Formation of Charge Structures in a Supercell

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ABSTRACT

Lightning mapping, electric field, and radar data from the 26 May 2004 supercell in central Oklahoma are used to examine the storm’s charge structure. An initial arc-shaped maximum in lightning activity on the right flank of the storm’s bounded weak echo region was composed of an elevated normal polarity tripole in the region of precipitation lofted above the storm’s weak echo region. Later in the storm, two charge structures were associated with precipitation that reached the ground. To the left of the weak echo region, six charge regions were inferred, with positive charge carried on hail at the bottom of the stack. Farther forward in the storm’s precipitation region, four charge regions were inferred, with negative charge at the bottom of the stack. There were different charge structures in adjacent regions of the storm at the same time, and regions of opposite polarity charge were horizontally adjacent at the same altitude. Flashes occasionally lowered positive charge to ground from the forward charge region. A conceptual model is presented that ties charge structure in different regions of the storm to storm structure inferred from radar reflectivity.

1. Thunderstorm charge regions and storm structure

This study is concerned with the ability to predict charge regions, associated lighting, and their evolution in time by examining several radar reflectivity cross sections through a supercell. More generally, it tests the expected relationship between precipitation formation and arrangement within the storm as indicated by radar reflectivity and the formation of local cellular maxima in total lightning activity. To facilitate the analysis, it is useful to adopt some terminology from previous radar analyses of supercells.

Precipitation forms in thunderstorm updrafts and falls out where the hydrometeor terminal fall speed is not compensated by an updraft (Byers and Braham 1949). Both updrafts and downdrafts persist simultaneously in quasi-steady-state supercells. The strongest surface convergence is typically near the right-rear flank of the storm where forward flank downdrafts (FFDs) and rear flank downdrafts (RFDs) both impinge on boundary layer flow to sustain a concentrated, rotating updraft (Lemon and Doswell 1979). (Throughout this study, the terms forward, rear, left, and right are oriented relative...
to the storm motion vector.) The presence of a persistent weak echo region \((Z < 20 \text{ dBZ})\) below precipitation-sized hydrometeors on the right flank of the storm indicates updraft speeds are compensating for the terminal fall speed of hydrometeors aloft (Browning and Donaldson 1963; Browning 1965; Browning and Foote 1976). At midlevels the weak echo region may be bounded by reflectivity on all sides; this vault feature is indicative of the largest updraft speeds. In this study, the terms “main updraft” or “strongest updraft” refer to the portion of the storm indicated by these reflectivity characteristics. Precipitation to the right and forward of the bounded weak echo region has been termed the “embryo curtain,” and precipitation to the left of the weak echo vault the “hail cascade,” after Browning and Foote (1976). Updraft speeds diminish somewhat to the sides of the vault within the lofted precipitation. Upward motion may also be present in other regions of the storm, including ahead of the weak echo vault (Sand 1976). Divergent flow at the top of the main updraft carries most lofted precipitation into the forward flank of the storm. Precipitation falling into the forward flank forms an echo overhang that slopes toward the left flank of the storm due to sheared winds (Browning 1964).

Noninductive charging of ice hydrometeors during rebounding collisions is thought to explain the formation of net charge regions within thunderstorms. Reynolds et al. (1957) and subsequent laboratory studies (Takahashi 1978; Baker et al. 1987; Saunders et al. 1991; Pereyra et al. 2000) demonstrated the efficacy of this process and its enhancement by active riming. This process is sometimes called the relative growth rate mechanism, wherein supercooled water is thought to enhance the difference in vapor flux to two species of colliding hydrometeors. There is continued debate about how temperature and supercooled water concentration (or riming rate) influence charging polarity (Takahashi and Miyawaki 2002; Saunders et al. 2006). There is broad agreement that collisions in an environment of moderate liquid water contents and temperatures between \(-10^\circ\) and \(-30^\circ\)C lead to negative charging of graupel. Large liquid water contents cause positive charging of graupel during collisions, as do moderate liquid water contents at temperatures just colder than \(0^\circ\)C.

The noninductive mechanism readily explains the normal-polarity tripole model of thunderstorm charge structure (Simpson and Robinson 1941; Williams et al. 1989). In this model, lower positive charge is carried on graupel, midlevel negative charge is carried on graupel and ice crystals, and upper positive charge is carried on ice crystals. The model is a satisfactory explanation of measurements in mountain thunderstorms (e.g., Ziegler et al. 1991; Bateman et al. 1999) and multicellular convection in weak shear environments (e.g., Bruning et al. 2007).

Stolzenburg et al. (1998b) presented the most recent synthesis of charge structures inferred from electric field soundings in several thunderstorm types. They found that a four-layer stack of charges was typical of updraft regions while six or more layers characterized non-updraft regions of storms. Their definition of updraft versus non-updraft regions depended on storm type (e.g., multicellular, MCS, or supercell). In supercells, updraft regions were defined as areas where updraft speed was greater than \(5 \text{ m s}^{-1}\). The major contributions of Stolzenburg et al. (1998b) were 1) in demonstrating storm charge complexity beyond the tripole model (see also Marshall and Rust 1991), 2) in tying complexity to relative vigor of convective regions, and 3) in verifying that the altitude of the charge layers was higher for stronger updrafts, as hypothesized by MacGorman et al. (1989).

MacGorman et al. (2005) and Wiens et al. (2005) examined supercells from the Severe Thunderstorm Electrification and Precipitation Study (STEPS) 2000 program (Lang et al. 2004). Ground flashes were dominated by positive strokes produced out of inverted polarity electrical structure [i.e., the vertical profiles of charge inferred from lightning mapping and vector electric field measurements \(E\) were inverted in polarity from those found by Stolzenburg et al. (1998b)]. The STEPS measurements were interpreted to mean that because of the large gradient in updraft speed and supercooled liquid water concentration across the broad updraft region in the storms, graupel and/or hail gained positive charge near the core of the updraft, while graupel farther away from the updraft core gained negative charge. The aggregate effect of updraft proximity and temperature (altitude) dependence was used by MacGorman et al. (2005) and Wiens et al. (2005) to explain the production of the inverted polarity structure associated with positive ground flashes. Little charge was indicated within the bounded weak echo region of the storms that possessed them, and charge profiles were more complex outside the strongest updraft.

Extant studies do not pinpoint specific microphysical or structural features that are associated with the local separation of charge in a storm. The relevant kinematic and precipitation structures referenced in the studies are relatively simplistic ones such as strong and not strong updraft, or regions of large and small radar reflectivity, and occasionally the transition between these two regions. Because of the coarseness of the final conceptual models in, for example, Stolzenburg et al. (1998b) and the STEPS studies, it is sometimes difficult to reconcile them with radar depictions of supercells.

Lightning mapping measurements are used in this study to construct a conceptual model of charge separation...
and of the formation of charge regions within supercells that is directly comparable to the supercell structures annotated in Fig. 1. Those features are readily inferred from radar reflectivity, and are used to infer the gross kinematic structure since quantitative observations of vertical velocity are not available. Changes in the charge structure revealed by lightning within a single updraft pulse cycle are examined to infer the process by which charge structures come to exit. The temporal continuity in the process description, made possible by the high time resolution of the lightning mapping data, is one of the most unique features of this study.

2. Data and methodology

During the Thunderstorm Electrification and Lightning Experiment (TELEX) field program (MacGorman et al. 2008) on 26 May 2004 a storm developed west of Hinton, Oklahoma and tracked toward Oklahoma City. The storm was supercellular and non-tornadic. It took on a low-precipitation appearance as it decayed. Four balloon-borne electric field meters, the Oklahoma Lightning Mapping Array (LMA), and the KOUN polarimetric radar sampled the storm. In addition, a single Shared Mobile Atmospheric Research and Teaching Radar (SMART-R) C-band mobile radar (Biggerstaff et al. 2005) provided more rapid updates of reflectivity at 3-min intervals. The National Lightning Detection Network (NLDN; Biagi et al. 2007; Cummins and Murphy 2009) provided ground strike data. In this study, charge polarity and geometry are inferred from LMA measurements and radar observations are used to place the coverage of lightning and inferred charge in the context of the storm. Electric field profiles are compared with charge inferred from the LMA data.

**Charge regions: Lightning Mapping Array**

The primary source of lightning and charge data in this study is the Oklahoma Lightning Mapping Array (LMA). The LMA maps very high-frequency (VHF) radiation sources radiated by lightning channels as they propagate impulsively through the air. Errors in mapped locations and the characteristics of the array are described by Thomas et al. (2004). Tens to hundreds of these sources are produced by a typical flash. The following discussion describes how the LMA data are used to infer charge on a flash-by-flash basis.

![Fig. 1. Supercell structural terminology used in this study overlaid on contours (dBZ) of radar reflectivity for (top) two altitude–distance cross sections: (left) A–B and (right) C–D. Cross section locations are indicated in schematic plan views of reflectivity (bottom) low, middle, and upper levels, where contours correspond to approximately 25 and 50 dBZ. The terms—forward, rear, left, and right—indicate relative position in a reference frame moving with the storm. Reflectivity contours in the vertical and plan sections were generalized from the 2249 UTC 26 May 2004 SMART-R volume (Fig. 4).](image)
Flashes are thought to be initiated in regions in which the magnitude of $E$ is large (e.g., Kasemir 1960; Mazur and Ruhnke 1998; Maggio et al. 2005; Marshall et al. 2005; Lund et al. 2009), typically in the transitional region between negative and positive inferred charge. After lightning is initiated, channel leaders of opposite polarity propagate in opposite directions from the location of initiation (Kasemir 1960; Mazur and Ruhnke 1993). Negative leaders propagate much more impulsively, and so produce many more VHF sources than positive leaders. As lightning approaches regions of net charge opposite the leader polarity, the leaders spread outward into those regions (MacGorman et al. 1981, 2001; Williams et al. 1985; Coleman et al. 2003). Two levels of extensive horizontal propagation connected by a vertical channel indicate the existence of vertically stacked horizontal regions of charge (e.g., MacGorman et al. 1981, 2001; Shao and Krehbiel 1996). Positive storm charge is inferred above negative in normal polarity flashes. This vertical arrangement is reversed for inverted polarity flashes. For more compact and less layered charge regions, this easily interpretable lightning structure might be expected to devolve into more tortuous and compact lightning flashes, such as the “knots” noted by Proctor (1983) and the “compact flashes” of Wiens et al. (2005).

Mazur (2002) used these ideas to infer storm charge from lightning mapping data (see applications in, e.g., Rust et al. 2005; Wiens et al. 2005). They noted that preferential detection of negative leaders, typically propagating through positive storm charge, makes it somewhat more difficult to assess regions of negative charge, except where fast recoil leaders [k changes; as reviewed in Mazur (2002)] propagate from negative charge toward positive charge. Furthermore, no quantitative information about the magnitude of storm charge is available from this type of analysis. Finally, charge cannot be inferred by this method in areas in which lightning does not propagate. Nevertheless, this study uses the LMA-based charge analysis because it resolves a significant portion of the four-dimensional charge structure of storms, a crucial capability unavailable with other types of datasets.

Total storm flash rate is the sum of flashes that remained within the cloud (cloud flashes) and flashes in which a channel reached to ground (ground flashes, as indicated by the NLDN). Flash rates in this study were calculated as described in MacGorman et al. (2008). While the flash-sorting algorithm may split or merge flashes in error, the relative trends in flash rate are generally reliable (Wiens et al. 2005; Murphy 2006).

NLDN data from 26 May 2004 were filtered according to criteria determined by Johnson and Mansell (2006) to account for misclassified cloud flashes (Biagi et al. 2007). All positive NLDN detections with peak current greater than 15 kA were retained. Also retained were detections with negative peak current between $-10$ and $-15$ kA and stroke counts greater than or equal to 2, and all negative detections with peak current less than $-15$ kA.

### 3. Storm life cycle

The 26 May 2004 storm began between 2030 and 2045 UTC just behind a bulging dryline. It crossed the dryline by 2145 UTC, and rapidly intensified by 2215 UTC into an east–west-oriented chain of strong cells spaced 5–10 km apart with maximum reflectivity in excess of 60 dBZ.

The first lightning activity began at 2130 UTC as the storm moved across the dryline into a moist boundary layer. Total flash rates (Fig. 2) were initially 20–30 min$^{-1}$, but suddenly jumped to 100 min$^{-1}$ at 2200 UTC as the storm became well established in the moist air. The flash rate then fluctuated between 80 and 150 min$^{-1}$ until about 2330 UTC, when a gradual decrease in flash rate began. Lightning became infrequent by 0020 UTC and lingered until 0100 UTC.

Between 2230 and 2300 UTC, the storm turned right, slowed, and exhibited a bounded weak echo region and prominent hook echo (Figs. 3a–l and 4a–l). These developments indicated the transition of the storm to a supercell (Klemp 1987). During this transition, there was evidence of pulses in the updraft in radar data at upper levels (10–14 km). Three successive reflectivity maxima appeared, increased in area and maximum reflectivity, and then decreased as precipitation fell out as each maximum was advected toward the forward flank of the storm. New reflectivity maxima were present at 2242 (Fig. 3m), 2245 (Fig. 3n), and 2253 UTC (Fig. 4n), which, respectively, may be used as the approximate beginning time of each pulse. Such pulses indicate the storm had some characteristics of a weak-evolving storm mode (Foote and Frank 1983; Fovell and Ogura 1989).
FIG. 3. SMART-R (a)–(c), (g)–(i), (m)–(o) radar reflectivity and (d)–(f), (j)–(l) radial velocity from 2241 to 2249 UTC in plan projection for (a)–(f) 1.7°, (g)–(l) 11.5°, and (m)–(o) 27.4° elevation angles. Vertically integrated counts of LMA sources are contoured in black (>64 sources per kilometers squared). The LMA data window is 30 s before the start and after the end of each radar scan. Complete balloon paths are plotted in white, with the balloon position during the LMA window in black. White dashed line indicates location of the RHI in Fig. 10.
FIG. 4. As in Fig. 3, but for 2249 to 2258 UTC. White dashed lines in (a),(g),(m); (b),(h),(n); and (c),(i),(o) indicate locations of RHIs in Figs. 11, 12, and 13, respectively.
A sounding representative of the storm’s environment during its supercellular phase was launched just to the southwest of the storm at 2331 UTC near Cogar, Oklahoma (Fig. 5). The atmosphere was effectively uncapped \((\text{CIN} < 5)\) with \(\text{CAPE} = 3064 \text{ J kg}^{-1}\).

Figure 6 shows a summary of lightning data during the period of greatest flash rate, which includes the supercell transition. Before 2250 UTC, most flashes to ground lowered negative charge. After 2250 UTC, most ground flashes lowered positive charge. During 2240–2340 UTC, the time–height plot of source density exhibited occasional vertical surges. Lhermitte and Krehbiel (1979) and Ushio et al. (2003) proposed that these pulses were associated with particularly vigorous pulses in updrafts.

The time history of source density in plan view (Fig. 7) supports the idea of new updraft pulses leading to the overshooting lightning activity. Three new clusters of lightning activity, the latter two arc-shaped, developed on the right flank of the storm at 2241, 2245, and 2254 UTC. The 2241 and 2254 UTC clusters are highlighted by gray polygons in Fig. 7, while the 2245 arc is highlighted by colored polygons. As each lightning cluster developed, it became the dominant center of lightning activity. The polygons encompass local maxima in lightning density that persisted from minute to minute. Each further subdivision of otherwise contiguous density maxima in the 2245 UTC arc reflects a region of commonality in flash extent and charge structure noticed during the tedious manual charge analysis.

The development of the arcs of lightning was coincident and collocated with the appearance of local maxima in radar reflectivity near the storm top that indicated updraft pulses (Figs. 3m–o and 4m–o), suggesting that the development of both features was related. In the next section, one of these time-evolving, arc-like patterns in

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Fig. 5. Skew \(T\)–\(\log p\) plot of temperature \(T\) (thick black line) and dewpoint \(T_d\) (thick gray line) observed by radiosonde at 2331 UTC 26 May 2004 near Cogar, OK. The \(T\) for a parcel yielding 3064 J kg\(^{-1}\) of CAPE is represented by a thin black line. Environmental winds (m s\(^{-1}\)) are plotted to the right. Short barbs indicate 5 m s\(^{-1}\), long barbs 10 m s\(^{-1}\), and flags 50 m s\(^{-1}\). (1 m s\(^{-1}\) = 1.95 kt).
lightning is considered in detail. The relationship of lightning to the evolving precipitation structure from the onset of an updraft pulse through formation of a mature precipitation shaft is considered from minute to minute, with the goal of making more apparent how complex supercellular charge structures are formed.

4. Details of the arc that began at 2245 UTC

a. Summary of inferred charge structure

The relationships among the supercell structures discussed in section 1 and storm charge inferred from the LMA data were examined by considering the time-evolving patterns in radar and LMA data for a single arc. Figure 8 summarizes these relationships and may serve as a helpful guide while examining the detailed analysis of flashes that follows. The arc was characterized by a single vertical profile of charge until 2250 UTC. After 2250 UTC the charge structure became more complex and necessitated separate analysis in forward and rearward portions of the arc. The rearward cross section (Figs. 8a,b) cut across the weak echo region, including the vault and the hail cascade on the immediate left flank of the vault. The forward cross section (Figs. 8c,d) was through the embryo curtain and toward the sloping echo overhang. As will be shown, both cross sections shared a common charge structure where they intersected.

b. 2245–2250 UTC

As in the arcs before and after it, initial lightning within the 2245 UTC arc took place on the right flank of the weak echo vault in the embryo curtain, and the observed charge structure there was an elevated, normal polarity tripole. The charge structure of the arc inferred from lightning in a time–height view (Figs. 9a–c) was relatively consistent from 2245 to 2250 UTC, when a transition to a more complex charge structure took place.

Initially, inverted polarity flashes revealed positive charge at 7–8 km and negative charge at 8–10 km. Similar flashes continued and revealed the region of positive charge deepening through 2250 UTC.

The LMA began mapping sources near 12-km altitude at 2246 UTC. A rising plume of intermittent sources ascended from 12 km at 2247 UTC to 15 km by 2250 UTC (a rate of about $20 \text{ m s}^{-1}$). Most of the sources were isolated events, but a few tens of sources occasionally organized into small flashes. From these flashes, positive charge was inferred within the initial stage of the ascending band of sources. Negative charge was inferred near 11 km. One such flash, at 2247:43.05 UTC, was in or near the overshooting top of the storm, and exhibited recoil processes that helped to verify the determination of charge. By 2250 UTC, sources became more diffuse, and the charge structure in the rising band was less clear, with many single-source detections. Such detections may represent very small or aborted flashes restricted in propagation by the small size of charge regions, as would be expected in a turbulent overshooting turret. Vonnegut et al. (1966) observed that turbulence prevented screening layer formation in the overshooting top, which is consistent with the idea that turbulence was also acting to inhibit organized accumulation of net charge.

Another band of sources appeared at 2248 UTC near 12 km, and small flashes within this band occasionally
exhibited enough structure that positive charge could be inferred near 12 km and negative charge near 10.5 km.

Radar and lightning data from 2246:54–2248:48 UTC (Fig. 10) show lightning within the lofted echo in the embryo curtain region to the right of the weak echo vault. Inferred positive charge was within the reflectivity gradient near the top and bottom edges of the precipitation, with negative charge in between in intense echo ($Z > 60 \text{ dBZ}$). The upper positive charge was associated with the tallest echo.

The region with flashes extended rearward within the arc from 2245 until 2250 UTC, when the gap in lightning...
between the rear tip of the arc and the rest of the storm was filled. By this time, the notch in the LMA data between the arc and the older lightning activity in the 2250 and 2251 UTC lightning density plots (along the north edge of the forward purple polygon; Fig. 7) corresponded to the gap between the newest high-altitude radar reflectivity core \((Z > 50 \text{ dBZ})\) and the older core to the north and east where similarly large reflectivities were at low and midlevels (Figs. 4g,h). This lightning-free region was not associated with the weak echo vault, which is often thought to be a manifestation of the storm’s strongest updraft. Instead, the weak echo vault was located in the lightning-free region southwest of the arc at this time.

c. Rearward portion of arc, after 2250 UTC

Radar data showed that by 2249:39–2251:30 UTC (Fig. 11) inverted flashes were found across the entire width of the lofted precipitation above the weak echo region, including above the weak echo vault. All flashes near the right edge of the rear part of the arc (Figs. 11a,b) had inverted polarity. The lower positive charge was centered at about 8 km; negative charge was above it, centered at 10 km. As in the previous volume scan, normal polarity flashes were inferred to lie on and below the large-reflectivity gradient near the storm top (Figs. 11c–f), with positive charge at about 12 km. Together, the upper normal flashes and lower inverted flashes indicated that the charge structure above the weak echo region was a normal polarity tripole.

Positive charge was also associated with descending precipitation on the left flank of the weak echo region (Fig. 11c at 25–35-km range), where radar reflectivity in excess of 60 dBZ suggested there was hail. A local minimum in differential reflectivity (values 0–1 dB) from KOUN data below the melting level correlated well with the region of large reflectivity, further supporting an inference of hail. Flashes in the precipitation shaft and those inverted polarity flashes above the weak echo region revealed the deep positive region seen in the time–height plot until 2254 UTC (Fig. 9b, 4–9 km).

Lightning during 2252:24–2254:16 UTC became increasingly disassociated from the precipitation above the weak echo region (Fig. 12); only a few flashes comprising a normal tripole occurred there. This transition is interesting because the lofted echo and bounded weak echo region appeared in radar data for all volume scans, indicating persistence of these gross storm features. Compare the 330° scan in Fig. 11 with the 339° scan in Fig. 12. During this interval the rear portion of the arc had five layers of charge associated with a mature precipitation shaft.

The arc of lightning activity beginning at 2245 UTC had become the area with the largest extent and density of mapped lightning sources by the time of the 2255:09–2257:03 UTC volume scan (Fig. 13). The lofted normal polarity tripole above the weak echo region was no longer associated with the 2245 UTC arc. Lightning in the 2245 UTC arc was contained entirely within the precipitation shaft, where the flash and charge structures were as described for the previous radar volume scan.

The time–height view of lightning data (Fig. 9b) suggests that the transition of lightning activity in the 2245 UTC arc...
away from above the weak echo region and into the precipitation shaft to the left of the weak echo region was the final stage in the positive updraft perturbation inferred to have been associated with this arc. Upward surges of lightning sources ceased and banded regions of lightning sources characterized by common inferred charge began to descend.

As can be seen in Fig. 9b, the band of LMA sources at 12-km altitude continued during the transition to a more complex charge structure after 2250 UTC, and there was an upward surge at 2251–2254 UTC (rising at \( \pm 30 \text{ m s}^{-1} \)). Normal polarity flashes were inferred at this altitude, with the upper positive charge in the rising band of sources. Radar sections (Figs. 11 and 12) through the largest lightning source density in the rear portion of the arc showed that the tallest echo of \( Z > 60 \text{ dBZ} \) contained these normal polarity flashes. One such flash took place at 2252:43.5–2252:43.7 UTC and can be seen relative to radar in Fig. 12c. It exhibited positive charge at 14 km and negative charge at 12.5 km. Both of these charge regions were at temperatures colder than \(-40^\circ\text{C}\), suggesting the possibility of charge exchange between hydrometeors at lower altitudes followed by vertical advection of the charged hydrometeors and sedimentation of the heavier particles.

Another band of sources appeared at 12 km from 2253 to 2257 UTC, with some evidence of singleton sources rising above 12 km from 2255 to 2256 UTC. Flashes within this band were also of normal polarity, and were within the tallest echoes on radar.
Beginning at 2251:30 UTC, a band of lightning centered at 10-km altitude (Fig. 9b) developed and descended to around 9 km by 2255 UTC. Another band developed in the same manner at 2256 UTC. Both of these bands were characterized by normal polarity flashes. Flashes composing these bands were located near the top of the precipitation shaft on the left flank of the lofted echo. Positive charge inferred from these normal polarity flashes was at the same altitude as the lower positive charge in the lofted tripole. This new pair of charges appeared to indicate negative charging to the larger hydrometeors, a process which took place about 4 km lower than in the lofted tripole. Charge may have been generated by the noninductive relative growth rate mechanism in an environment with less supercooled water; such generation would require the presence of updraft at midlevels well into the deep precipitation shaft of the storm. It is also possible that the negative charge was carried on hydrometeors that advected from the charging zone near the summit of the strongest updraft. Since the lower positive charge above the weak echo region was associated with large hydrometeors that fell out of the storm relatively quickly, it is unlikely that positive charge at this altitude was formed as part of the same noninductive process as in the embryo curtain.

Throughout 2254–2300 UTC, there was evidence of intervening negative charge from 4 to 10 km in the overall charge structure. Evidence for many thin intervening layers was a 6-charge stack inferred from nearly simultaneous flashes to the left of the weak echo vault at 2254:35.5–2254:38 UTC, where positive charge was found at the bottom and negative at the top. The topmost negative charge layer, a feature often associated with a screening layer, was also inferred in a nearby balloon electric field profile (see section 5). Much of the activity in the stack of 6 charges was within somewhat lower reflectivity ($Z \approx 50$ dBZ) adjacent to the largest hail and farther from the strongest updraft. Later, a pair of nearly simultaneous inverted polarity cloud flashes revealed 4 of the 6 charges at once on the north edge of a hail shaft at 2257:44.2–2257:44.6 UTC, with negative charge centered at 11.5 km and 8.0 km, and positive charge at 9.5 km and 7.5 km.

Because of their position near the top of the storm, it is speculated that cloud ice particles carried the uppermost positive charge at about 12-km altitude and the negative charge at about 10 km in the 6-layer charge structure atop the precipitation shaft. The polarity of charge carried by cloud ice in each region is suggested to have been separated in one of the two charging pairs above the weak echo region, as indicated in Figs. 8c,d. The charged ice crystals remained lofted due to their small terminal fall speeds, unlike the lower positive charge above the weak echo region that was carried on precipitating hydrometeors.

d. Forward portion of the arc, after 2250 UTC

From 2249:39–2251:30 UTC, the forward portion of the arc was within the sloping echo overhang (Fig. 11f). The outline of the lower positive charge revealed by lightning followed the contour of a $Z \approx 65$ dBZ maximum of reflectivity (centered at about 22-km range) that was likely descending as it was advected forward in the divergent outflow near the top of the most vigorous updraft. This descending maximum in reflectivity represented a developing wave of precipitation that was about to form a new leading edge of the forward flank downdraft at the surface.

Around the time of the next radar volume, the initial, elevated normal polarity tripole transitioned to an inverted polarity tripole encompassing a greater depth of the storm (Figs. 12d–f). The forward most portion of the arc exhibited the clearest inverted polarity tripole (Fig. 12f). Rearward positions (Figs. 12e,d) showed increasing interleaving of other lightning-indicated charges and a less clearly layered structure. The onset of the forward-inverted structure was gradual and apparently dependent on the separation of lighter negative graupel precipitating toward the forward flank from heavier positive graupel or hail that fell out more toward the rear.

As indicated in Figs. 8c,d, the upper negative charge in the forward portion of the arc was interpreted to be contributed by cloud ice-sized hydrometeors associated
with the lower charging pair above the weak echo region. The lower negative charge could have fallen out from the upper charging pair of the normal tripole. The midlevel positive-above-negative charging pair (described in the previous section) may have also contributed to the middle positive charge and lower negative charge in the inverted tripole.

The idea that many of the net charge regions were changing their relative vertical and horizontal positions because of advection and different relative fall speeds is supported by the time series perspective in the transition between the normal and inverted tripoles at around 2250 UTC (Fig. 9a), where the charge structure is hard to discern.
At 2252:18.9 UTC enough net negative charge had accumulated at low altitudes in the forward portion of the 2245 UTC arc to support the first of many normal polarity cloud flashes that continued through at least 2300 UTC. Negative charge in these flashes was centered at an altitude of 5.0 km and positive charge at 8.5 km. Inferred storm charge from 8.5 to 11.0 km was positive with few exceptions, and negative charge was inferred at and above 12 km. The upper two charges in the tripole extended horizontally away from the heaviest precipitation shaft indicated by radar and away from the main updraft in the storm.

The 1–2-km-deep bands of relatively dense LMA sources with inferred positive charge were noted within the gross positive charge of the forward flank from 7 to 11 km (Fig. 9a). The deep net positive charge appeared

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Fig. 12. As in Fig. 11, but for (a)–(f) 339°, 343°, 348°, 351°, 359°, and 13° azimuth, 2252:24–2254:16 UTC. (a)–(c) Through the weak echo region, hail cascade, and the incipient left split cell. (d),(e) Transition toward the forward flank. (f) Shows a sloping echo overhang and fully developed forward flank charge structure.
to have a slow (~3 m s⁻¹) upward ascent from 2250 to 2300 UTC. Two finer, descending bands appeared within the deep band. Both appeared at 10.5 km at 2251:20 and 2253:50 UTC, and descended to 7.4 km by 2256:00 and 2257:40 UTC, respectively. A positive charge region was persistent in the rear of the arc at the source altitude of the fine bands, suggesting that advection of charge from generation sites nearer the rear of the arc might have acted to replenish the positive charge region from outside the arc’s forward region.

By 2255 UTC, more of the forward region of the arc exhibited a clearly inverted tripolar charge structure (Figs. 13b,c). Negative leaders propagated within \( Z > 50 \text{ dBZ} \), following the maximum radar reflectivity in the main precipitation shaft, and also propagated to the north, sometimes entering \( Z \approx 40 \text{ dBZ} \).

About once per minute a flash with in-cloud structure similar to the low-level normal polarity in-cloud flashes was reported as a positive ground flash by the NLDN. One such positive ground flash at 2256:52 UTC began at 6 km, and propagated into a positive charge region from 6.5 to 10 km and a negative charge region from 3 to 5 km. Negative propagation through positive charge favored the region to the north of initiation, beginning in \( Z = 65 \text{ dBZ} \) and terminating in \( Z = 40–50 \text{ dBZ} \). After a return stroke detected by the NLDN, a negative leader propagated westward at a median altitude of 5 km into hail (\( Z > 65 \text{ dBZ} \)) west of the initiation location.

For any positive ground flash, mapped in-cloud activity prior to the ground stroke was extensive and similar in extent and morphology to those normal polarity cloud flashes at the same altitude that did not produce ground strokes. Some flashes (such as a flash at 2256:52 UTC) showed propagation through lower negative charge followed by a recoil extension at the other end of the flash into positive charge. In those flashes, the recoil process might repeat a few times, at progressively lower altitudes, before a stroke to ground finally took place. This process is reminiscent of the rapid flickering of short segments of highly branched leaders seen just before the return stroke in a recent high speed video taken of positive ground strikes (Saba et al. 2008).

When compared to the lightning activity in the rear of the storm, the cloud and ground flashes in the forward portion of the storm demonstrate that adjacent regions of positive and negative charge may exist simultaneously in one storm at the same altitude (see also MacGorman et al. 2005; Weiss et al. 2008). A single, horizontally stratified stack of charge was not representative of conditions across the entire storm.

e. Left split

From 2249:39–2251:30 UTC, an additional region of midlevel normal polarity flashes were observed where
the rear of the arc intersected with the main storm (Fig. 11d). This region was spawning a left-splitting cell. It appeared that larger hydrometeors were gaining negative charge near 7 km, which was 3–4 km lower than within the lofted tripole above the storm’s main precipitation vault.

After 2253 UTC, the cluster of lightning associated with the left-moving cell was distinct from lightning in the rest of the arc. An upward surge from 2253 to 2256 UTC (rising at \( \approx 20 \) m s\(^{-1}\)) again had positive charge in the rising plume of sources with negative charge centered at 10.5 km. The midlevel charge structure from 2253 to 2256 UTC appeared to show rising positive charge (6–8 km rising to 8–10 km) with negative charge initially interspersed from 6–8 km. After 2256 UTC, lightning revealed a persistent positive charge region from 8 to 10 km, and a persistent negative charge region from 6 to 8 km. A few flashes also revealed positive storm charge from 4 to 6 km.

The left-split charge structure inferred from lightning at the end of the analysis period was that of a normal polarity tripole. Inclusion of a positive screening layer near the upper cloud boundary would produce the full normal stack of Stolzenburg et al. (1998b). The normal polarity stack in the left-moving cell was situated at lower altitude (warmer temperature) than in the arc from which it split, which suggests that charge in the left split was probably being separated in weaker updraft and lower supercooled water content than in the main updraft analyzed by Stolzenburg et al. (1998a). The negative charge was inferred at about 5 km, just above the loop.

### 5. Electric field meter data

As an exercise in comparing the understanding of charge structure proposed by this study to those published in the literature, balloon-borne electric field meter (EFM) profiles were analyzed according to the methodology of Stolzenburg et al. (1998a), which used ascent rate instead of radar data to place the profiles in the storm context. The first two of four flights on 26 May were chosen for analysis because of their completeness and proximity in space and time to the intensive analysis period.

The ascent of flight 10 (Figs. 14a and 15) had a mean balloon ascent rate of 4.3 m s\(^{-1}\) and a median ascent rate of 4.4 m s\(^{-1}\). The maximum ascent rate was 12.3 m s\(^{-1}\). Excluding all negative ascent rates in flight 10 increased the mean and median ascent rates to 4.9 and 4.6 m s\(^{-1}\), respectively, which was less than the balloon’s nominal free rise rate of 5 m s\(^{-1}\). Using the methodology of Stolzenburg et al. (1998a), flight 10 would be classified as a sounding outside strong updraft.

The ascent of flight 12 (Figs. 14c and 16) had a mean balloon ascent rate of 9.0 m s\(^{-1}\) through 12.25 km, where \( E \) dropped to near zero and the balloon briefly halted its upward motion. The median ascent rate was 9.3 m s\(^{-1}\), and the maximum ascent rate was 17.5 m s\(^{-1}\). Subtracting the expected rise rate of the balloon gives mean storm vertical velocity of 4 m s\(^{-1}\), which is too low to be classified as a strong updraft using the Stolzenburg et al. (1998a) method.

While the sounding from flight 12 exhibited a moist adiabatic profile from 650 to 800 mb that was characteristic of the surface mixed layer parcel from the 2331 UTC environmental sounding (Fig. 16), all other portions of both soundings were cooler than the theoretical parcel given by the 2331 UTC sounding. The thermodynamic characteristics provide further confidence that the soundings were not representative of undiluted updraft environments and are best compared with the soundings outside of strong updraft analyzed by Stolzenburg et al. (1998a).

A one-dimensional application of Gauss’s law to the vertical component of the electric field was completed for flights 10 and 12 (Figs. 14b and 14d, respectively). Only those charge regions with charge density greater than 0.1 nC m\(^{-3}\) for a depth greater than 200 m were included in the analysis, as suggested by Stolzenburg and Marshall (1994).

All inferred layers were relatively thin (median of 620 and 720 m for flights 10 and 12, respectively), and no layer was deeper than 2 km. The largest absolute charge densities were at 5–9 km in the flight 10 profile, but were at the top of the flight 12 profile.

An ascending–descending–ascending loop from 4 to 5 km in flight 10 showed some inconsistency, with positive charge on the first ascent and essentially neutral charge on the descent and second ascent. The charge profile (Fig. 14b) reflects the ascending positive charge. The negative charge was inferred at about 5 km, just above the loop.

There were 10 significant charge regions in flight 10 and 8 in flight 12. Both profiles were consistent with the outside-strong-updraft profiles of Stolzenburg et al. (1998a). The lowest significant charge in both flights was positive near 4 km. The uppermost charge in both flights was negative just above 12 km. Most of the significant charge was above 5 km, which both balloons reached between 2250 and 2300 UTC. The upper negative charge may have been a screening layer which formed because of the negative ion current at the top of the cloud induced by the strong positive storm charge inferred from lightning mapping data.

By 2300 UTC, both flights were within the minimum in lightning activity between the rear of the 2245 UTC arc and the left split, and at 2303 UTC flight 12 caught and passed flight 10 at 7.5 km. For comparison, the nearest charge profile inferred from lightning activity is that through the rear portion of the arc in the hail.
cascade (Fig. 8, sections A–B), where five charge regions were inferred from lightning. Negative charge in flight 10 from 5.5 to 6.3 km was corroborated by a few flashes in the vicinity. The lowest significant charge was positive in both EFM soundings and in the lightning data. The presence of an upper negative screening layer was corroborated by both EFMs, and this is the polarity of charge that should accumulate at the cloud boundary if influenced by the upper positive charge inferred from LMA data below the cloud boundary.

FIG. 14. Balloon soundings with EFMs launched at (a) 2234 and (c) 2250 UTC just south of Hinton, OK. Plotted are the vertical component of the electric field ($E_z$), temperature ($T$), relative humidity with respect to water (RH) and ice (RHice), and ascent rate (Asc) of the balloon. Color for each variable is indicated by the x-axis label. Only the up soundings are plotted. (b),(d) Charge inferred from a one-dimensional application of Gauss’s law to the vertical component of the electric field.
There were more intervening layers from 6–12 km in the EFM profile than were inferred on the left flank of the main updraft. The additional regions may have had too little total charge to be energetically favorable for lightning propagation or may have been artifacts of the assumption of infinite layers of charge in the computation of charge from the electric field profile. Lightning corresponding to the upper portion of the balloon trajectory was at increasing distance from this study’s intensive analysis domain, which may also explain some of the discrepancy. Overall, however, the EFM profiles agree with the lightning data in the sense that more charges were inferred in the left-rear region of the storm than elsewhere, and that the lower- and uppermost (significant and non-screening) charges were positive.

6. Discussion

a. Electrification and precipitation formation

Figure 8 summarizes the synthesis of lightning and radar data and relates it to the supercell structural features indicated in Fig. 1. As charge has been inferred primarily from lightning mapping data, it is not necessarily a complete record of all charge regions. Balloon soundings revealed a negative screening layer at cloud top in the rear of the arc, which is indicated in the figure. The absence of balloon soundings in the forward portion of the arc prevented the assessment of a screening charge there. A positive screening layer is included in the forward portion of the arc (Fig. 8, right-hand side of sections C–D), where one might be expected based on physical principles.

As drawn, Fig. 8 is primarily spatial. However, the precipitation formation process in thunderstorms illuminates a temporal component to the figure. The weak-evolving characteristics of the 26 May storm draw attention to this aspect. Lightning was observed to develop first in the main updraft immediately surrounding the weak echo region. Lightning activity then tracked with precipitation as it fell out on the forward and left flanks of the main updraft. Viewed another way, the temporal evolution of spatially extensive maxima in lightning is
an indication of episodes of precipitation development in the storm.

Supercells are able to maintain their long life in part because storm dynamics set up microphysical trajectories that permit much of the precipitation to fall out downshear of the updraft in the forward flank. Reconfiguration of the precipitation trajectories during the transition to supercellular structure around 2240 UTC may explain the cessation of negative ground flashes and the development of the inverted charge region in the forward flank that produced occasional positive ground strikes.

Figure 8 indicates regions of charging in addition to regions of net charge. They represent a synthesis of the noninductive relative growth rate and screening layer charging principles with gross updraft structure and cycling inferred from reflectivity structure and the appearance and disappearance of charge regions with time. The lightning density patterns and inferred charge structures varied spatially and temporally on 1-min intervals. These details cannot be addressed even with the relatively quick 3-min volume scans by the SMART-R.

The scenario as inferred, therefore, represents only an attempt to explain regions of charging as they relate to storm reflectivity and kinematic structure. Such an attempt is useful as it makes concrete predictions that future studies can test.

b. Supercooled water and altitude of charging regions

Comparison of the altitude of three charging regions inferred in this storm provides a consistency check on ideas about how supercooled liquid water (SLW) impacts charging. A positive-above-negative charging dipole was inferred in the precipitation above the weak echo region, on the left flank of the weak echo region in the hail cascade, and in the left-splitting cell. The altitude of charging was greatest above the weak echo region, consistent with the likelihood of the storm’s strongest updraft and largest SLW concentrations being in that location. There, it seems vertical advection pushed just-separated upper positive charge above the −40°C isotherm (about 1 km). The lower charging pair appeared to straddle about 9 km, at

![Fig. 16. As in Fig. 15, but at 2250 UTC from Hinton, OK.](image-url)
approximately -25°C to -30°C. The altitude of charging was somewhat lower adjacent to the weak echo region, where weaker updraft and reduced SLW is expected. From the data, it is difficult to infer relative updraft speeds in the left-splitting cell, but a lower maximum altitude of comparable reflectivity contours suggests it had the weakest updraft and lowest SLW. The upper normal-polarity charging dipole was at its lowest altitude in the left split.

The charge structure in the rear portion of the mature arc is consistent with a process of interleaving of the charge from local charging processes and from the charging region associated with precipitation above the weak echo region. Such patterns in the data argue for the importance and interplay of these regions of varied SLW concentration.

c. Flash size

Experience indicates that flashes with larger numbers of sources tend to have larger spatial extent. Impulsive breakdown into regions with no preexisting lightning channels appears to generate most of the detected sources in a flash, so flashes necessarily produce more VHF sources as they increase in extent through regions of charge.

At all times, flashes were typically quite compact (sources per flash <100) in the region surrounding the vault and above the weak echo region. One reason for the flashes’ small extent may be that charge-bearing precipitation was being turbulently mixed outside the strongest updraft (represented by the vault). Alternatively, the interaction of complex three-dimensional flow (circulating horizontal flow and gradients in updraft strength) with a range of hydrometeor sizes of mixed charge polarities may have resulted in more variability in the location and amount of charging and differential sedimentation. The advective and thermodynamic environment experienced by charged and charging particles was by no means homogeneous across the updraft-supported region of lofted precipitation.

In addition to continued small flashes, larger flashes were found with increasing distance from the main updraft. The forward precipitation region (and to a lesser extent, the hail cascade) was more favorable for organized, layered differential sedimentation. The relatively long time taken for hydrometeors to reach the forward part of the storm allowed hydrometeors discharged in the divergent flow near the storm top to organize into the simpler inverted tripole structure. Charging in lower SLW near the rear portion of the forward part of the maturing arc of lightning activity apparently contributed much of the midlevel positive charge, and the absence of positively charged, large hydrometeors that quickly fell out farther to the rear might have assisted the formation of the lower negative charge.

7. Concluding remarks

The model in Fig. 8 is necessarily a conceptual simplification of complex, time-evolving, and finely structured regions of charge. The details of the data show a close relationship with localized precipitation features of horizontal scale on the order of a few kilometers. The conceptual model includes only the most persistent charge regions.

Even with these simplifications, Fig. 8 facilitates comparison of charge structure to published conceptual models of supercell morphology in a way that is advanced beyond previous studies. For instance, the cross section through the embryo curtain, weak echo vault, and hail-bearing precipitation shaft (Fig. 8, sections A–B) is similar to the cross section of Browning and Foote (1976, their Fig. 11). Such a conceptual model facilitates clear comparisons of charge structure from storm to storm, since it predicts what charge is expected in kinematic and microphysical regions readily identifiable with weather radar.

The identification of the arc-like lightning density maxima and a description of its evolution is a new contribution. The arcs followed the development of precipitation in accordance with established schematics and trajectories of precipitation formation in supercells, as reviewed in the introduction. A consistent elevated normal polarity tripolar charge structure was found in precipitation held aloft in the strongest updraft. Within the precipitation cascade, the charge structure was more complex and depended on the forward-aft position within the storm. The complexity manifested itself in evolving charge structures that were compatible at times both with the normal polarity model of Stolzenburg et al. (1998b) and with the inverted structure of MacGorman et al. (2005) and Wiens et al. (2005).

The complexity was presumably due in part to the three-dimensional flow and its advection of charged hydrometeors, as well as to the contribution of a range of sedimentation speeds. Regions of updraft within the precipitating region (though not strong enough to loft all precipitation) probably also contributed to charging, though presumably in a different supercooled water regime where the charging tripole operated at lower altitudes than in the main updraft.

The storm required a time-evolving three-dimensional depiction of charge to accurately represent reality. Any approach that neglected the multidimensionality of the storm would have difficulty in explaining where, when, and why important events such as positive ground flashes took place.
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