Airborne studies of electric fields and the charge and size of precipitation elements in thunderstorms

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SUMMARY

During the summer of 1976 the ONR/NMIMT research aeroplane was employed in studies of the electrical properties of thunderstorms. Flights through clouds were made in Florida, as part of the Thunderstorm Research International Project, and in New Mexico. The most important measurements were of electric field and the charge, \( Q \), and size, \( d \), of individual precipitation elements. A novel device was constructed for the \( Q \) and \( d \) measurements. The charge carried on a particle passing through a metal cylinder was sensed by induction, and its size by a shadowgraph technique involving a linear array of photo-diodes. The penetrations were generally through the lower regions of the clouds.

The major findings of the studies in New Mexico were as follows:

1. Volume charge densities on precipitation, \( \rho_p \), were often around \(-5 \text{nCm}^{-3}\) over horizontal distances of several kilometres. \( \rho_p \) was almost always negative, but positive charge densities, of lower magnitude, were occasionally observed over shorter distances. The major contribution to the measured values of \( \rho_p \) was made by particles of size around 1 mm, or smaller.

2. Simultaneous measurements of \( Q \) and \( d \) showed that no simple relationship existed between them. Charges of about 100 pC were commonly observed on particles around 1 mm in size. These are much too high to be explicable in terms of the inductive theory.

3. Positive and negative charges were found to coexist, except when the precipitation rate, \( p \), was very low. However, charge of one sign (almost invariably negative) was always strongly dominant.

4. Values of \( p \) could be estimated crudely from the \( d \) pulses. In regions of high \( \rho_p \) they were rarely in excess of 10 mm h\(^{-1}\); on some occasions when \( \rho_p \) was substantial \( p \) was below 1 mm h\(^{-1}\).

Our primary conclusions are that in the clouds studied substantial currents were often carried on precipitation, and that the charges on individual precipitation elements are not explicable in terms of the inductive mechanism of thunderstorm electrification.

1. INTRODUCTION

The importance of precipitation in generating strong electric fields in thunderclouds has been the subject of considerable recent discussion (for example, Mason 1976; Moore 1976). However, the issue is far from resolved. The major difficulty is the absence of comprehensive and reliable field data on the electrical structure and evolution of thunderstorms. In particular, there exists no detailed information concerning the charges carried by precipitation elements in thunderclouds, and the net current which these particles carry during their fall through the cloud.

Of the precipitation-based mechanisms of thunderstorm electrification the one that has received greatest attention and been most generally favoured in recent years has been the inductive mechanism (for example, Müller-Hillebrand 1954; Sartor 1967; Mason 1972; Scott and Levin 1975) under which rebounding collisions between large and small hydrometeors (hail pellets and ice crystals, pellets and supercooled droplets, raindrops and droplets) polarized in the electric field of the cloud result in charge transfer, followed by gravitational separation which enhances the electric field. These workers have concluded that this mechanism is readily capable of producing breakdown fields within the available time. On
the other hand, it should be stated that no direct experimental evidence exists for the operability of this mechanism over the ranges of conditions which are obtained in thunderstorms, and Moore (1965, 1976) has raised some possible objections which, if upheld, would diminish the efficacy of this charge transfer process, particularly for collisions involving droplets. Finally, we mention that recent calculations by Illingworth and Latham (1977), which take account of the finite dimensions of thunderclouds, suggest that of the various categories of inductive mechanism only the one involving ice–ice collisions is likely to be sufficiently powerful to be of possible importance in thunderstorm electrification – and then only if some uncertainties associated with contact and charge relaxation times are satisfactorily resolved.

This paper describes some airborne experiments on thunderstorms conducted during the summer of 1976 – in Florida, as part of the Thunderstorm Research International Project (TRIP), and subsequently in New Mexico, from the New Mexico Institute of Mining and Technology (NMIMT). The major tool in this study was the ONR/NMIMT Schweitzer aeroplane, which is described, together with the equipment that it carried, in section 2. A major objective of the studies was to measure the volume charge density on precipitation, \( \rho_p \), and the charge, \( Q \), and size, \( d \), of individual precipitation elements. This latter measurement was desirable because it afforded a direct test of the role played in these clouds by the inductive mechanism, under which the maximum charge \( Q_M (\text{pC}) \) that can be acquired by a spherical element of diameter \( d (\text{mm}) \) in a vertical field \( E (\text{kV cm}^{-1}) \) is given (Müller-Hillebrand 1954; Sartor 1967; and others) by

\[
Q_M = 5.5Ed^2. 
\]  

(1)

Since \( Q \), \( d \) and \( E \) were measured in these experiments the pattern of charges could be examined in the light of Eq. (1).

Considerable attention is devoted, in section (2), to a description of the design and testing of a novel device for the simultaneous measurement of \( Q \) and \( d \). Subsequent sections are concerned with the field experiments and the interpretation of the measurements obtained.

2. THE SCHWEITZER AEROPLANE AND ITS EQUIPMENT

The ONR/NMIMT Schweitzer aeroplane is illustrated in Fig. 1. It was originally a drone, but it has recently been modified to accommodate a pilot. Its particular virtue – which renders it excellent for these studies – is that it flies very slowly (around 40 ms\(^{-1}\)) and thus has minimal influence upon any cloud through which it passes. Its ceiling altitude is 13 km.

The electric field in three mutually perpendicular directions was measured using five appropriately sited field mills, four of which are shown in Fig. 1. Each of the three components of electric field was recorded on two separate sensitivity ranges, and the signals from each mill were telemetered to ground and stored on magnetic tape. They were also played out, in real-time, on an 8-channel hot-wire chart recorder. This procedure was adopted with all the electrical measurements made. The full-scale deflections for the measurements of vertical field strength, \( E \), were 300 V cm\(^{-1}\) on the insensitive range and 10 V cm\(^{-1}\) on the sensitive range. The uncertainty in the values of \( E \) was estimated to be \( \pm 20\% \). The determination of the axial (horizontal) component of electric field was less reliable in 1976 and none of the horizontal field measurements were utilized in our analysis of data.

Measurements were also made of airspeed, heading, air temperature, pressure altitude, and the electric field due to charge on the aircraft. The voice commentary from the pilot (Mr J. W. Bullock) was recorded on magnetic tape, and also heard in real-time at the ground station. Two-way radio communication between the pilot and a scientist at the ground
station played an important role in these experiments. A 'black rod', loaned to us by the Meteorological Office, was used to indicate whether or not ice crystals were present in the vicinity of the aeroplane. The device was slightly modified to permit its exposure through the perspex canopy over the cockpit. The pilot had an excellent view of the leading edge of the rod and would report through the voice channel on the presence or absence of specular reflections from ice crystals. At the end of each penetration the rod was drawn into the cockpit, inspected, wiped clean, and replaced in position. Verbal descriptions of the particles hitting the canopy were provided by the pilot, in his commentary to ground.

Various considerations had to be taken into account in designing the charge/size sensor. It is well known that high velocity collisions between hydrometeors (solid or liquid) and metals can give rise to the separation of large charges, in excess of those possessed by particles within clouds. Consequently it was necessary to be able to distinguish between these charge measurements and spurious ones resulting from collisions between hydrometeors and the charge sensor. It was also desirable to avoid saturation effects by minimizing the proportion of charging events which involve collisions. The charge was detected by induction as the hydrometeors passed through the inner of two co-axial cylinders located beneath the aircraft wing with their axes parallel to the airflow. The inner metal cylinder was connected to a charge amplifier, while the outer one was earthed to act as a screen and to give a rapid rise and fall of the induced charge on the inner cylinder as the hydrometeor entered and left it. The bandwidth of the aircraft telemetry limited to 1 ms the minimum pulse length whose amplitude could be faithfully transmitted to within 5%. The length of the inner cylinder was fixed at 8 cm which resulted in a pulse length of about 2 ms from the 'clean' passage of a hydrometeor at aircraft speeds. The time constant of the charge amplifier was 22 ms. A hydrometeor hitting the cylinder resulted in a waveform with a rapid rise followed by a 22 ms decay which could easily be distinguished from the 2 ms symmetrical pulse of a clean passage.

The depth of focus of the shadowgraph optics employed in hydrometeor sizing limited the maximum diameter of the induction cylinder to 5 cm. Had the cylinder been longer than 8 cm, then there would have been an unacceptable increase in the fraction of the hydrometeors colliding with it. This arises because the terminal velocity of the larger drops is
significant compared with the aircraft speed, and also because the airflow under the wing aerofoil may not be horizontal. With the chosen dimensions the induced charge on the cylinder is always more than 90% of the hydrometeor charge.

The calculations of the expected ranges of rate of receipt of charge pulses based on Eq. (1) and an assumed Marshall–Palmer size distribution of precipitation elements suggested that with these dimensions, the probability of confusion resulting from pairs of charged particles passing through the cylinder at the same time would be negligible.

False readings that would result from the sensing, by the cylinder, of charged particles passing between it and the outer, screening, cylinder were eliminated by wrapping round the outer surface of the sensor earthed foil – from which it was carefully insulated. The outer surface of this foil was also coated with insulation, in order to prevent short-circuiting resulting from the passage of water over it. In theory, the input impedance of the charge amplifier is very low and it should still function with a water bridge between the input and earth. However, small variations in the currents flowing through the water bridge due to contact potentials are sufficient to cause the amplifier output to oscillate randomly. The amplifier functioned normally when coated with ice.

Figure 2. The charge/size sensor flown on the aeroplane. The metal box houses the circuitry. The illumination system is housed on the right hand side. The inner cylinder is the charge sensor, and the outer one is for electrostatic screening.

The charge/size device flown on the aeroplane is illustrated in Fig. 2. Aluminium was used for the metallic portions and nylon for the insulating ones.

The size of hydrometeors passing through the induction cylinder was measured using a shadowgraph technique (Knollenberg 1970). Hydrometeors passing cleanly through a band of light directed perpendicularly to the axis of the induction cylinder, at its centre, produced an electrical pulse related, in a manner determined by calibration experiments, to its dimension in the direction perpendicular to the beam and to the axis of the cylinder. The shadow size was detected using a linear array of 64 photo-diodes (manufactured by IPL, Dorchester, England) spaced 100\,\mu m apart. Each photo-diode has an inherent capacitance in parallel with it and has a discharge rate dependent on the light intensity falling on it.
A 'Chicago Miniature' beam emitter was found to give the required parallel beam of homogeneous intensity across the diodes. The individual fully illuminated diodes gave an output of $5 \pm 0.5\text{V}$, but in shadow this always fell to 0V. The 64 diodes were scanned sequentially, each individual diode being sampled every 25\(\mu\text{s}\), the output being the integral of the total light incident since the previous scan. A 500\(\mu\text{m}\) diameter drop passing the array at 40\(\text{ms}^{-1}\) would interrupt the beam for 12.5\(\mu\text{s}\), so giving a voltage swing of only half the maximum. A large drop in the beam for more than a scan gives a train of pulses of varying width as the drop gradually moves through the beam.

The electronic circuit, shown in Fig. 3, gives a single pulse output of height proportional to the maximum diameter measured, and, when appropriate, a 'flag' to indicate that one of the end diodes has been obscured. When the output voltage variation across the array is sufficient to trigger the comparator, the following stage integrates the square wave output of the comparator to give a pulse height proportional to the width of the diodes blocked, the integrator being reset by a scan pulse which is present at the commencement of each scan of the diodes. A pulse height detector follows the integrator and stretches the pulse to the order of 5 ms. Thus if a train of pulses appears at the input to the circuit then the output is a single pulse the height of which is proportional to the maximum pulse width of the train. To obtain the flag which indicates that one of the end diodes is obscured the outputs of the comparator and the scan pulse are applied to an 'AND' gate. The first diode of the array is actually scanned when the scan pulse is present, and by introducing suitable delaying and stretching we can also arrange for this to be true for the last diode. The pulse output from the 'AND' gate is stretched to 1-0 ms, and then subtracted from the signal pulse as shown in Fig. 3.

The diode array was encapsulated in plastic along with a thermistor and two heating resistors in close contact with the array. The thermistor and resistors are connected in circuit. When the temperature of the diode and thermistor falls, current was switched through the resistors to bring the diodes back to a value of 16°C. This stopped the system from icing up during flight and evaporated within a few seconds the occasional drop which landed on the diode. Such an event in flight produced a temporary DC shift in the size pulse baseline. The encapsulated device was mounted in the housing shown in Fig. 2 to provide mechanical strength and to offer further protection against the weather. The bulb was similarly protected.

To test the complete device in the laboratory, airgun pellets, charged by friction in their journey along the barrel, were fired through the cylinder at a velocity of about 80\(\text{ms}^{-1}\), and the output waveforms viewed on a storage oscilloscope. These, together with the waveforms recorded in flight, show the device to have worked to specification.

The size sensor was also calibrated by inserting wires of known diameter into the light
beam illuminating the photo-diodes. It was found that because of imperfect collimation the size of the shadow cast on the photo-diodes (and thus the resulting pulse height) was larger than the object itself and varied with distance from the diodes. The diode response added a further constant offset of 2 mm to the calibration. As a consequence, the maximum size of particle that could pass through the beam without 'flagging' was about 4.4 mm instead of a theoretical 6.4 mm. For particles below 0.5 mm the triggering of the comparator depended on the position of the object within the beam and so no specific value of \( d \) could be assigned to them. The uncertainty in the measured values of \( d \) for particles larger than 0.5 mm was \( \pm 0.3 \) mm.

The sensitivity of the charge sensor was adjusted in the light of \( Q \) values measured in early flights in 1976 and a full-scale deflection of \( \pm 130 \) pC was adopted. In this situation the values of \( Q \) could be read to an accuracy of \( \pm 5 \) pC.

The charge/size sensor was mounted below a wing of the Schweitzer aeroplane.

3. THE FIELD EXPERIMENTS

The aeroplane, after being instrumented and tested in New Mexico, was flown to Florida in early June 1976 and employed in the TRIP experiments until mid-July. It then returned to NMIMT and the field research continued in New Mexico until the end of August.

In view of the novelty of some of the equipment mounted on the aeroplane a substantial fraction of the flight-time was consumed with instrument testing and in-flight calibration, especially in Florida. The general approach in the main experiments was to isolate an evolving cumulonimbus cloud at an early stage of its development and to make a succession of horizontal penetrations through it. The two-way voice communication system, together with the real-time display of electrical data on a chart recorder and a storage oscilloscope (for the \( Q \) and \( d \) pulses), proved to be advantageous in suggesting immediate modifications to the pre-arranged flight plan. Often, however, it was best to leave the choice of cloud and penetration level to the pilot.

Although some traverses were made at higher levels, instrumental constraints (which should be eliminated in subsequent seasons of these experiments) restricted the majority of penetrations to levels around cloud base. Useful information was obtained on about 10 flight days, but particularly comprehensive measurements (with all the major equipment operational) were confined to 3 days: 26 and 31 July and 9 August 1976. These three experiments were performed in New Mexico. The cloud bases on these days were at around +4°C, the corresponding altitude being about 12000 feet.

The role of the pilot was very important in these experiments, especially in view of the rapidity with which clouds could develop. We were fortunate that he had many years experience of flying in such conditions, that his verbal descriptions over the communications system were models of clarity and conciseness and that he did not baulk at flying into the most extreme situations, if they appeared to warrant investigation. His sketches and amplification of descriptions of flight details given in the debriefing session immediately following touchdown were also of great use. This information was reinforced by tape-recordings of voice broadcasts and photographs taken with cine-cameras mounted on the aeroplane and at a ground site.

We were also fortunate that no restrictions were placed on the times at which the aeroplane could be flown, either in Florida or in New Mexico. It was employed on all seven days of the week, at any time of day, and could take off within ten minutes of a decision to fly. The aeroplane was well maintained by the pilot and was not grounded at any time within the research period.
Although the charge/size device functioned reasonably well at the outset, certain problems were soon encountered which took two or three weeks to identify and resolve. However, it was fully operational towards the end of the TRIP period and throughout the subsequent weeks in New Mexico. A high level of background noise on the charge records was found to be associated with mechanical vibration, and the mounting was changed to minimize this effect. A tendency for the charge sensor to saturate in heavy precipitation was eventually shown to be principally associated with large spurious charge signals produced by impact between raindrops and the plastic coating employed to preserve the insulation of the earthed foil. Replacement of this coating with insulating tape was efficacious. Some low level of vibrational noise was always present on the \( Q \) records, but it did not significantly obscure the true \( Q \) pulses, which could readily be distinguished. Although charge saturation occurred sometimes, for periods of about 100ms, when high fluxes of charged particles entered the sensor, such events could readily be identified, and allowed for in computing \( \rho_p \). Thus it is likely that the values of \( \rho_p \) presented herein are somewhat conservative in the conditions of strongest electrification. Signals recorded by the charge sensor when a lightning strike occurred within the cloud were readily distinguishable from those due to precipitation elements. The rates of change of displacement current associated with other field changes were far too small to produce signals.

![Graph](image)

Figure 4. Tracing of a one-second stretch of charge (Q) and size (D) record obtained on penetration 3 of the flight on 9 August 1976. A, acceptable charge pulses; C, collisional (unacceptable) charge pulses; F, flag pulses.

Figure 4 shows a tracing of a one-second stretch of a characteristic charge/size record. It is seen that despite the presence of noise and baseline drift in the \( Q \) trace the acceptable pulses (A) are readily distinguishable from other excursions and those pulses produced by collisions (C). Both A pulses correspond to negative charges of about \( -50 \) pC. The size pulses (half of which were flagged, F, indicating that the particles passed through the edge of the beam) have negligible background noise. In the particular case illustrated all the particles were smaller than the lower acceptable limit of calibration (0.5 mm).
4. Results

Figures 5(a) and (b) present tracings from the strip-chart recorders obtained in two penetrations through precipitation in the lower regions of cumulonimbus clouds. They display the variations with time of vertical electric field strength, $E$, and precipitation charge density, $\rho_p$, discussed later. The words IN and OUT define the times of entry into and exit from precipitation, as indicated by the $Q$ pulse records. Although $Q$ pulses were observed continuously throughout these penetrations, there was often intermittency in the $d$ pulse records; this suggests that in some parts of the clouds measurable charges were carried on precipitation particles too small to be detected by the $d$ device. In these, and all other major penetrations, the particles, as described by the pilot, were preponderantly drops. In penetration 5(a) the field variations were complex, with both positive and negative fields, of maximum excursion close to the saturation values $\pm 300 \text{ Vcm}^{-1}$. In penetration 5(b) the

![Figure 5](image-url) Variations with time of vertical electric field $E$ and precipitation charge density $\rho_p$ during three penetrations of the lower regions of thunderstorms. (a) 26 July 1976, penetration 1, 13 400 ft, $+1^\circ$C. (b) 31 July 1976, penetration 2, 13 000 ft, $+2^\circ$C. (c) 9 August 1976, penetration 2, 12 500 ft, $+4^\circ$C. ‘IN’ and ‘OUT’ signify the times of entry into the precipitation, and exit from it, as revealed by the $Q$ pulses.

![Figure 6](image-url) Variations with time of vertical electric field $E$ and precipitation charge density $\rho_p$ during three penetrations of a thunderstorm on 9 August 1976. The penetrations were at 13 000 ft ($+2^\circ$C). (a) penetration 3; (b) penetration 4; (c) penetration 5. The sudden field change at L in (a) is probably due to lightning.
field was negative (a positive test-charge would move upwards), more-or-less constant, and just below the saturation value. The strip-chart speed (1 mm s\(^{-1}\)) was far too low to permit quantitative analysis of the \(Q\) and \(d\) pulses recorded on them, but it was useful nevertheless to have them presented. One advantage was that impressions of precipitation intensity and dominant sign of charge were presented in real-time. A second advantage was that malfunctioning of the \(Q/d\) device was revealed as it occurred and it was sometimes possible to take immediate remedial action.

The most informative penetrations were made on 9 August 1976, and field records for three of these are presented in Fig. 6. The penetrations were made very close to cloud base. The cloud was of several kilometres' horizontal extent at this level, and highly electrified (a field change probably resulting from lightning is indicated at point L in penetration (a)) with fields generally negative and of magnitude around \(-200\) V cm\(^{-1}\). The fields were never saturated in these penetrations.

Histograms of the charge distributions measured in 20 seconds of each of penetrations 3 and 4 on 9 August are presented in Fig. 7. They indicate the coexistence of charges of both signs, many more negative charges than positive ones, and very substantial individual charges (often \(-50\) to \(-100\) pC) on precipitation elements. These findings were characteristic of penetrations in which substantial numbers of charged particles were found over horizontal distances of a kilometre or more.

The corresponding size (\(d\)) histograms obtained in these sections of penetrations 3 and

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure7}
\caption{Particle charge \(Q\) and size \(d\) histograms obtained for twenty seconds of penetration 3 ((a) and (c)) commencing 1141 h 30 s and penetration 4 ((b) and (d)) commencing 1120 h 37 s on 9 August 1976. (a) 280 pulses, \(E = 230 \pm 10\) V cm\(^{-1}\), \(\bar{d} = -17\) C km\(^{-3}\). (b) 226 pulses, \(E = 220 \pm 10\) V cm\(^{-1}\), \(\bar{d} = -5.5\) C km\(^{-3}\). (c) 100 pulses, of which 56 not displayed as too small for accurate \(d\) determination. (d) 61 pulses, of which 44 not displayed as too small for accurate \(d\) determination.}
\end{figure}
4 on 9 August are also presented in Fig. 7. It is seen that the particles are quite small, being generally below 1 mm in diameter. In addition, many $d$ pulses were observed which were smaller than the lower limit (0.5 mm) for which the calibration is considered acceptable. These are not included in the figures. These findings were characteristic of penetrations in which substantial numbers of significant $Q$ pulses were found.

It should be noted that the acceptance area for $d$ pulses was only about $\frac{1}{4}$ of that for $Q$ pulses. It should also be stressed that coincident $Q$ and $d$ measurements were made for only a minor fraction of the pulses incorporated into these, and similar, histograms. The great majority of the $Q$ and $d$ pulses had no unequivocally identifiable companions. Information on $Q-d$ coincidences is presented later in this section.

In Figs. 5 and 6 the variation with time of precipitation charge density $\rho_p$ is presented, and mean values, $\bar{\rho}_p$, are quoted for the histograms constituting Fig. 7. $\rho_p$ is defined by the equation

$$\rho_p = \sum \frac{N_t Q_t}{A U \tau},$$

where $N_t$ is the number of particles of charge $Q_t$ detected in a time interval $\tau$; $A$ is the acceptance area of the cylinder for true pulses; and $U$ is the speed of the aeroplane. $A$ is less than the internal cross-sectional area $\pi D^2/4$ of the charge-sensing cylinder for two reasons. The first is that particles are of finite size, $d$, and can only enter the cylinder without colliding with it if their centres are less than a distance $\frac{1}{4}(D-d)$ from the axis. Secondly, the particles have a terminal fall velocity, $V$, which prohibits those entering the lowest regions of the cylinder from passing through it without touching the inner surface. Analysis of these two effects shows that

$$A(\frac{1}{4}\pi D^2) = (2/\pi)(1-d/D)^2\{\cos^{-1}\theta - 2\theta(1-\theta^2/2)\}.$$  

(2)

where $\theta = Vt/U(D-d)$. Taking a mean $d = 1$ mm, $V = k d$ (where $k = 3000$ s$^{-1}$), $U = 48$ m s$^{-1}$ (typical in New Mexico), $l = 80$ mm and $D = 50$ mm, we find that $A(\frac{1}{4}\pi D^2) = 0.78$, whereupon $A = 1500$ mm$^2$. It was reassuring to find that the observed ratio of collisional to acceptable charge pulses was close to that predicted on the assumption that the particle trajectories through the induction cylinder were unaffected by its misalignment or turbulence.

The precipitation current density $j$ is given by $j = \rho_p \bar{V}$, where, as before, it was assumed that $\bar{V} = 3$ m s$^{-1}$, corresponding to $d = 1$ mm. It is estimated that the values of $j$ and $\rho_p$ calculated were correct to within a factor of two.

The figures show that $\rho_p$ is nearly always negative – and is consistently negative for the three penetrations 3, 4 and 5 on 9 August, when the highest values of $\rho_p$ and $j$ were found. The averages $\bar{\rho}_p$, $j$, and $E$ for these five penetrations are presented in Table 1, together with values of $\Delta t$, the period of penetration, $\Delta X$ its horizontal extent ($\Delta X = U\Delta t$), and total precipitation current, $\bar{I}$, defined by

$$\bar{I} = \frac{1}{4}\pi (\Delta X)^2 j.$$  

(3)

It is seen that over horizontal distances of several kilometres the mean precipitation charge densities are around $5 \text{Ckm}^{-3}$ (or $5 \text{nCm}^{-3}$) and $\bar{I}$ can be several tenths of one amperes.

Table 1 also presents mean values of the precipitation rate $p$. This is defined by the equation

$$p = \frac{1}{6}\pi (\rho/\rho_w) \sum \frac{n_t d_t^3}{A} V_t$$  

(4)

where $\rho$ is the density of the particles, $\rho_w$ is the density of water, and $n_t$ is the number of particles per unit volume of diameter $d_t$ and terminal velocity $V_t$. However, in calculating $n_t$ and the associated rainfall rate $p$ from the $d$ pulse records it is necessary to take account of the decreasing probability that larger particles will pass cleanly through the light beam illuminating the photo-diodes.
TABLE 1. MEAN VALUES OF VERTICAL ELECTRIC FIELD, $\bar{E}$, PRECIPITATION CHARGE DENSITY, $\rho_p$, PRECIPITATION CURRENT DENSITY, $\bar{j}$, PRECIPITATION RATE, $\bar{p}$ AND TOTAL PRECIPITATION CURRENT, $\bar{I}$ (DEFINED BY EQUATION (3)) FOR THE 5 PENETRATIONS LISTED. THESE WERE OF DURATION $\Delta t$ AND HORIZONTAL EXTENT $\Delta X$.

<table>
<thead>
<tr>
<th>Date</th>
<th>Penetration</th>
<th>$\Delta t$ (s)</th>
<th>$\Delta X$ (km)</th>
<th>$\bar{E}$ (V cm$^{-1}$)</th>
<th>$\rho_p$ (C km$^{-3}$)</th>
<th>$\bar{j}$ (mA km$^{-2}$)</th>
<th>$\bar{p}$ (mm h$^{-1}$)</th>
<th>$\bar{I}$ (mA)</th>
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<tbody>
<tr>
<td>26.vii.76</td>
<td>1</td>
<td>55</td>
<td>2.64</td>
<td>?</td>
<td>-1.2</td>
<td>-3.5</td>
<td>5.8</td>
<td>19</td>
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<tr>
<td>31.vii.76</td>
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<td>33</td>
<td>1.58</td>
<td>-250</td>
<td>-2.0</td>
<td>-6.0</td>
<td>1.7</td>
<td>12</td>
</tr>
<tr>
<td>9.viii.76</td>
<td>3</td>
<td>152</td>
<td>7.30</td>
<td>-86</td>
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<td>-16</td>
<td>14</td>
<td>670</td>
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<tr>
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<td>-12</td>
<td>7.7</td>
<td>64</td>
</tr>
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</table>

The values of mean rainfall rate $\bar{p}$ presented in Table 1 must be treated with great circumspection, even though they are averages over traverses of appreciable length. This is principally because the sampling rate is so low, especially for the larger particles. It is doubtful whether the values of $\bar{p}$ quoted can be accepted to within a factor of two. They are seen, in these five penetrations, to be around 5 to 10 mm h$^{-1}$. However, in some shorter cloud traverses, where values of $\rho_p$ were still substantial (around 1 or 2 C km$^{-3}$) the measured rate of receipt of pulses (and the size of the drops detected) were so small that although it would be meaningless to attempt to calculate an accurate value of $\rho$, it can be asserted that the rainfall rates were below 1 mm h$^{-1}$.

The rate of occurrence of measurable charge-size coincidences was not great, in comparison with those of unpaired $Q$ pulses, in part because the acceptance area for $d$ pulses was much less than that for $Q$ pulses, especially for the larger drops. In addition, many of the coincidences observed involved $d$ pulses smaller than the reliable limit of calibration. In fact, it was commonly observed that there were no $Q$ pulses (true or collisional) associated with $d$ pulses; and conversely, that there were sometimes long sequences of true $Q$ pulses without any associated $d$ pulses. The typical interval between consecutive $Q$ pulses (which were generally more frequent than $d$ pulses) was about 100 ms, whereas a pair of $Q$-$d$ events were defined as coincident if they were separated by less than 2 ms. Thus one can be sure that the measured $Q$-$d$ coincidences were truly correlated events. The coincidences obtained for two particularly extensive penetrations on 9 August are displayed in Fig. 8; those involving

![Figure 8. Charge-size ($Q$-$d$) coincidence events measured during penetrations 3 (○) and 4 (●) on 9 August 1976. 60 coincidences are not displayed because the $d$ pulses were below the limit of reliable calibration. 2 positive coincidences are not plotted. Curve A. Rayleigh disintegration criterion. Curve B. Maximum change $Q$ produced under inductive mechanism (Eq. (1)) in positive breakdown field of 3 kV cm$^{-1}$. The uncertainty in $d$ was ±0.3 mm and in $Q$ ±5 pC.](image-url)
$d$ pulses below the reliable limit of calibration are excluded. It is apparent from the figure that no simple relationship exists between $Q$ and $d$. Furthermore, charges carried on the drops are usually much greater than the maximum that they could acquire (curve B, deduced from Eq. 1) under the inductive mechanism, even when operating in a breakdown field of 3 kV cm$^{-1}$. In fact, the sign of the charge on the particles (negative) is opposite to that predicted by the inductive mechanism since the field was negative in these lower regions of the thunderclouds; though if the field was positive at higher levels inductive charging could explain the sign of the measured charges. A substantial number of $Q$ values were close to the Rayleigh bursting threshold (curve A), particularly for the smaller drops.

The five major penetrations, listed in Table 1, involved about 400 seconds (about 20 km) of flight through precipitation near cloud base and revealed, consistently, net negative charge on the particles. The mean value of $\rho_p$ for these five traverses was 3.9 C km$^{-3}$. However, penetration 2 on 9 August, which was made through mixed ice and water particles of small size, provided a departure from this pattern. It is illustrated in Fig. 5(c). 24 seconds of $Q$ pulses which were exclusively negative were followed by a similar period within which the pulses were exclusively positive. There were 42 negative pulses in the first interval and 108 positive ones in the second. The mean value of $\rho_p$ for the complete penetration was +0.35 C km$^{-3}$. The abrupt transition from negative to positive charge is seen to be coincident with the change in sign of the horizontal gradient of $E$. There were only six $d$ pulses measured during this penetration, and although it would be ridiculous to attempt to estimate the precipitation rate, it must have been well below 1 mm h$^{-1}$. The pilot reported that no precipitation was observed during this penetration.

A number of other penetrations made on 26 and 31 July and 9 August 1976 have been analysed, in part at least. In general, these either involve low precipitation currents and rates or are difficult to interpret unequivocally. It can be stated, however, that the general conclusions drawn from the records discussed in this section are unaffected. These are that high precipitation charge densities (in excess of 1 C km$^{-3}$) are always negative, that individual particle charges in the range 30 to 100 pC are commonly found, that most drops carrying detectable charges were around 1 mm in size, or less, and that precipitation rates did not exceed about 10 mm h$^{-1}$ (averaging over a penetration) and were often much smaller.

5. Discussion

The field experiments described in this paper were seriously limited in several respects. No information was obtained concerning the dynamical structure and evolution of the clouds investigated. Most penetrations were made through the lowest regions of the clouds, whereas the major electrical activity is likely to have occurred at substantially higher levels. The spatial relations between the sections of the clouds studied and the precipitation and lightning centres were unknown. Measurements were made during each traverse only along a single line. And finally, with the exception of the black rod and the voice commentary of the pilot, no information on the microphysical properties of the clouds was available. In the final two summers of these experiments (1977 and 1978) these deficiencies should be substantially remedied. Radar coverage of the clouds will be made, the balloon-borne field-measuring equipment devised by Winn and Byerley (1975) will be employed in the same clouds, penetrations will be made by the Schweitzer aeroplane at higher levels, a network of precipitation collectors will be located beneath the clouds, and it is planned to install on the aircraft equipment to measure precipitation charge density (directly), liquid water content, precipitation water content, and the size distributions of liquid and solid hydrometeors. In addition, refinements to the $Q/d$ sensor should increase the sampling rate for both charge and size pulses by a factor of about ten.
Despite the limitations of the 1976 studies some tentative conclusions related to the major questions defined in section 1 can be drawn:

The charge densities on precipitation were sometimes as high as 5 or 10 C km\(^{-3}\) over horizontal distances of several kilometres. In these situations \(\rho_p\) was always negative, and the associated precipitation currents (if flowing also at higher levels) would be such as to enhance the electric field in the central regions of thunderclouds; they are locally dissipative near cloud base. Such values of \(\rho_p\), measured in clouds which were highly electrified but were not (in general) producing lightning during the periods of penetration, approach those calculated by Illingworth and Latham (1977) to be sufficient to produce breakdown fields in thunderclouds. However, we do not have sufficient evidence to establish whether the precipitation played a significant role in the electrification of the clouds studied, or whether these high values of \(\rho_p\) are characteristic of summer thunderstorms over New Mexico.

The individual charges on precipitation elements are commonly so much in excess of the values predicted by Eq. (1) that it does not seem possible that the inductive charging mechanism played a significant role in the clouds investigated. Although a minor fraction of the \(Q-d\) coincidence measurements may have been made in clear air close to cloud base, rather than in cloud, calculations show that increases in \(Q/d\) values resulting from partial evaporation would be negligible. No evidence was found for the \(Q/d^2\) pattern of charging predicted by the inductive mechanism.

The great majority of the precipitation particles carrying substantial charges were small (of diameter around or below 1 mm). The mechanism by which they became charged remains an open question.

In the regions flown through, the charges on precipitation elements were generally negative and the electric field was negative (i.e. in opposition to the fine weather field). Thus the electric force on the particles acts in the same direction as gravity and no possibility of levitation exists. However, it is possible that at higher levels within the cloud the fields were positive and, in some regions, close to breakdown values. In such circumstances most of the particles whose \(Q-d\) values are displayed in Fig. 8 carry charges sufficiently high for levitation to occur. However, this possibility does not appear to be inconsistent with our observations. There is a body of recent evidence suggesting that the regions of intense field are highly localized, so that field growth towards breakdown can continue even if levitation is occurring in certain regions of the cloud.

Although gross uncertainties are attached to the estimation of rainfall rates from the size sensor flown on the Schweitzer, it seems safe to state that substantial precipitation charge densities (∼5 C km\(^{-3}\)) were often found when \(p\) was not significantly in excess of

![Figure 9](image)

**Figure 9.** Measured values of number of \(d\) pulses (\(n\)), fraction of \(Q\) pulses that are positive (\(N_+/N_T\), ○), and fraction of total charge that is positive (\(Q_+/Q_T\), ●) for equal time intervals during the whole of penetration 4 on 9 August 1976. On four occasions \(N_+/N_T = Q_+/Q_T = 0\) when no \(d\) pulses were observed.
10 mm h\(^{-1}\); and that \(p_F\) was often appreciable (\(\sim 0.5 \text{Cm}^{-3}\)) when \(p\) was well below 1 mm h\(^{-1}\).

Finally, we consider the finding that except when the precipitation rate was very small, a mixture of positive and negative charges existed, although charge of one sign (almost invariably negative) was predominant. This could be a consequence of the simultaneous operation of two charging processes (one much more powerful than the other), but it is attractive to contemplate the possibility, raised by Levin (1976), that the presence of the minor sign of charge (positive) is simply a result of mutual interactions of the precipitation particles. If this is so, one would expect the proportion of drops of the minor sign to increase with increasing concentrations of particles (and thus higher interaction rates). This idea has been tested for several penetrations, an example being presented in Fig. 9. It is found that despite considerable scatter, probably associated with low rates of sampling of \(d\) pulses, the proportion of positively charged drops increases with increasing particle concentration. Thus it appears possible that the existence of a mixture of positive and negative charges on precipitation elements is a consequence of their mutual collision and separation.

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