^{-1}$ we find that if $F = 1$ the observed increase in $Z$ from 0.1 to 25 mm$^3$ m$^{-3}$ in 25 s is achieved if $\beta \sim 0.21$, which corresponds to $E_c L \sim 1.7$ g m$^{-3}$, which appears to be explicable in terms of the field observations (for example, Dye 1980) and laboratory measurements presented in section 3. If $F = 0.1$, the required value of $E_c L$ is $\sim 4$ g m$^{-3}$, which appears to be just within the bounds of possibility; and if $F = 0.01$ then $E_c L \sim 9$ g m$^{-3}$, which appears inconsistent with the evidence. We conclude that echo intensification may be explicable in terms of greatly enhanced velocities of directly charged drops in the intense fields of the thunderstorm, thereby increasing the coalescence rates. The major features of the observations of Szymanski et al. are reproduced in this crude analysis, but a proper test of the validity of this suggestion requires the determination of characteristic values of $F$. Barker (1978) performed an analysis which suggested that $F$ might decrease from around one in the vicinity of the channel to around 0.01 at distances of several hundred metres. More direct information on this point is required.

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