Charge separation in a Florida thunderstorm

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SUMMARY

A simple explanation of the location and movement of the breakdown region in a Florida storm is given in terms of the separation resulting from dynamical equilibria between aerodynamic and electrostatic forces on charged particles.

1. INTRODUCTION

The storm discussed in this analysis occurred at about 1900 GMT on 13 August 1978 in the Titusville-Cocoa Airport, Florida. Observations on this thunderstorm appear to be the most complete of any measurements made to date. They were made by three groups led by Lhermitte, Krehbiel and Lennon working together, and the results have been discussed by Lhermitte and Krehbiel (1979). The main features of the observations are summarized briefly as follows. (1) Lightning activity was observed to be associated with a single updraught column for which Doppler radar velocity measurements were obtained. (2) Radar echoes provided locations of precipitation intensities. (3) Lightning Detection and Ranging (LDAR) measurements gave the locations and times of electrical breakdown bursts during the storm. (4) Field change measurements showed that electric moment changes, associated with six intercloud (IC) flashes, were correlated in space and time with definite breakdown bursts located by LDAR. Results from all four techniques are given by Lhermitte and Krehbiel (1979) and by Krehbiel (1981), and will be used as the basis for the present analysis.

2. BASIC INFORMATION

Approximate (smoothed) curves of air velocities $v$, height in the updraught column are shown for specific times in Fig. 1. These velocities were obtained directly from Lhermitte and Krehbiel's contours of maximum air velocity, expressed in an altitude-time plot. It is difficult to attribute errors to the velocities represented by the curves, which were drawn through values obtained from
intercepts of already smoothed velocity contours and time lines. As originally determined, the
velocity measurements were probably accurate to 1 m s\(^{-1}\) and the heights to 0.3 km. Undoubtedly, the
relative accuracies of the curves are sufficient to justify the conclusions drawn.

Probably one of the most outstanding results of the Florida experiments was the observation of a spectacular increase in the LDAR breakdown rate, which at approximately 1907 GMT suddenly increased to 60 events/min and continued at this rate until about 1910 GMT. During this interval the LDAR bursts were largely confined to a narrow height region of approximately 1.5 km thickness, which was located near the top of the updraught column and which rose from a height of 8.5 km at its centre at 1907 GMT to a height of approximately 10.0 km at its centre at 1910 GMT. From available data the velocity of rise of the active LDAR region was approximately constant at (9.5 ± 1.7) m s\(^{-1}\); Lhermitte and Krehbiel commented that the region of maximum LDAR signal intensity moved up at the same rate as the updraught maximum. The regions of these intense LDAR burst rates are shown by double lines on the velocity vs. height curves of Fig. 1, where the ends of the double lines are probably uncertain to some 0.5 km; see Lhermitte and Krehbiel (1979) for further details.

3. **Charge Separation Model**

The LDAR measurements taken from 1907 to 1910 GMT suggest that the positive and negative charge centres were held in a state of constant separation, creating a field between them which was sufficiently strong to cause breakdown. It is suggested that this quasi-steady state is a corollary of the location of the breakdown region in a part of the updraught exhibiting decreasing vertical velocity with height.

Let us assume that from 1907 to 1910 h all the particles retain unchanged terminal velocities and that the electric field in the separation region is constant. Let us denote the terminal velocities of particles in the positive and negative charge centres by \(u_+\) and \(u_-\), respectively, and denote the vertical air flow velocities at the upper and lower heights of the LDAR breakdown region by \(u_0\) and \(u_0\), respectively. It is then obvious that, for \((u_0 - u_-)\) to have had the same value as \((u_+ - u_-)\), as indicated by the fact that the thickness of the LDAR region remained constant during this period, then \((u_0 - u_+)\) must have equalled \((u_0 - u_0)\); i.e. approximately 2.3 to 3.9 m s\(^{-1}\), as derived from the decrease of air velocities in double line regions of Fig. 1.

Calculated terminal velocities of particles of different radii are given in Table 1, both for zero electric field and for a breakdown field of 3 kV cm\(^{-1}\). These velocities were calculated using standard techniques, e.g. using the standard method for evaluating drag coefficients (Mason 1971), and using typical values for the mass densities and sizes of the particles, and for the air density expected at the height of the Florida storm. Particle charges were calculated from the formula \(q(nC) = 2\pi \rho\), where \(r\) is the radius of the particle in centimetres (Latham 1981). The terminal
TABLE 1. PARTICLE TERMINAL VELOCITIES

<table>
<thead>
<tr>
<th>Particle radius (mm)</th>
<th>Terminal* velocity ((E = 0)) (cm (s^{-1}))</th>
<th>Particle charge (pC)</th>
<th>Terminal** velocity ((E = 3\text{kV cm}^{-1})) (cm (s^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>crystal 0.075</td>
<td>-41</td>
<td>+0.1125</td>
<td>-113</td>
</tr>
<tr>
<td>pellets 0.20</td>
<td>-171</td>
<td>-0.80</td>
<td>+116</td>
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<tr>
<td>0.30</td>
<td>-267</td>
<td>-1.80</td>
<td>-42</td>
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<tr>
<td>0.40</td>
<td>-355</td>
<td>-3.20</td>
<td>-183</td>
</tr>
<tr>
<td>0.60</td>
<td>-525</td>
<td>-7.20</td>
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</tr>
<tr>
<td>0.90</td>
<td>-750</td>
<td>-16.20</td>
<td>-616</td>
</tr>
<tr>
<td>1.30</td>
<td>-1015</td>
<td>-33.80</td>
<td>-894</td>
</tr>
</tbody>
</table>

*Negative velocities vertically downward
**\(E\) field vertical and downward on + charge

velocities in Table 1 depend on the characteristics of particles and fields in a very complicated way. The velocities are directly proportional to the square root of the sum of the weights of the particles and the electrostatic forces on the particles, and inversely proportional to the square root of the drag coefficients, the density of the air, and the cross-section of the particles. So many factors are involved in the choice of the characteristics of the particles and of the aerodynamics as to preclude a useful error analysis; suffice to note that plausible assumptions yield self-consistent results overall.

The value of the internal field at which breakdown occurs in a thundercloud has been discussed thoroughly by Latham (1981) who concluded that breakdown commences between 3 and 4 kV/cm. Arbitrarily, we have chosen the smaller value. The dependence of terminal velocity on field value differs from particle to particle, but some indication of the sensitivity is shown by a comparison of the values in two columns of Table 1.

In all cases in this paper, the direction of the \(E\) field vector has been assumed vertically downward. Krehbiel's (1981) data on the directions of the field change vectors in the six IC flashes indicate that these directions are downward to within approximately 5 or 10° of the vertical. Another complication arises, however, if the drag is not vertical. The evidence from Lhermitte and Krehbiel indicates that the updraught could have been inclined up to about 15° from the vertical. It is to be expected, therefore, that there will be uncertainties to the extent of \(\cos 15°\) (about 5%) in any comparison with real data. Uncertainties in air velocities with respect to height are, however, much larger.

It is seen from Table 1, that if it is assumed that the positive charge centre was comprised of ice crystals having a terminal velocity of \(-113 \text{ cm s}^{-1}\), and if it is assumed that a breakdown field of \(-3\text{kV cm}^{-1}\) is constantly present, then the negative charge centre, in the Florida storm, was located in the vicinity of the ice pellets having radii 0.6-0.9 mm.

An interesting question is why the highly active LDAR period was confined to between 1907 and 1910 GMT. This question can be partly answered in terms of the profiles of terminal velocities and the air velocity \(v\) height. For example, the 1905–06 h profiles (Fig. 1) are strikingly different from the 1907–10 h profiles. Thus, the maximum values of the 1905–06 h curves are significantly lower than those of the 1907–10 h curves, and the decreases of velocity with height are significantly steeper in the 1905–06 h curves at larger heights than the maxima. Both of these qualities are not conducive to a stable separation of charge centres because a large fraction of negative charge is still not being lifted by the updraught above the maximum air velocity heights, and also because the positive charges are apparently too close to the negative charges. However, a time element is also probably involved, for it takes a certain duration of separation of charges to build up a breakdown field. This feature will be discussed in a later note dealing with concentrations of charges in the storm.

At later times, after 1910 GMT, the fact that high LDAR activity was not observed is undoubt- edly attributable to the weakening of the updraught. At 1911 GMT, for example, the maximum air velocity had fallen to 16 ms\(^{-1}\) and the velocity over 15 ms\(^{-1}\) extended over a wide region from approximately 7.5 to 11.2 km. At 1912 GMT, the maximum air velocity was only 12 ms\(^{-1}\). As will be clear from later discussion, these velocity conditions allow the slippage of negative charges
below the maximum air velocity heights into a region of the updraught where the heavier negatively charged pellets may have downward velocities relative to the ground.

4. **Particle locations**

Using Table 1, a simplified diagram of the locations of particles in the breakdown region can be constructed. For 1907 GMT, such a diagram is shown in Fig. 2. This construction was begun by placing the positive (ice crystal) centre at 10-km. At this height, the upward vertical air velocity read from the 1907 GMT curve (Fig. 1) was 1130 cm s\(^{-1}\). For a terminal velocity of 113 cm s\(^{-1}\), the

<table>
<thead>
<tr>
<th>km</th>
<th>mm</th>
<th>cms(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.075</td>
<td>113 + 1130</td>
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<td></td>
<td>0.40</td>
<td>183 + 1200</td>
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<td>376 + 1393</td>
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<tr>
<td></td>
<td>0.90</td>
<td>616 + 1633</td>
</tr>
<tr>
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<td></td>
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<tr>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.30</td>
<td>894 + 1191</td>
</tr>
</tbody>
</table>

Figure 2. Derived particle distribution v. height in breakdown region of the updraught at 1907 GMT. Values of particle group radii (between vertical lines) and of terminal and air velocities of groups correlate with Table 1 and with Fig. 1 at 1907 GMT.

The actual velocity of the positive particles relative to the ground was therefore 1017 cm s\(^{-1}\). This value is close to the observed velocity with which the upper end of the breakdown region advanced. Height locations of the other particle groups in the Fig. 2 construction were easily determined by correlating air and terminal velocities which had a constant advance velocity of 1017 cm s\(^{-1}\).

The groups of particles in Fig. 2 should not be regarded as located more accurately than an estimated ½ km, since their evaluations are based on an air velocity v. height profile which has similar errors. Also the high precision of the terminal and air velocities in Fig. 2 have been retained purely for the pedagogical reason of ensuring that the velocity of advance of the whole system of particles had a constant value, shown equal to 1017 cm s\(^{-1}\). It is further important to emphasize that the location of the head (i.e. the ice crystal bin) of the system of particles at 10 km was chosen to be consistent with two observational requirements: (1) that the upper height limit of the active LDAR region was close to 10 km; (2) that the advance upward of the whole LDAR region, observed to be close to 10 ms\(^{-1}\), had to be compatible with the air velocity v. height curve at 1907 GMT and location of the ice crystal bin of particles at that time.

The distribution in Fig. 2, since it does not include particle concentrations, gives little detail of the actual charge distributions, except that there appears to be a narrow band of positive charge at the head of the system of particles and a wider distribution of negative charge in the lower
sections. A study of the concentrations of positive and negative charged particles will be presented later in a separate note. It is worth remarking, however, that all charged particles become more widely dispersed than merely being at the equilibrium locations shown in Fig. 2. The reason is that particles are continually streaming towards their equilibrium locations. In particular, it is found that concentrations of positive charges at 1907 GMT dominate over negative charges down to at least 9 km. It may be noted that the 0-2 and 0-3 mm groups are not represented in Fig. 2. It will be shown in the later note that these groups are completely dominated by the ice crystal group and its positive charge density will be reduced slightly thereby.

In somewhat broad outline at this stage, therefore, the Fig. 2 distribution is consistent with the observations that the active LDAR region and the IC discharges occurred between 7 and 10 km at 1907 GMT. The vector electric moment changes calculated by Krehbiel for the six IC discharges which occurred close to 1907 GMT originated at (9.7 ± 0.5) km and ended at (6.2 ± 0.6) km. The LDAR bursts at 1907 GMT given by Lhermitte and Krehbiel showed predominant activity between 8 and 9.5 km.

5. Conclusion

In this note it has been demonstrated that the positive and negative charge centres in a thunderstorm could have resulted from aerodynamic separation of charged particles in a strong updraught, in the presence of an electric field which caused breakdowns responsible for VHF radiation signals and IC lightning flashes.

Acknowledgment

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References


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