

The Effects of Charge and Electrostatic Potential on Lightning Propagation

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ABSTRACT: Three-dimensional lightning mapping observations are compared to cloud charge structures and electric potential profiles inferred from balloon soundings of electric field in New Mexico mountain thunderstorms. The comparisons consistently show good agreement between the altitudes of horizontal lightning channels and the altitudes of electric potential extrema or wells. Lightning flashes appear to deposit charge of opposite polarity in relatively localized volumes within the preexisting lower positive, midlevel negative, and upper positive charge regions associated with the potential wells. The net effect of recurring lightning charge deposition at the approximate levels of potential extrema is to increase the complexity in the observed storm charge structure. The midlevel breakdown of both normal intracloud flashes and negative cloud-to-ground flashes is observed to be segregated by flash type into the upper and lower parts of the deep potential well associated with the midlevel negative charge. The segregation is consistent with perturbations observed in the bottom of the negative potential well due to embedded positive charge that was probably deposited by earlier flashes. It is also consistent with an expected tendency for vertical breakdown to begin branching horizontally before reaching the local potential minimum. The joint observations reconcile the apparent dichotomy between the complex charge structures often inferred from balloon soundings through storms and the simpler structures often inferred from lightning measurements.

1. INTRODUCTION

This poster will present information and conclusions from *Coleman et al.*, 2003, in addition to some subsequent work. In that study, we addressed the question, “After a lightning flash is initiated in a cloud, what controls where various branches of the flash go?” From visual observations we know that both cloud-to-ground (CG) flashes and intracloud (IC) flashes have branches with substantial horizontal extents. Measurements from electric field change arrays and radar, radio, and acoustic mapping of lightning [e.g., *Pierce*, 1955; *Ogawa and Brook*, 1969] have provided ample evidence that many lightning flashes travel predominantly horizontally. Recent high-resolution interferometric observations by *Shao and Krehbiel* [1996] also show that many IC flashes have a relatively short vertical channel connecting two extensive horizontal regions of discharge, which often contain a number of horizontal branches. Their measurements indicated that IC flashes begin with “upward propagating negative breakdown” followed “after a time delay” by radiation associated with previously undetected positive polarity breakdown. Presumably the two polarities of breakdown were initially driven by the primarily downward pointing electric field (E) commonly seen between the main negative and upper positive charge regions [e.g., *Winn et al.*, 1978; *Stolzenburg et al.*, 1998a, 1998b, 1998c]. In this presentation we will attempt to show a relation between these horizontal lightning branches and electric field soundings taken during the thunderstorm.

2. DATA DESCRIPTION

The data presented herein were acquired during the Studies of Electrical Evolution in Thunderstorms (SEET), conducted in July and August of 1999 at the Langmuir Laboratory for Atmospheric Research in the mountains of central New Mexico. Multiple series of four to seven instrumented balloons were launched at 5 to 15 min intervals into storms over the mountain top. These storms were also observed with a four-station surface electric field mill network, a time-of-arrival lightning mapping system, ‘fast’ and ‘slow’ electric field change antennas, and two meteorological radars. Times and ground strike locations of CG lightning flashes were obtained from the National Lightning Detection Network (NLDN) [e.g., *Cummins et al.*, 1998].

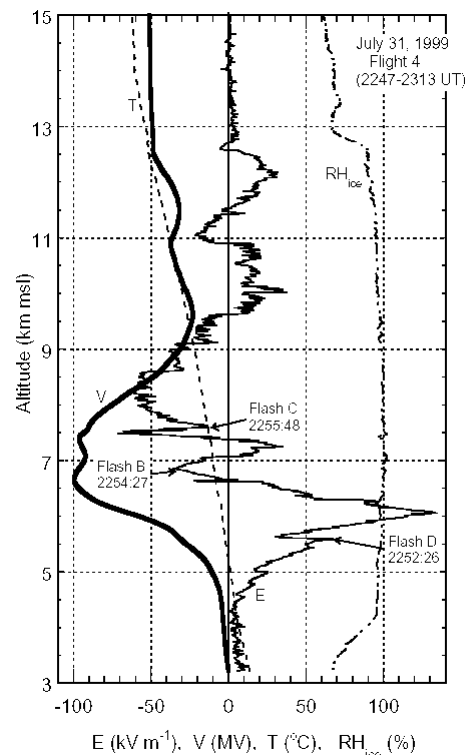


Figure 1. Sounding data from the fourth balloon launched on July 31, 1999. The graph shows electric field (E), potential (V), temperature (T), and relative humidity with respect to ice (RH_{ice}). Arrows indicate field changes caused by Flashes B, C, and D.

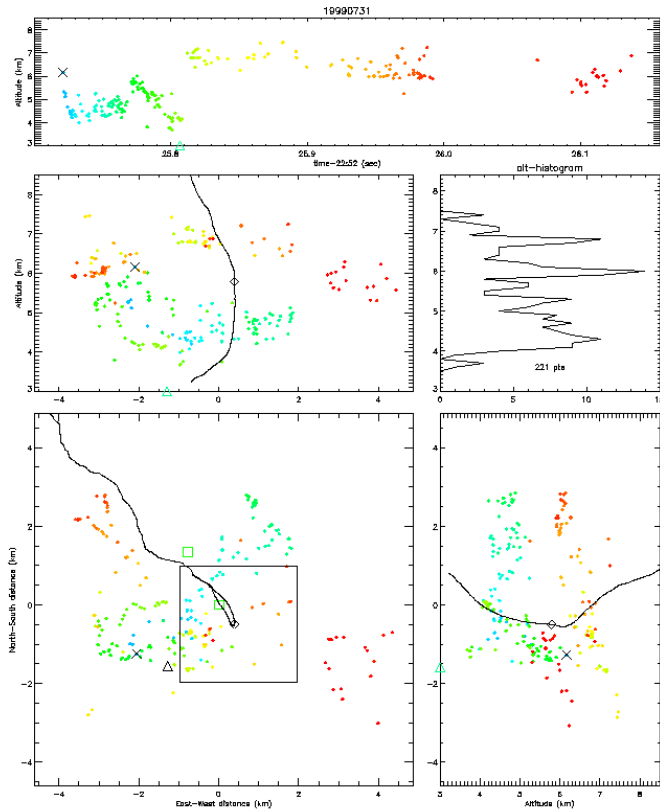


FIGURE 2. Flash D. This cloud-to-ground (CG) flash occurred at 2252:25 on July 31, 1999. The five graphs show located radiation sources. The x's mark the first LMA event, and the diamonds show the location of the balloon at the time of the flash. Triangles indicate the ground strike events based on the NLDN data. The two small squares in the middle of the horizontal projection represent two LMA stations in the middle of the array. The box in the horizontal projection encloses events included in the histogram in Figure 3. The balloon was at 5.7 km msl at the time of the flash and a horizontal position of (0.4 km, -0.6 km).

1 km to the northwest and 0.7 to 1.7 km below the balloon location. This initial breakdown lasted for about 50 ms. Subsequent to this, new breakdown began close to the initial radiation source. The new breakdown indicated the start of the stepped leader, which traveled more directly downward to ground and initiated the return stroke 35 ms later.

Radiation sources associated with positive polarity breakdown were detected only after the return stroke, and for the remainder of the flash all of the sources were associated with positive polarity breakdown in the upper level of the flash. Two sets of branches simultaneously developed away from the initiation region in the upper level, one eastward and northeastward from the initiation region and the other northward from the initiation region. The eastward

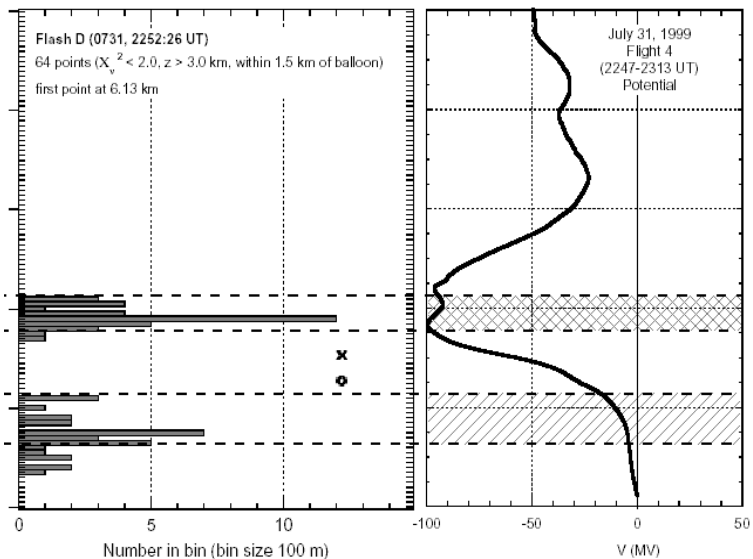


Figure 3. Potential and LMA events of Flash D. On the left is an altitude histogram of the events from the box in Figure 9 on the right is the voltage profile as shown in Figure 5. The "x" marks the altitude of the first LMA event and the likely location of flash initiation. The "o" marks the altitude of the balloon at the time of the flash.

3. RESULTS

One CG from *Coleman et al* is a particularly nice example which illustrates many of the results of the study. This CG flash, shown in Figure 2, occurred at 2252:26 UT during the July 31 sounding shown in Figure 1, where it is denoted as Flash D. At the time of Flash D, the balloon was at 5.7 km altitude and ascending through the inferred lower positive charge region. Prior to the flash, E at the balloon was positive; Flash D reduced the field from its pre-flash value of $+67 \text{ kV m}^{-1}$ to $+38 \text{ kV m}^{-1}$, consistent with the addition of negative charge below the balloon and or positive charge above the balloon, as indicated by the LMA observations that the flash had negative polarity breakdown below and positive polarity breakdown above the balloon.

Flash D was detected by the NLDN as a single stroke negative CG flash; this is confirmed by the fast antenna data and is consistent with the LMA observations. The initial radiation source was detected at an altitude of 6.1 km, which was also the altitude of the maximum positive E measured during the balloon sounding. Negative polarity breakdown initially progressed downward and then horizontally to the northeast, over a 4 km distance between 4 and 5 km altitude. The breakdown passed about

and northeastward branches passed 0.5 to 1 km above the balloon between 6.4 and 7.2 km altitude, then gradually descended to between 5.2 and 6.4 km altitude. The northward branch was between 6.0 and 6.5 km altitude.

Figure 3 shows the comparison of the LMA sources with the inferred charge regions and potential profile from Figure 1. The LMA source-altitude histogram is for the portion of Flash D within the box shown in Figure 2. The box excludes the mainly vertical portions of Flash D in the initiation region 2 to 3 km west of the balloon and focuses on the upper and lower level horizontal branches that passed near the balloon. The resulting histogram shows two well-defined levels of activity. The upper level sources associated with positive polarity breakdown are between about 6.5 and 7.2 km altitude and were situated in the lower part of the potential well for positive charge centered at 7 km.

The lower level sources of Flash

D, associated with negative polarity breakdown, were between about 4 and 5.5 km altitude in the histogram of Figure 3. These sources did not correspond to a well in the potential profile. Rather, the potential steadily increased from the ground up, due to E being positive all along the lower part of the balloon trajectory. To further understand these observations, we have examined electric field measurements made at the ground beneath the storm. Figure 4 shows a 10-min interval of electric field data at two ground stations. The bottom record is from the ‘Annex’ ground station, which was collocated with the Annex LMA station. This station was the southeastern-most of the two LMA stations shown in Figure 2, which served as the coordinate origin for the analyses. The balloon was located 0.7 km southeast of the Annex station and 2.5 km above it at the time of Flash D. The top record is from the ‘Kiva’ station situated 1.8 km northwest of the Annex station, immediately north of the northwestern LMA station in Figure 2. The balloon was launched partway between the two sets of stations and drifted southeastward over the Annex site as it ascended into the base of the storm.

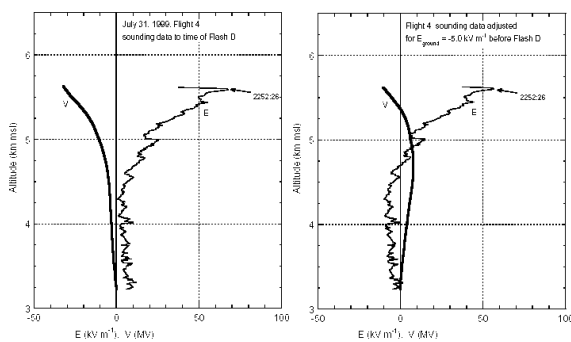


Figure 5. Lower portion of the balloon sounding from the fourth balloon launched on July 31, 1999. On the left are the electric field (E) and potential (V) data, as shown in Figure 1, between launch (at 2246:53) and Flash D (at 2252:26 UT). On the right is a hypothetical sounding, where the observed data are shifted by -11 kV m^{-1} to adjust the E at the ground in the sounding to match the measured E at the ground (shown in Figure 4) just before Flash D.

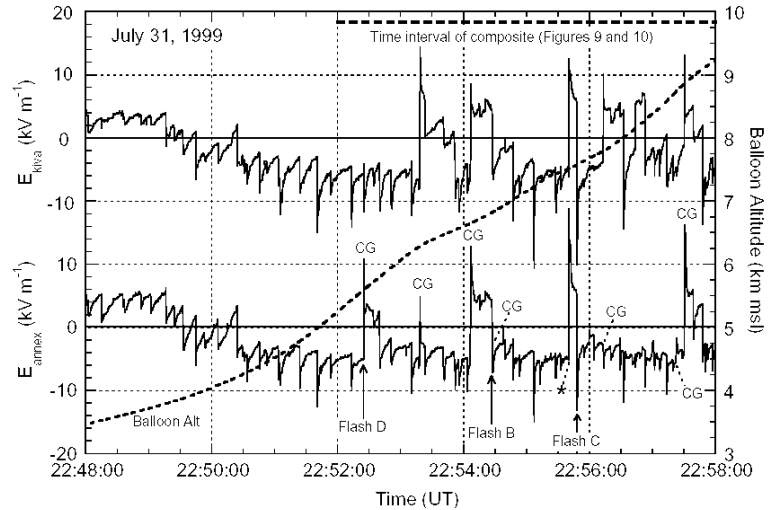


Figure 4. Surface E and balloon altitude data from July 31, 1999, for the period 2248:00 to 2258:00 UT. Data were recorded before and during the field excursion associated with precipitation (FEAWP) that began at about 2249:30. The times of Flash D is marked with an arrow. These measurements were taken at 10 Hz with electric field mills located at Langmuir Laboratory ‘Annex’ station (0.0, 0.0) and ‘Kiva’ station (-0.6, 1.7).

At the time of Flash D an electric “field excursion associated with precipitation” (or FEAWP) [Holden *et al.*, 1983; Marshall and Winn, 1982] was occurring at the ground. As seen in Figure 4, the FEAWP caused the electric field at the ground to reverse from positive to negative polarity during the course of the balloon flight prior to Flash D. A FEAWP is believed to result from an increase in the lower positive charge of a storm, causing E at the ground to be dominated by positive charge overhead rather than negative charge [Holden *et al.*, 1983; Marshall and Winn, 1982]. This FEAWP was often interrupted by lightning-produced “lockovers” that cause the field to revert temporarily back to positive polarity. Flash D produced such a lockover at the Annex station that lasted about 20 s. This is consistent with the LMA and sounding observations, which indicate that the flash deposited negative charge in the lower positive charge region near the Annex station.

The FEAWP caused the polarity of E to be negative over a wide area at the ground just prior to Flash D. At the same time the polarity of E at the balloon location remained positive. The latter was a result of the balloon being in the

upper part of the lower positive charge region, and below the main negative charge. Thus an instantaneous profile from the ground up to the balloon would have exhibited a change in the polarity of E at some height and therefore a potential maximum at that height. This is illustrated in Figure 5, which shows the balloon sounding data (E and V) from the ground to the altitude where Flash D occurred. The figure also shows a hypothetical sounding in which the E values have been shifted by -11 kV m^{-1} to give the measured E at the ground at the time of Flash D.

The fact that E was negative at low altitudes results in the formation of a potential well for negative charge. As indicated in Figure 12, the potential well would have been relatively broad and not very deep, on the order of 10 MV. A relatively broad and not very deep well is consistent with the development of the low-level branch during Flash D and also with the fact that the channel eventually reached ground.

CONCLUSION

The above example gives insight into many of the observations made from Coleman *et al.*, 2003. For the sake of brevity, no more examples are possible. However, the basic results of the study are that the comparisons consistently show good agreement between the heights of the horizontal lightning channels and the altitudes of potential extrema or wells obtained from the sounding measurements. Because a potential well of a given polarity is produced by dominant charge of the same polarity, the heights of the lightning channels also agree with the altitudes of dominant charge in the storm. The upper and lower levels of breakdown in bilevel IC flashes were found to be at the same altitudes as the potential wells associated with dominant positive charge in the upper part of a storm and with dominant negative charge at the middle level in a storm. Similarly, the midlevel breakdown of negative CG flashes was at the same altitude as the midlevel well associated with dominant negative charge. Most of the CG flashes studied also exhibited breakdown at lower altitude that was found to be correlated with positive charge and an inferred potential well in the lower part of the storm. The results were obtained both for individual flashes and for groups of flashes, and in situations having different lightning rates and heights of the charge regions.

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