SUPERCELLS AND SPRITES

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We investigate why sprites are often induced by positive polarity cloud-to-ground lightning strokes (+CGs) in high plains mesoscale convective systems but rarely by +CGs in supercell storms.

A very large sprite over Kansas observed during the STEPS research program in the summer of 2000. Sprites are primarily red in color, except for some bluish tinge in the downward extending tendrils. (Image: Walter Lyons, FMA Research, Fort Collins, Colorado)

Since the serendipitous discovery of sprites above a Minnesota thunderstorm during low-light television (LLTV) tests in July 1989 (Franz et al. 1990), sprite detection above high plains convective storms has become routine (Lyons 1994, 1996; Lyons et al. 2003a; Sentman et al. 1995). Over 10,000 sprites have been monitored from LLTVs from Colorado's Yucca Ridge Field Station (YRFS) and all for which a parent cloud-to-ground lightning stroke could be associated were of positive polarity (+CG). Barrington-Leigh et al. (1999) discuss two of the less than a dozen confirmed negative CG sprite parents. High plains summer convection is characterized by high percentages of +CG strokes (Orville and Huffines 2001), many with very large peak currents (Lyons et al. 1998). Sprites are generally agreed to result from ▶

conventional dielectric breakdown at approximately 70–75-km height (Stanley et al. 1999), induced by an intense but transient electric field due to the removal to ground of large amounts of electric charge in a CG flash (Pasko et al. 1996). While the peak current of sprite parent +CGs (SP+CGs) is typically 50% larger than the other +CGs in the same storm (Lyons et al. 2006), peak current by itself is not a good predictor of sprite formation. As initially suggested by Wilson (1925), the key metric is the charge moment change,

$$\Delta M_q(t) = Z_q \times Q(t), \tag{1}$$

defined as the product of Z_q, the mean altitude (AGL) from which the charge is lowered to ground and the amount of charge [$Q(t)$] lowered, with this second term most appropriately considered as a function of time. Huang et al. (1999) and Williams (2001) refined Wilson's original theory and proposed, based upon initial radio measurements gleaned from Schumann resonance extremely low-frequency (ELF) transient analyses (Boccippio et al. 1995), that for sprite breakdown to occur, ΔM_q values would need to be on the order of 500 to 1,000 C km. Hu et al. (2002) present a probability distribution of ΔM_q threshold values, suggesting there was a 10% chance of a sprite for CGs with ΔM_q = 600 C km, increasing to 90% for values >1,000 C km. These ΔM_q values are many times larger than commonly reported "normal" CG values (Rakov and Uman 2003). Interestingly, the consequences of Wilson's theory do not require that the parent CG event be of positive polarity. Williams et al. (2007) have noted this "polarity paradox" while presenting global ELF measurements, which suggest that at least 10% of all ΔM_q measurements exceeding sprite breakdown are associated with negative CGs. Recent satellite measurements (Frey et al. 2005) indicate that the negative TLEs (primarily halos and elves) may likely be concentrated over saltwater, where there is growing evidence that −CGs are more powerful (Lyons et al. 1998).

Over a decade of midcontinent sprite monitoring has produced yet another puzzle. Only certain storm types, and only during certain phases of their life cycles, produce SP+CGs. Sprites are extremely rare above supercells, though this convective regime is often accompanied by large numbers of high peak current +CGs (Stolzenburg 1994; Marshall et al. 1996; Rust and MacGorman 2002). Lyons et al. (2003b, 2006) documented that SP+CGs tend to occur above portions of the stratiform precipitation region of mesoscale convective systems (MCSs), generally in areas with reflectivities <35–40 dBZ once this region had attained a size of >10–20 × 10^3 km^2. In addition, Williams (1998) proposed that the SP+CGs were most likely associated with charge removal (Z_q) from the lower stratiform charge layers, in the 0° to −10°C region, including the melting layer. This contrasts sharply with numerous theoretical modeling papers of sprite energetics that postulated Z_q values between 10 and 20 km, in part to generate a sufficiently large ΔM_q triggering mesospheric breakdown.

Approximately half of all sprites are delayed >10 ms from their SP+CG return stroke, consistent with the notion that much of the charge transfer occurs after the CG return stroke, and is accomplished by continuing currents of considerable magnitude. These are likely fed by the extensive dendritic patterns of "spider" lightning (Mazur et al. 1998) spreading outward into the large laminae of positive charge found in the MCS stratiform region. While both MCS stratiform regions and supercells often have large numbers of +CGs, frequently with large peak currents, it would appear the latter's structure precludes the routine production of CGs (of either polarity) with sufficiently large continuing currents to allow ΔM_q to attain sprite breakdown values.

SPRITE MONITORING DURING STEPS.

The Severe Thunderstorm Electrification and Precipitation Study (STEPS) was conducted in eastern Colorado, western Kansas, and southwest Nebraska from 22 May through 10 August 2000 (Lang et al. 2004). The observational program was designed for coordinated measurements of the dynamical, microphysical, and electrical processes within severe storms, especially those producing positive CGs. Most relevantly, STEPS deployed an operational 3D Lightning Mapping Array (LMA), which provided information on intracloud (IC) discharges to ranges

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approaching 150–200 km (Thomas et al. 2004). Centered near Goodland, Kansas, the LMA domain was ideally situated to allow monitoring sprites and other transient luminous events (TLEs) using LLTVs deployed at YRFS 275 km to the northwest. Coincident with the optical monitoring, ELF transients were recorded at Duke University (Cummer and Lyons 2004, 2005) for the purpose of extracting ΔM_q values for the CGs. STEPS represented the first large-scale effort to determine not only lightning polarity and peak current within these storms, but also ΔM_q, and for events within the LMA, Z_q and the charge (Q) lowered to ground.

Two MCSs passed through the LMA domain on 19 July 2000 (Lyons et al. 2003b). Two independent techniques for estimating ΔM_q for 13 SP+CGs yielded averages of ~800 (Duke) and ~950 C km (E. Williams, MIT, 2002, personal communication). Analyses of the LMA's very high-frequency (VHF) lightning emissions within the MCSs show +CGs did not produce sprites until the mature phase of the storm, when the stratiform region grew to >30 × 10^3 km^2. Moreover, the centroid of the maximum density of VHF lightning radiation sources dropped from the upper part of the storm (7–11.5 km AGL) to much lower altitudes (2–5 km AGL) as the sprites commenced. The average height of charge removal (Z_q) by the SP+CGs during the MCS late mature phase was 4.1 km AGL. Thus, the total charges lowered by SP+CGs were very large, on the order of 200 C (maximum 345 C), in great part due to intense and long-lasting continuing currents. The average area from which charge was removed was ~1,300 km^2. Cummer and Lyons (2004, 2005) examined the distribution of ΔM_q values from several STEPS storms finding negative CGs rarely, if ever, approached sprite ΔM_q threshold levels.

During STEPS, over 1,200 TLEs were recorded, all above MCSs, save five sprites observed above a supercell. This paper examines the electrical characteristics of that atypical storm, and a second +CG-dominated supercell that did not produce any CGs exceeding the ΔM_q threshold. We will compare the nature of supercell +CGs to those in MCS stratiform regimes. Jacobson and Krider (1976), in reviewing ΔM_q values for numerous smaller convective systems worldwide, found none in excess of 600 C km. Whether this will be so in electrically active high plains supercells, often hail and tornado producers, but an order of magnitude or more smaller than most MCSs, will herein be explored.

THE 29–30 JUNE 2000 SUPERCELL. After sunset on 29–30 June 2000, a large MCS produced 18 sprites over central Kansas. The average +CG peak current was 42 kA, with a mean ΔM_q of 1,086 C km. All SP+CGs occurred in the lower reflectivity, stratiform region at a considerable distance from the MCS's convective core. Supercells, a major focus of STEPS, tend to occur during daylight hours when LLTV monitoring for TLEs is not feasible. During the afternoon prior to the MCS development, a compact supercell formed in the same air mass in northwestern Kansas within the LMA domain and spawned an F1 tornado and numerous large hail reports (Fig. 1a). The path of this much-investigated, right-moving tornadic supercell, in which 60-dB*Z* reflectivities reached as high as 10 km (Wiens et al. 2005), is evident in Fig. 1b. The supercell's CGs were dominant positive polarity (91%, average 46 kA) while the –CGs averaged 17 kA (Fig. 1c). The total flash rate in the storm at times reached 300 flashes per minute, with most (>90%) being intracloud discharges. The +CGs tended to cluster around the heavy precipitation core.

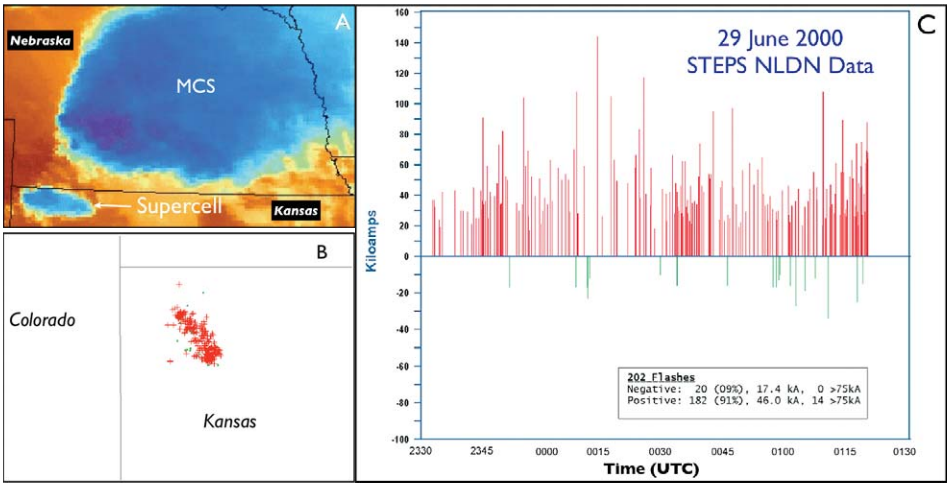

Fig. 1. (a) GOES IR showing both a Kansas supercell and a developing MCS in Nebraska at 0000 UTC 30 Jun 2000, (b) along with the track of the supercell NLDN CGs (red positive; green negative), and (c) the time history of the supercell stroke peak currents and polarity.

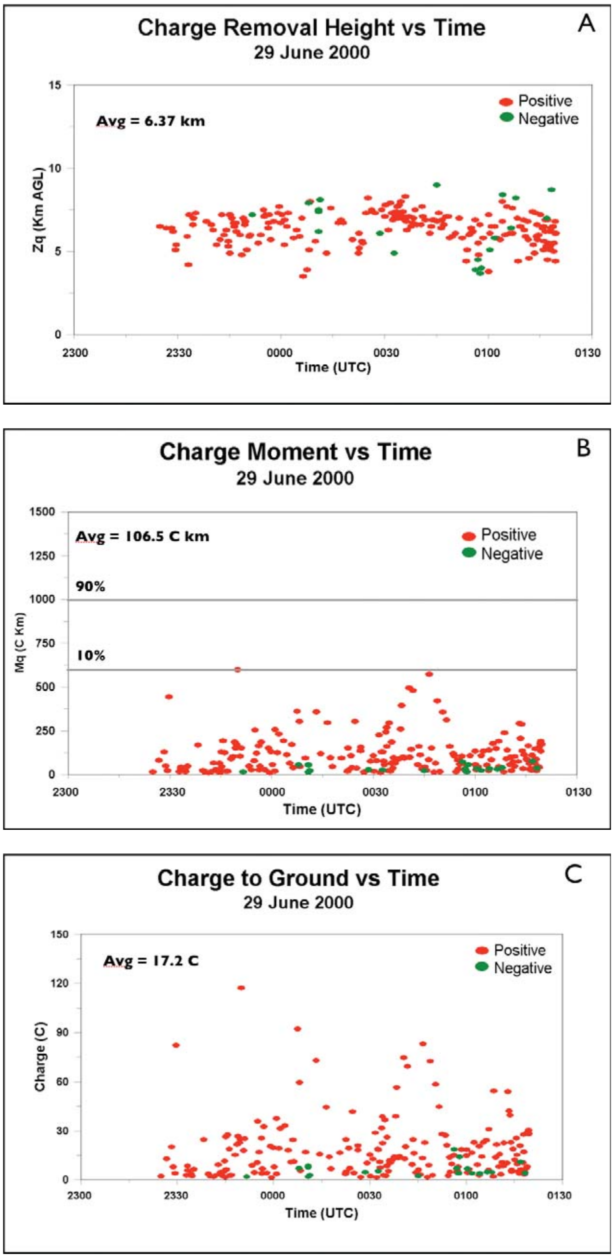

Fig. 2. (a) Height of the charge removal by CGs from a supercell traversing the LMA on 29–30 Jun 2000, (b) the measured charge moment change, and (c) the charge lowered to ground (Coulombs). Positive polarity strokes in red; negative in green.

The Duke ΔM_q retrieval technique, even with the sensitivity available at that time (it has since been markedly improved), was able to determine charge moment changes for most of the storm's CGs (Fig. 2b). No +CG had an ΔM_q >600 C km, consistent with the dearth of sprites above supercells. While nine +CGs did attain ΔM_q values >300 C km, no −CG exceeded 100 C km. LMA data were processed at Colorado State University determining the Z_q values for each CG (Fig. 2a). With typical values around 7 km AGL, the characteristic charge lowered by these supercell CGs was <50 C, though one +CG lowered 118 C (Fig. 2c).

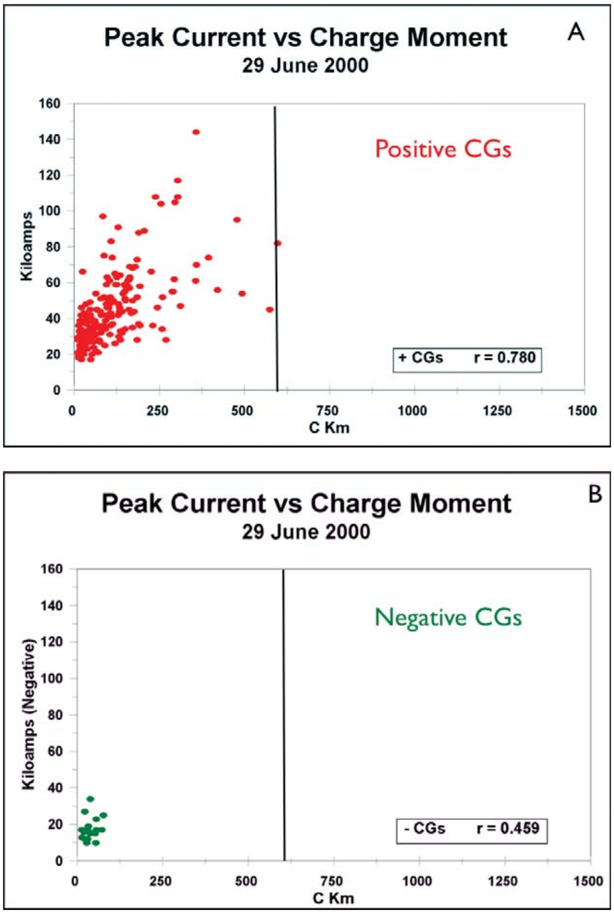

Fig. 3. Measured charge moment changes for both (a) positive and (b) negative CGs plotted against NLDN peak currents, 29–30 Jun 2000 STEPS supercell. While fairly large, the +CG charge moment changes do not exceed 600 C km, the nominal threshold for sprites, and are also substantially larger than for negative CGs.

A plot of ΔM_q versus National Lightning Detection Network (NLDN) peak currents for CGs of both polarities is shown in Fig. 3. The fairly robust correlation, especially for the +CGs, suggests that the ΔM_q values were produced by rather impulsive CGs, with much of the charge lowered during the return stroke. Given the small size of the storm, there were no large horizontal laminae of positive charge to draw upon for production of significant continuing currents. Moreover, while the −CG sample is small, with few values reaching even 50 C km, part of the sprite polarity paradox over the high plains may be explained by systematically smaller ΔM_q values for −CGs. The lack of +CGs >600 C km is consistent with

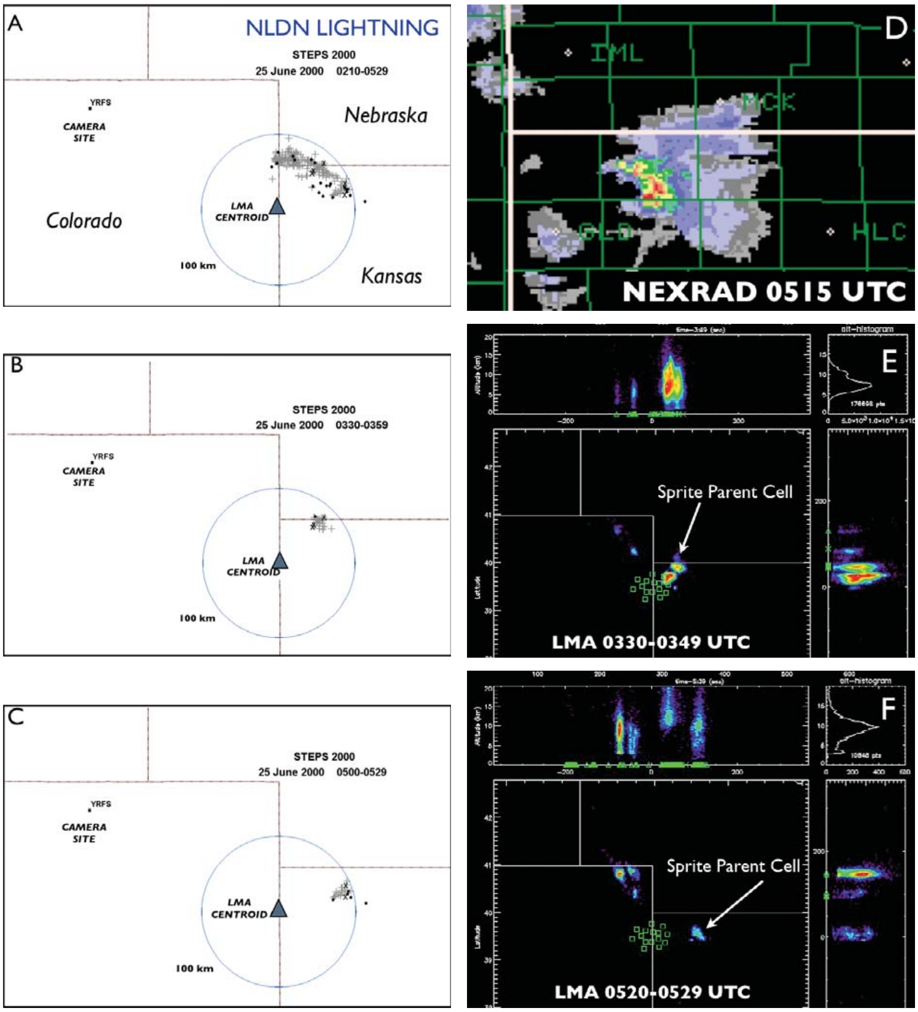

Fig. 4. For the 25 Jun 2000 supercell within the LMA domain, plots of NLDN CGs (positive gray; negative black; sprites shown as X) for periods (a) 0210–0529, (b) 0330–0359 (during storm's maximum intensity), and (c) 0500–0529 UTC during the end-of-storm phase, plus (d) the Next Generation Radar (NEXRAD) image for 0515 UTC, and 10-min summaries of VHF source densities (e) at 0340–0349 (intense mature supercell) and (f) at 0520–0529 UTC showing the very small area of electrical activity remaining in the decaying supercell east of the sensor grid (green squares). The radar areal coverage at 10 dBZ at 0529 UTC (not shown) was about 10,000 km².

the absence of sprites in typical supercells.

THE 25 JUNE 2000 SUPERCELL. Prior to STEPS, the few sprites observed above supercells had appeared during their decaying stage when significant stratiform precipitation had developed around their collapsing cores. On 25 June 2000, a supercell that produced some hail to 0.75 in. (1.7 cm), nearly continuous IC discharges, and 80% positive CGs traversed the LMA between 0200 and 0530 UTC (Figs. 4a and 5). Monitored by several LLTVs, it was thought to be producing no sprites, until the very last two +CGs of the storm (Fig. 5). These "end-of-storm" sprites occurred above

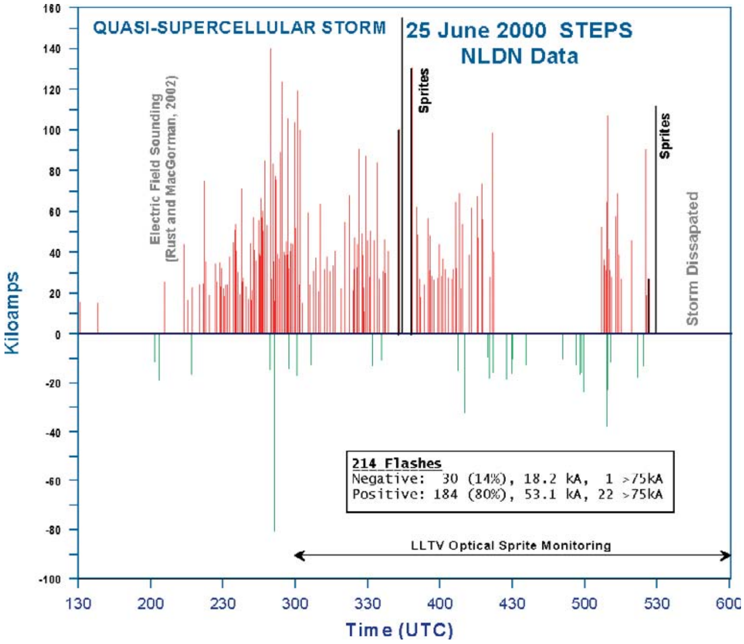

Fig. 5. Plot of NLDN CG peak currents for the 25 Jun 2000 supercell (up/red are positive polarity). The five sprite events are highlighted in black. The marked lull in +CGs before the onset of the storm's decaying stage is not readily explained.

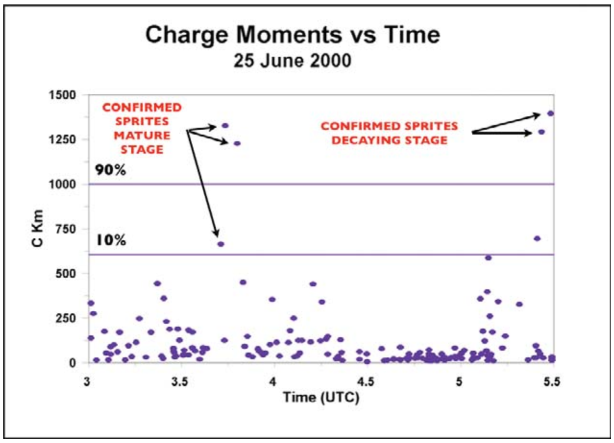

Fig. 6. Measured charge moment changes for the supercell of 25 Jun 2000. The last two +CGs of the storm produced large charge moment changes, both of which triggered sprites. Also during the most intense phase of the storm, three of four successive +CGs produced charge moment changes large enough to trigger small sprites.

the low reflectivity portion of the decaying storm, which had enlarged to an area of ~10 × 10^3 km^2 (Fig. 4d). The computed ΔM_q values for these last two +CGs were 1,293 and 1,396 C km, well above the sprite threshold (Fig. 6).

Just before sunset, electric field soundings (Rust and MacGorman 2002) confirmed an apparent "inverted polarity" structure in this cell. Thus, it is not surprising that the supercell had been producing high peak current +CGs during its quasi-steady-state mature phase and no sprites—at least that was the conclusion upon an initial review of the LLTV tapes. The Duke ELF transient analysis system subsequently retrieved the ΔM_q values for a majority of +CGs between 0300 UTC (the onset of LLTV monitoring) and the end of the storm. The very high ΔM_q values for the two end-of-storm sprites are evident. But also appearing are three ΔM_q events >600 C km that unexpectedly occurred during the most intense period of the storm (Fig. 6). A recheck of the LLTV tapes indeed found three sprites associated with these +CGs, which, albeit dim and easily overlooked, nevertheless confirmed mesospheric electrical breakdown.

The plot of the LMA's VHF sources (Fig. 7) show electrical activity consistently reaching 11 to 14 km until the storm's demise began around local midnight. The centroid of maximum VHF returns remained near 6–8 km AGL until it dramatically decreased in altitude as dissipation onset. Reminiscent of the pattern found for the MCSs of 19 July 2000 (Lyons et al. 2003b), the two end-of-storm sprites occurred during this collapsing phase as the stratiform precipitation area was expanding (Fig. 4d) and major electrical activity was rapidly waning (Fig. 4f). The earlier three sprites are another matter. They occurred during a period of presumably intense updrafts and strong electrical activity (Figs. 4b,e), when prior experience suggests sprites were uncommon.

Figure 8 illustrates the storm's electrical structure for the last end-of-storm sprite. The LMA shows the entire discharge, with the horizontal IC discharge in the period between the return stroke and the end of the sprite luminosity (yellow and pink points) extending laterally over a circular region of ~25-km diameter at an altitude of 5 to 7 km AGL. The +CG peak current was a robust +112 kA, and the ΔM_q was an impressive 1,396 C km. The LMA indicated Z_q to be approximately 5–6 km AGL, resulting in a computed ~255 C of charge lowered to ground. The area discharged prior to sprite termination was ~500 km^2. Assuming that 1) most of the charge was removed from a layer 2,000 m in depth, and 2) that 25% of the charge in this volume was removed by the flash, this implies an initial charge density on the order of 1.0 nC m^{-3}. Revealingly, a slow antenna electric field measurement made about 75 km from the parent +CG (by coauthor Stanley), indicated an exceptionally intense continuing current after the return stroke, as large as 11 kA in the period 5–10 ms after the return stroke.

By contrast, one of the midstorm events is shown in Fig. 9. The 10-dB*Z* area was smaller (~7,500 km^2)

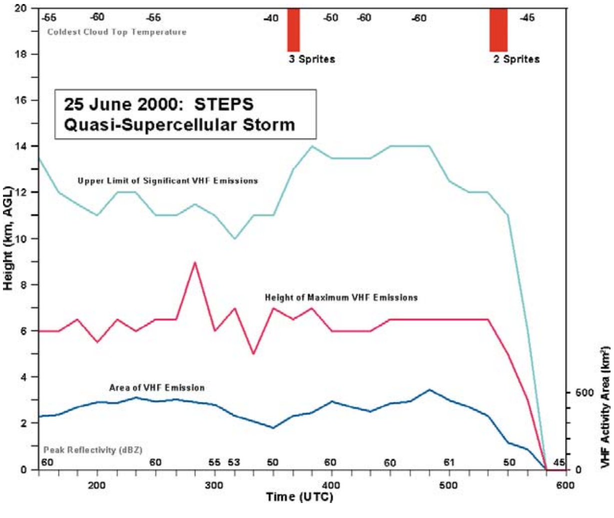

Fig. 7. History of the centroid of the height of the maximum VHF source emissions, as well as their vertical extent and areal coverage, recorded by the LMA during the passage of the 25 Jun 2000 supercell. The time of occurrence of the two clusters of sprites and the coldest cloud-top temperatures are indicated at the top.

at this time, and the area discharged during the sprite was smaller, about 12.5 km in diameter, covering no more than ~125 km^2 and was about 2,000 m in depth. The NLDN peak current was +155 kA and the ΔM_q estimated at 1,327 C km. The charge was removed from a layer centered at 4–6 km AGL, yielding a lowered charge of ~265 C. Again assuming 25% charge depletion in this volume, the initial charge density in the volume is estimated at 4–5 nC m^{-3}. This is a value larger than those typical of MCS stratiform positive charge laminae (Schuur and Rutledge 2000) and is likely more typical of convective cores. The slow antenna indicated the +CG electric field was much more impulsive with a less significant continuing current >2.5 ms after the return stroke.

We propose that the final two end-of-storm sprites occurred within a cloud structure more reminiscent of an MCS stratiform region. By contrast, the unexpected sprites during the intense stage of the supercell may be considered exceptions that prove the rule. Charge generation within the intense updrafts may have been so vigorous that the charge lowered primarily during the return strokes was sufficient to initiate breakdown with little or no contribution required from subsequent continuing currents. Of the four +CG strokes that occurred in roughly a 5-min period, three produced sprites, suggesting an intense but transient electrical configuration within the storm.

CONCLUSIONS. U.S. high plains sprites appear almost exclusively induced by +CG lightning strokes, though only by those possessing unusually large charge moment changes (ΔM_q). While +CGs are especially numerous in both supercell storms and in the stratiform precipitation region of large mesoscale convective systems (MCSs), sprites are common above large MCS stratiform precipitation areas but rare above supercells. Case studies have confirmed MCS stratiform region +CGs (though rarely –CGs) are

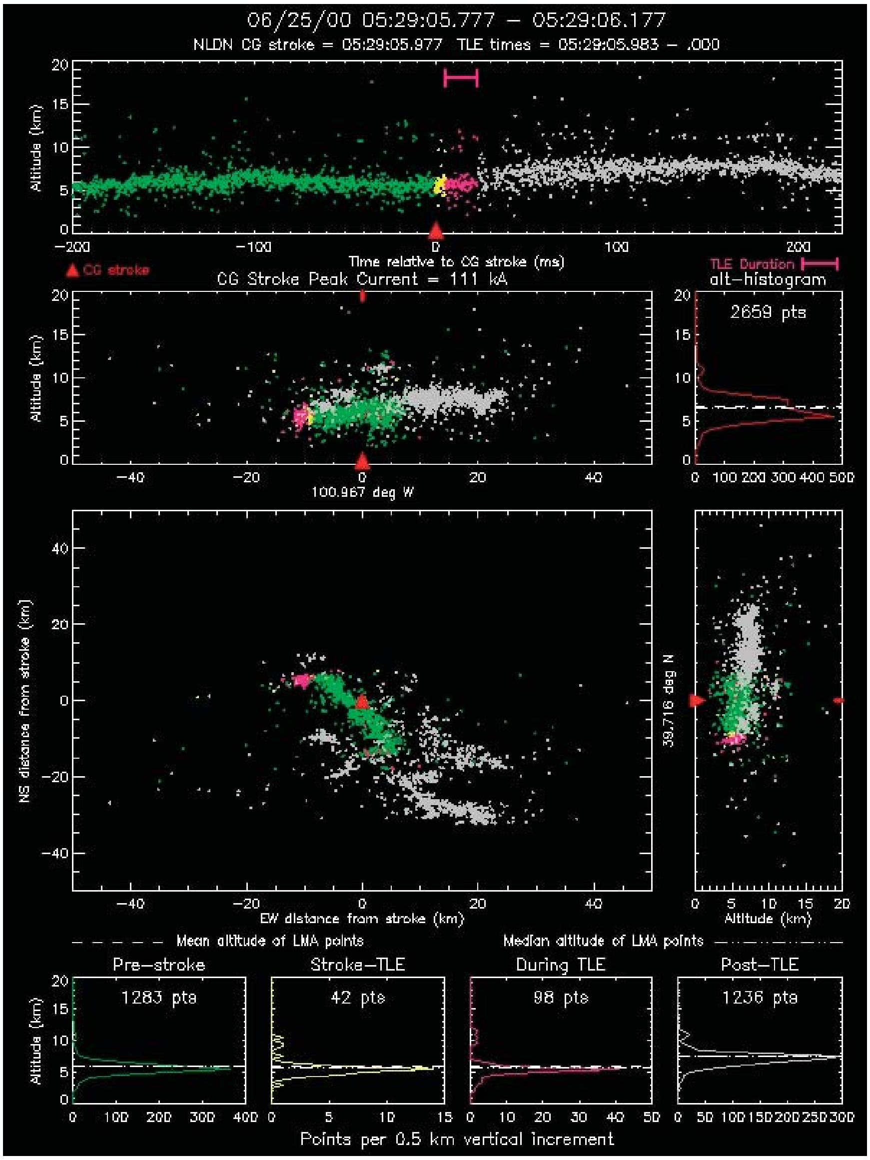

Fig. 8. LMA portrayal of the discharge producing the last +CG in the supercell of 0529 UTC 25 Jun 2000. The VHF sources are mapped in the horizontal, time-height, and meridional-height planes, with sources before the +CG shown in green, those between the return stroke and the onset of sprite luminosity in yellow, those during sprite luminosity in pink, and the remaining sources in white. The +CG is indicated by the red triangle and the period of sprite luminosity in the video is shown at the top of the time-height plot. The number of VHF sources as a function of altitude (MSL) during the several stages of the discharge are shown as inserts. The entire discharge extended over ~50 km and lasted for ~400 ms while remaining in the 4–7 km (AGL) altitude layer.

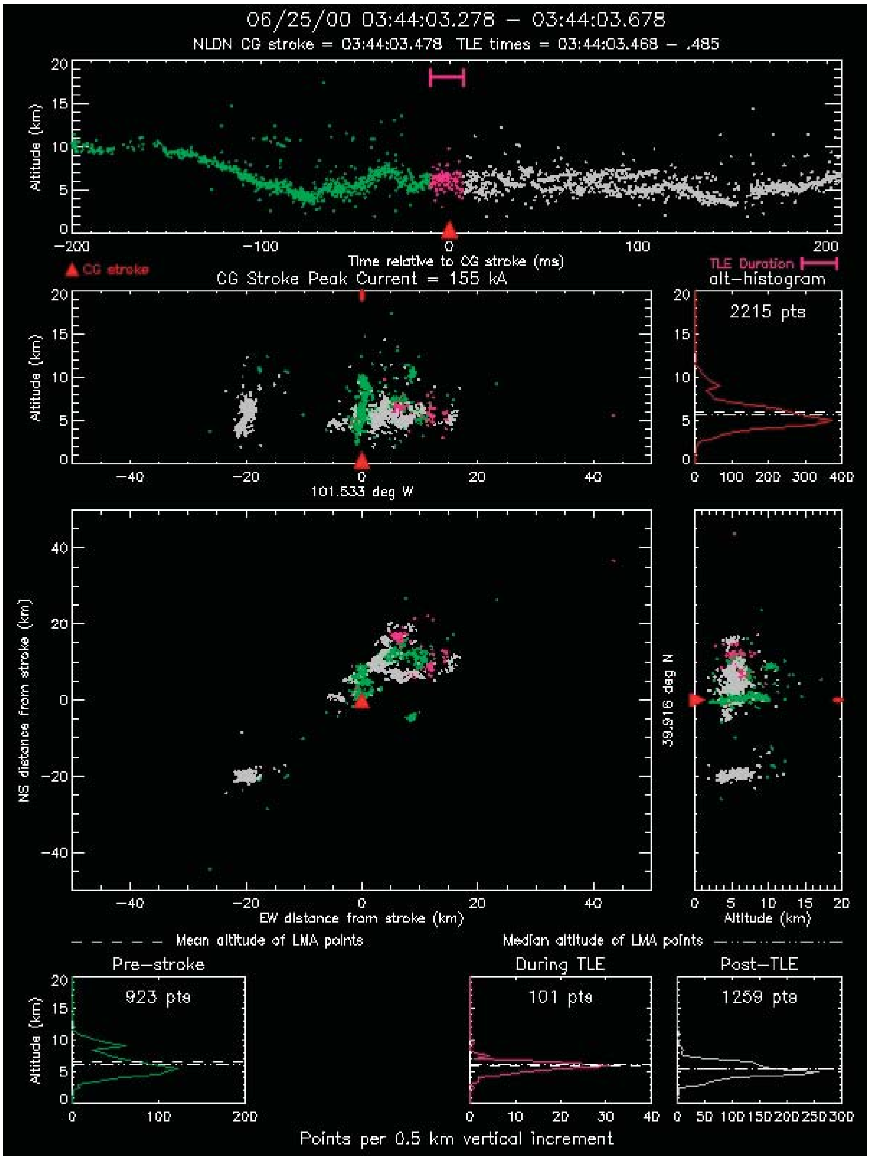

Fig. 9. Same as in Fig. 8 but portraying a sprite parent discharge and +CG during the supercell of 0344 UTC 25 Jun 2000, during its most intense mature stage. The sprite luminosity began during the same 16.7-ms video field in which the return stroke occurred. The entire discharge extended for about ~20 km over ~400 ms and appeared to originate high within the storm (~10 km) before descending into lower charge layers.

frequently associated with ΔM_q values >600 C km, the nominal threshold for sprite production. STEPS provided the opportunity to investigate supercellular storms within range of a 3D Lightning Mapping Array (LMA) and coincident with extremely low-frequency (ELF) and electric field measurements. On 29 June 2000, the CGs from a compact, late afternoon, inverted polarity supercell were 91% positive polarity, yet all had ΔM_q values <600 C km. During the evening of 25 June 2000, a supercell was observed to produce two brief bursts of sprites. The final two +CGs in the decaying storm produced sprites (average ΔM_q values of 1,345 C km) as the stratiform precipitation region grew to >10,000 km^2 and the storm structure began to more resemble a sprite-generating MCS. However, three sprites occurred during a brief interval during the most intense stage of the supercell. These +CGs, the first known to induce sprites during the mature stage of a supercell, had peak currents ranging from 101 to 155 kA. While both sets of sprite parent +CGs exhibited detectable continuing currents, the electric field data showed the midstorm sprite +CGs were far more impulsive, suggesting much of the charge lowered was during the return stroke.

Thus, based upon our understanding of supercell evolution, it does seem reasonable to expect that SP+CGs would most likely occur near the end of the storm. In rare cases during the mature storm phase, sufficiently large quantities of charge may be lowered by very impulsive return strokes, which initiate a sprite.

While infrequent sprite producers, supercells are increasingly being found the source of a variety of electrical discharges from the cloud top extending anywhere from 1 to 50 km above the cloud. A summary of blue starters, blue jets, gigantic jets, and upward lightning (Lyons et al. 2003b) suggests supercells with overshooting domes penetrating the stratosphere bear closer observation. The recent report of the first gigantic jet over North America (van der Velde et al. 2007) emerged from a supercell, which overshot the tropopause by several kilometers. Later, as this storm evolved upscale into an MCS, it produced 30 sprites.

The growing number of metrics available to routinely investigate convective storm electrical activity (IC and CG structure and counts, stroke multiplicity, polarity and peak current, and now, charge moment change and estimated charge lowered and potentially continuing current) are providing the means to understand the complexities of electric charge generation and discharge. Charge moment change, with the assumption of a mean height from which the discharge occurs, also provides an estimate of a heretofore rarely available quantity, the absolute amount of charge lowered to ground. This may prove valuable in forensic investigations, fire weather meteorology and electrical transmission and distribution system design, to name but a few.

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REFERENCES

Barrington-Leigh, C. P., U. S. Inan, M. Stanley, and S. A. Cummer, 1999: Sprites directly triggered by negative lightning discharges. *Geophys. Res. Lett.,* **26,** 3605–3608.

Boccippio, D. J., E. R. Williams, W. A. Lyons, I. Baker, and R. Boldi, 1995: Sprites, ELF transients and positive ground strokes. *Science,* **269,** 1088–1091.

Cummer, S. A., and W. A. Lyons, 2004: Lightning charge moment changes in U.S. High Plains thunderstorms. *Geophys. Res. Lett.,* **31,** L05114, doi:10.1029/2003GL019043.

——, and ——, 2005: Implications of impulse charge moment changes in sprite-producing and non-sprite-producing lightning. *J. Geophys. Res.,* **110,** A04304, doi:10.1029.2004JA010812.

Franz, R. C., R. J. Nemzek, and J. R. Winckler, 1990: Television image of a large upward electrical discharge above a thunderstorm system. *Science,* **249,** 48–51.

Frey, H. U., and Coauthors, 2005: Beta-type stepped leaders of elve-producing lightning. *Geophys. Res. Lett.,* **32,** L13824, doi:10.1029/2005GL023080.

Hu, W., S. Cummer, W. A. Lyons, and T. E. Nelson, 2002: Lightning charge moment changes for the initiation of sprites. *Geophys. Res. Lett.,* **29,** 1279, doi:10.1029/2001GL014593.

Huang, E., E. Williams, R. Boldi, S. Heckman, W. Lyons, M. Taylor, T. Nelson, and C. Wong, 1999: Criteria for sprites and elves based on Schumann resonance observations. *J. Geophys. Res.,* **104,** 16 943–16 964.

Jacobson, E. A., and E. P. Krider, 1976: Electrostatic field changes produced by Florida lightning. *J. Atmos. Sci.,* **33,** 103–110.

Lang, T., and Coauthors, 2004: The Severe Thunderstorm Electrification and Precipitation Study (STEPS). *Bull. Amer. Meteor. Soc.,* **85,** 1107–1125.

Lyons, W. A., 1994: Low-light video observations of frequent luminous structures in the stratosphere above thunderstorms. *Mon. Wea. Rev.,* **122,** 1940–1946.

——, 1996: Sprite observations above the U.S. High Plains in relation to their parent thunderstorm systems. *J. Geophys. Res.,* **101,** 29 641–29 652.

——, M. Uliasz, and T. E. Nelson, 1998: Climatology of large peak current cloud-to-ground lightning flashes in the contiguous United States. *Mon. Wea. Rev.,* **126,** 2217–2233.

——, T. E. Nelson, E. R. Williams, S. A. Cummer, and M. A. Stanley, 2003a: Characteristics of sprite-producing positive cloud-to-ground lightning during the 19 July STEPS mesoscale convective systems. *Mon. Wea. Rev.,* **131,** 2417–2427.

——, T. E. Nelson, R. A. Armstrong, V. P. Pasko, and M. Stanley, 2003b: Upward electrical discharges from the tops of thunderstorms. *Bull. Amer. Meteor. Soc.,* **84,** 445–454.

——, L. M. Andersen, T. E. Nelson, and G. R. Huffines, 2006: Characteristics of sprite-producing electrical storms in the STEPS 2000 domain. Preprints, *Second Conf. on Meteorological Applications of Lightning Data,* Atlanta, GA, Amer. Meteor. Soc., 5.4. [Available online at http://confex.com/ams/pdfpapers/99787.pdf.]

Marshall, T. C., M. Stolzenburg, and W. D. Rust, 1996: Electric field measurements above mesoscale convective systems. *J. Geophys. Res.,* **101,** 6979–6996.

Mazur, V., X.-M. Shao, and P. R. Krehbiel, 1998: "Spider" lightning in intracloud and positive cloud-to-ground flashes. *J. Geophys. Res.,* **103,** 19 811–19 822.

Orville, R. E., and G. R. Huffines, 2001: Cloud-to-ground lightning in the United States: NLDN results in the first decade, 1989–98. *Mon. Wea. Rev.,* **129,** 1179–1193.

Pasko, V. P., U. S. Inan, and T. F. Bell, 1996: Sprites as luminous columns of ionization produced by quasi-electrostatic thundercloud fields. *Geophys. Res. Lett.,* **23,** 649–652.

Rakov, V. A., and M. A. Uman, 2003: *Lightning: Physics and Effects.* Cambridge University Press, 687 pp.

Rust, D. W., and D. R. MacGorman, 2002: Possibly inverted-polarity electrical structures in thunderstorms during STEPS. *Geophys. Res. Lett.,* **29,** 1571, doi:10.1029/2001GL014303.

Schuur, T. J., and S. A. Rutledge, 2000: Electrification of stratiform regions in mesoscale convective systems. Part I: An observational comparison of symmetric and asymmetric MCSs. *J. Atmos. Sci.,* **57,** 1961–1982.

Sentman, D. D., E. M. Wescott, D. L. Osborne, D. L. Hampton, and M. J. Heavner, 1995: Preliminary results from the Sprites94 aircraft campaign: 1. Red sprites. *Geophys. Res. Lett.,* **22,** 1205–1208.

Stanley, M., P. Krehbiel, M. Brook, C. Moore, and W. Rison, 1999: High speed video of initial sprite development. *Geophys. Res. Lett.,* **26,** 3201–3204.

Stolzenburg, M., 1994: Observation of high ground flash densities of positive lightning in summertime thunderstorms. *Mon. Wea. Rev.,* **122,** 1740–1750.

Thomas, R. J., P. R. Krehbiel, W. Rison, S. J. Hunyady, W. P. Winn, T. Hamlin, and J. Harlin, 2004: Accuracy of the lightning mapping array. *J. Geophys. Res.,* **109,** D14207, doi:10.1029/2004JD004549.

van der Velde, O. A., W. A. Lyons, T. E. Nelson, S. A. Cummer, J. Li, and J. Bunnell, 2007: Analysis of the first gigantic jet recorded over continental North America. *J. Geophys. Res.,* **112,** D20104, doi:10.1029/2007JD008575.

Wiens, K. C., S. A. Rutledge, and S. A. Tessendorf, 2005: The 29 June supercell observed during STEPS. Part II: Lightning and charge structure. *J. Atmos. Sci.,* **62,** 4151–4177.

Williams, E. R., 1998: The positive charge reservoir for sprite-producing lightning. *J. Atmos. Sol. Terr. Phys.,* **60,** 689–692.

——, 2001: Sprites, elves, and glow discharge tubes. *Phys. Today,* **54,** 41–47.

——, E. Downes, R. Boldi, W. Lyons, and S. Heckman, 2007: Polarity asymmetry of sprite-producing lightning: A paradox? *Radio Sci.,* **42,** RS2S17, doi:10.1029/2006RS003488.

Wilson, C. T. R., 1925: The electric field of a thunderstorm and some of its effects. *Proc. Phys. Soc. London,* **37,** 32D–37D.