

# EVOLUTION OF ELECTRIC CHARGE AND LIGHTNING TYPE IN DEVELOPING THUNDERSTORMS

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## INTRODUCTION

Much is known about the electric field, charge, and lightning in mature thunderstorms, both from in situ measurements with balloons, airplanes, sailplanes, and rockets and from remote measurements using radars and various types of lightning detection. In comparison, there is relatively little in situ information about electric field, charge, and lightning in developing thunderstorms. *Dye et al.* [1988] have provided some of the most comprehensive analyses of initial thunderstorm electrification to date, but some questions about the early evolution of electricity in thunderstorms still need to be resolved.

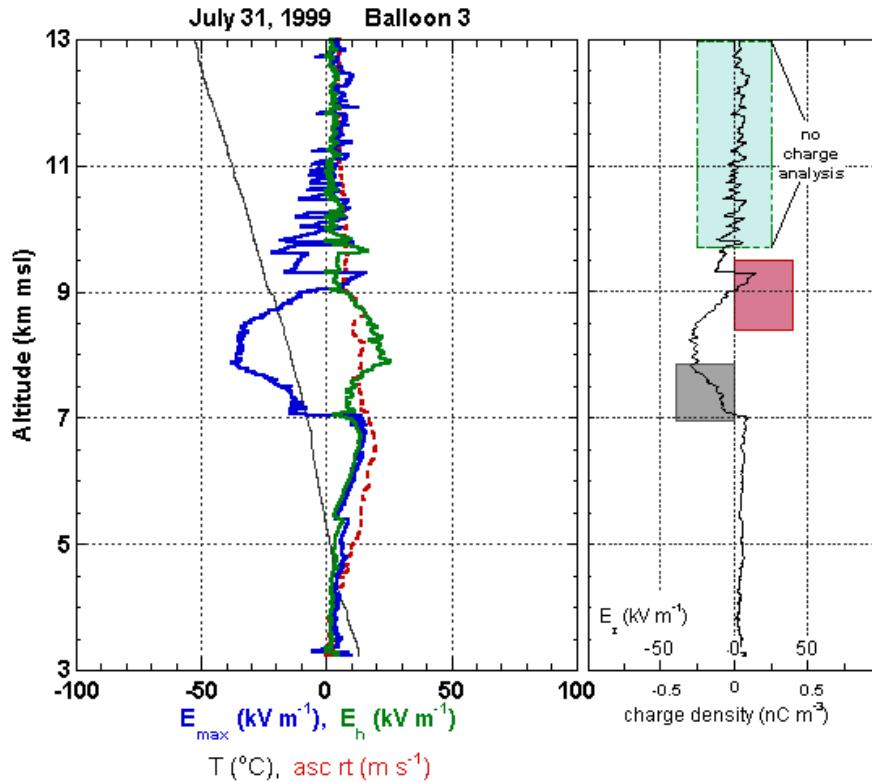
One of these questions concerns the type of lightning that first occurs in a storm. Although the first lightning flash of a storm may be either intracloud (IC) or cloud-to-ground (CG), many storms begin with a series of IC flashes [e.g., *Krehbiel*, 1986; *Defer et al.*, 2001]. Presumably the early evolution of charge and electric field inside a growing thunderstorm is responsible for the type of lightning flashes that occurs during its initial growth. The reason why IC flashes often occur first is not understood and is the main question addressed in this study.

During the summer of 1999, we flew instrumented balloons into mountain thunderstorms that developed over the Langmuir Laboratory for Atmospheric Research in central New Mexico. In addition to the balloon electric field ( $E$ ) data, three dimensional maps of individual lightning flashes were obtained using the New Mexico Tech Lightning Mapping Array (LMA). On July 31, 1999, there were many thunderstorm cells in the vicinity of Langmuir Laboratory. We flew a series of seven instrumented balloons into cells originating and evolving over the balloon launch site. The third balloon ("Balloon 3") was launched at 2232:40 UT and ascended into one of two new thunderstorm cells. These two cells were developing nearly simultaneously, though the development of the northeastern cell ("Cell 3" which Balloon 3 entered) slightly lagged that of the other cell ("Cell 4"). Cells 3 and 4 did not produce any flashes during the first 14 min of the Balloon 3 flight. The first flash in Cell 4 occurred at 2246:50, while the first flash in Cell 3 occurred less than a minute later.

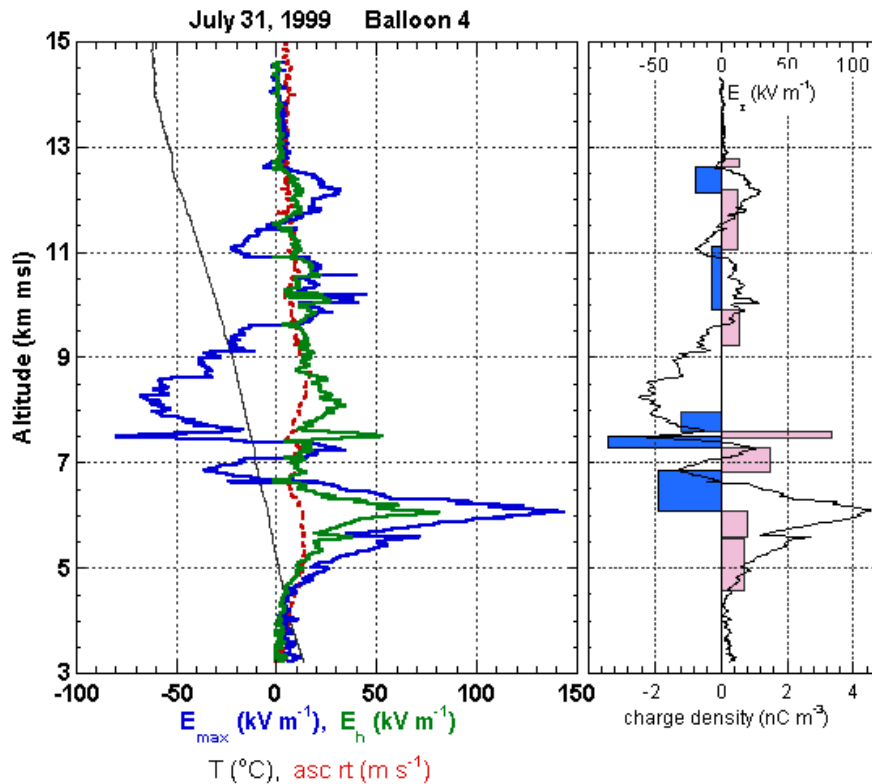
The lightning in each of Cells 3 and 4 began with a series of IC flashes. Balloon 3 traversed most of the depth of Cell 3 before the first lightning in the cell. The fourth balloon flown on July 31 was launched about 14 min after Balloon 3 and one minute before the first flash in Cell 3. Together the  $E$  data from these two balloons and the LMA lightning data provide unique information about the early electrical evolution of Cells 3 and 4.

## ELECTRIC FIELD DEVELOPMENT

Figure 1 shows the sounding data from Balloon 3, along with the charge regions inferred using the one-dimensional approximation to Gauss's law. ( $E_{max}$  shown in the figure is the measured total  $E$  vector magnitude, assigned the polarity of  $E_z$ . For simplicity, we refer to this as  $E$ .) The  $E$  sounding for Balloon 3 is significant because it documents the pre-lightning electrical structure through most of the depth of Cell 3: the balloon ascended to an altitude of 9.1 km before the first flash. The  $E$  sounding is also unique in several ways when compared to the group of mountain thunderstorm soundings presented in *Stolzenburg et al.* [1998]. First, the  $E$  magnitudes in Figure 1 are generally weaker, with the maximum magnitude of only  $35 \text{ kV m}^{-1}$  compared to about  $100 \text{ kV m}^{-1}$  in the published group of  $E$  soundings. Second, there were only two regions of substantial net charge inferred from the sounding: a negative charge region centered near 7.4 km altitude and a positive charge centered near 8.7 km altitude. In contrast, the published group of mountain thunderstorms has 4 to 8 inferred charge regions [*Stolzenburg et al.*, 1998]. Third, there were no substantial charge regions below about 7 km altitude, while each sounding in the published group had substantial charge regions as low as 5 km altitude. We suspect that all of these differences are due to the Balloon 3 sounding being made much earlier in the electrical development of Cell 3, before its first lightning flash.



**Figure 1.** Balloon 3 sounding of  $E$ ,  $E_z$ ,  $E_h$ , temperature, ascent rate (dashed curve), and altitude and density of charge regions (where  $\rho = \epsilon \Delta E_z / \Delta z$ ). The balloon entered cloud base at 2240:30, at 4.1 km alt. and ascended in the updraft.



**Figure 2.** Balloon 4 sounding of  $E$ ,  $E_h$ ,  $E_z$ ,  $T$ , ascent rate, and inferred charge structure. The balloon entered cloud base at 2250:00, 9.5 min after Balloon 3.

Another significant feature of the data from Balloon 3 is evident in the horizontal ( $E_h$ ) and vertical ( $E_z$ ) components of  $E$  as a function of altitude. The substantial  $E_h$  component (i.e., nearly as large as  $E_z$ ) between 5 and 9 km altitude in Figure 1 is not typical of the mountain thunder-storm soundings shown in *Stolzenburg et al.* [1998]. The  $E$  data indicate that only two substantial net charge regions had developed before the first lightning flash and that these regions were located at upper levels in Cell 3. (No charge analysis was possible at uppermost levels in the sounding due to the frequent lightning related field changes.) As shown by *Stolzenburg et al.* [2002], the relatively large  $E_h$  values suggest the negative charge was not centered along the balloon's path and probably had not yet developed appreciable horizontal extent.

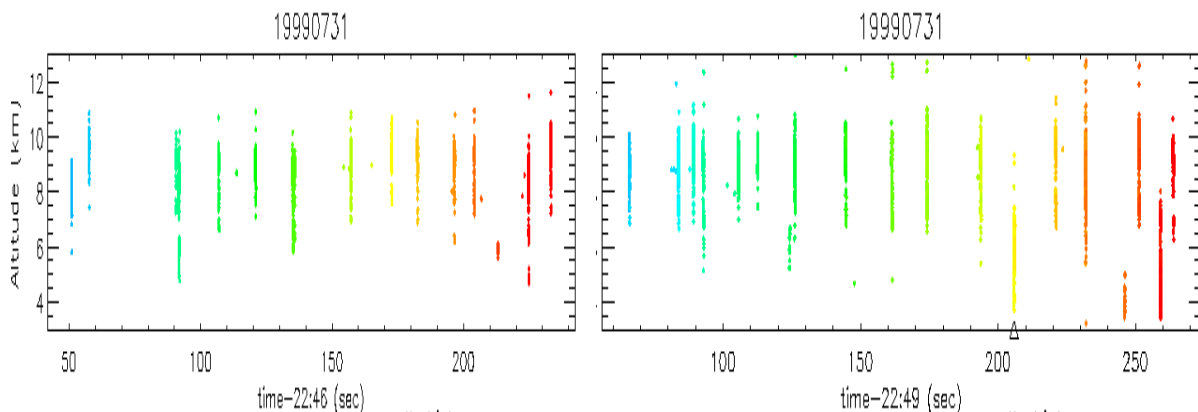
Figure 2 shows the sounding data of the fourth balloon. Unlike the  $E$  sounding of Balloon 3, the  $E$  sounding of Balloon 4 is similar to the group of mountain thunderstorm soundings presented by *Stolzenburg et al.* [1998]. There are large magnitudes of  $E$  (with a maximum of almost  $150 \text{ kV m}^{-1}$ ) throughout the sounding, numerous regions of inferred net

charge of both polarities, substantial  $E$  and charge regions below 7 km altitude, and relatively small  $E_h$  magnitudes compared to  $E_z$  through-out the sounding.

Together, the data in Figures 1 and 2 suggest that, by the time of the later sounding, Cells 3 and 4 had evolved from an “early” stage to an electrically mature stage. In the 10 minutes between these two soundings, the electric field magnitudes increased substantially at almost all altitudes. For example, the negative  $E$  peak at about 8 km has doubled in magnitude, and the positive  $E$  peak near 6 km is at least 10 times larger in magnitude. In addition,  $E$  magnitudes larger than  $10 \text{ kV m}^{-1}$  extend above 12 km in the later sounding, which is more than 2 km higher than in the earlier sounding.

## LIGHTNING DEVELOPMENT

Before 2246:50 UT, no lightning occurred in Cells 3 and 4. Figure 3 shows the radiation sources detected by the LMA between 2246:50 and 2253:30. Thirty-three flashes occurred in either Cell 3 or Cell 4 or both during this time period. A detailed analysis of each of the 33 flashes has shown that 30 were normal IC flashes with negative polarity breakdown moving upward initially from the first detected source; the other 3 flashes were normal CG flashes with negative polarity breakdown moving downward initially from the first source. Before the first CG flash, 11 IC flashes occurred in Cell 3 and 13 IC flashes occurred in Cell 4. The first CG flash (marked in Figure 3 at 2252:25) initiated in Cell 4 and developed into both Cells 3 and 4. (Of this group of 33 flashes, 8 extended into both cells, and all but one occurred after 2251:20, when the two cells merged.)



**Figure 3.** Altitude vs time of all the radiation sources detected by the LMA for flashes occurring in Cells 3 and 4 on 31 July 1999 between 2246:50-2249:59 (left) and 2250:00-2253:30 (right). The first CG flash is marked with a triangle at 2252:25 UT.

The first CG flash occurred when Balloon 4 was at an altitude of 5.6 km and measuring an  $E$  of  $68 \text{ kV m}^{-1}$ . When Balloon 3 passed through the same altitude about 9 min earlier (and about 1 km to the northeast of the Balloon 4), the magnitude of  $E$  was only  $6 \text{ kV m}^{-1}$ . These data are consistent with the idea that CG flashes do not occur in a thunderstorm cell until the magnitude of  $E$  in the lower part of the cell is sufficiently large for flash initiation to occur below the main negative charge region.

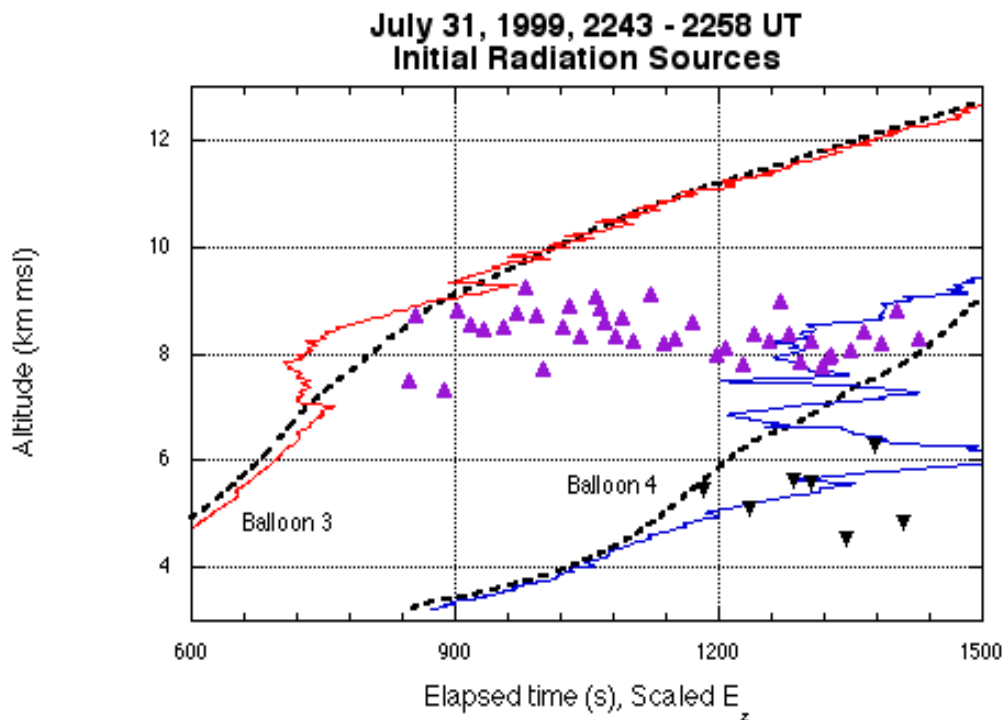
Figure 4 shows the altitude versus time of the initial LMA-detected radiation source of each flash in Figure 3. The first 24 flashes initiated between 7.3 and 9.3 km altitude while the 25<sup>th</sup> flash (the first CG flash) initiated at 5.4 km altitude. The initiation altitudes versus time show that initial sources occurring above 7.0 km developed into normal IC flashes, while initial sources occurring below 6.5 km developed into normal negative CG flashes. Assuming that lightning initiation requires a large electric field, the initiation altitudes provide another indication that large negative  $E_z$  values developed first at upper levels of Cells 3 and 4 and that large positive  $E_z$  values developed later at lower altitudes.

## CONCLUSIONS

In the thunderstorm cells investigated, early electrification occurred above about 7 km. The first instrumented balloon ascended to 9.1 km in the cloud before the first lightning flash occurred. This sounding showed relatively small magnitudes of  $E$  throughout and only two substantial regions of net charge, with

negative charge centered at 7.6 km ( $T = -12^{\circ}\text{C}$ ) and positive charge centered at 8.8 km ( $T = -20^{\circ}\text{C}$ ). The electrification in the cells went from “early” to mature stages in 10 minutes or less. In particular, within 10 minutes both a lower positive charge region and substantial positive electric field magnitudes had developed.

The main question addressed in this study is why some thunderstorm cells begin with a series of IC flashes. The data presented herein suggest the following answer: in cells that initially produce IC flashes only, the early electrification and net charge development occur at upper altitudes (above 7 km altitude in the case presented). This early stage of development included the large (negative)  $E$  necessary to initiate IC flashes, but did not provide a large (positive)  $E$  at lower levels to initiate CG flashes. The CG flashes began after development of a lower positive charge region and a substantial positive electric field at low levels.



**Figure 4.** Altitude vs time of the initial radiation sources detected for the first 10 min of flashes (2246:40-2256:20 UT) in Cells 3 and 4 on 31 July 1999. Upward pointing triangles are the first LMA-detected radiation sources of IC flashes; downward pointing triangles are first sources of CG flashes. Curves of the altitude vs time of Balloon 3 and Balloon 4 are also shown (dashed curves), along with a portion of the two  $E_z$  soundings. (The  $E_z$  values shown have been scaled about the time-altitude curve of each balloon.)

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