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Charge transfer and in-cloud structure of large-charge-moment positive lightning strokes in a mesoscale convective system

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[1] Lightning observations in the very high frequency band and measurements of ultra low frequency magnetic fields are analyzed to investigate the charge transfer and in-cloud structure of eight positive cloud-to-ground (+CG) strokes in a mesoscale convective system. Although no high altitude images were recorded, these strokes contained large charge moment changes (1500–3200 C·km) capable of producing nighttime sprites. Even though the convective region of the storm was where the flashes originated and where the CG strokes could occur, the charge transferred to ground was mainly from the stratiform region. The post-stroke long continuing currents were connected to highly branched negative leader extension into the stratiform region. While the storm dissipated, the altitude of negative leader propagation in the stratiform area dropped gradually from 8 to 5 km, indicating that in some and perhaps all of these strokes, it was the upper positive charge in the stratiform region that was transferred. **Citation:** Lu, G., S. A. Cummer, J. Li, F. Han, R. J. Blakeslee, and H. J. Christian (2009), Charge transfer and in-cloud structure of large-charge-moment positive lightning strokes in a mesoscale convective system, *Geophys. Res. Lett.*, *36*, L15805, doi:10.1029/2009GL038880.

1. Introduction

[2] Sprites have been extensively studied since their first documentation by *Franz et al.* [1990]. Nearly all sprites are associated with positive cloud-to-ground (+CG) strokes that transfer positive charge from the in-cloud reservoir to ground [*Boccippio et al.*, 1995], causing transient perturbations in the electric field above thunderstorms. Such perturbations sufficiently strong at mesospheric altitudes initiate and sustain dielectric breakdown at altitudes of 40–90 km [*Sentman et al.*, 1995; *Pasko et al.*, 1997].

[3] The sprite-associated lightning charge transfer in +CG strokes occurs mainly via two processes. The first one is an impulse current that removes substantial charge from the cloud within a few milliseconds after the return stroke, playing a major role in prompt sprite initiations. *Cummer and Lyons* [2005] analyzed the 2-ms impulse charge moment change (iΔM_q) in sprite producing and non-sprite producing strokes, finding consistency with a sharp initiation threshold of 600 C·km for two nights, and 350 C·km for a third night. The second process is a long continuing current that endures tens to hundreds of milliseconds and ignites sprites with long delays of 10 to >150 ms after strokes [*Li et al.*, 2008], sometimes through the electromagnetic effect of transient current surges referred to as *M* components [*Yashunin et al.*, 2007; *Li et al.*, 2008]. The typical amplitude of sprite-producing continuing currents is a few kA and the cumulative charge moment changes (ΔM_q) at sprite onset are usually larger than those with short delays [*Li et al.*, 2008].

[4] Both impulse and long continuing current with large amplitudes are remotely measurable with magnetic field sensors [*Cummer and Inan*, 1997; *Cummer and Füllekrug*, 2001]. In order to better describe the relationship between sprites and their parent strokes, we need a detailed picture of the charge transfer by +CG strokes in lightning context. Here we compare the concurrent lightning observations and magnetic field measurements to investigate charge transfer and flash evolution during positive strokes with $\Delta M_q >$ 1500 C·km.

2. Data and Analysis

[5] Sprites commonly occur above the stratiform region of a mesoscale convective system (MCS) [*Boccippio et al.*, 1995; *Lyons*, 1996]. We have analyzed a MCS on 4 July 2004 over the North Alabama Lightning Mapping Array (LMA), which consists of ten receiving stations to continuously locate sources of impulsive lightning emissions in the very high frequency (VHF) band [*Goodman et al.*, 2005]. More than 20 flashes, each having one or more +CG strokes detected by the U.S. National Lightning Detection Network (NLDN), occurred during the mature and dissipation stage of this storm. We focus on eight flashes that occurred in a recurring sequence between 04:57 and 05:28 UT (the dissipation began at about 05:10 UT). In one flash the NLDN peak current (I_p) of the first stroke was +7 kA, and for the rest I_p ranged between +30 and +167 kA. Ultra low frequency (ULF) magnetic fields from the lightning strokes were sampled continuously at 2.5 kHz with a sensor pair near Duke University, about 700 km from the storm. With the ULF waveforms, we applied the method used by *Li et al.* [2008] to derive the time-resolved current along the stroke channel and thus the charge moment change. The termination time of the continuing current is also reliably estimated.

[6] For the flashes examined, their spatial and temporal evolution was mainly mapped through the VHF emissions from negative stepped leaders, and positive leaders mainly confined in negative cloud regions were poorly resolved as

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they radiated weakly and continuously in VHF band [*Rison et al.*, 1999]. However, the absence of VHF emissions in the negative cloud region does not impact our analysis as our major concern is the charge transfer from the positive cloud region explored by negative leaders. In the analysis we divide the flash into four portions: pre-stroke, post-stroke (20 ms), long continuing current (LCC), and post-continuing current. While a post-stroke interval <20 ms would be more appropriate to study the impulse current, the lightning activity in such short intervals usually cannot be well resolved due to the intrinsic scarcity of VHF emissions along conductive lightning channels. Indeed, for our flashes there were too few (at most three) LMA sources within 5 ms after the NLDN strokes. Therefore, we use the VHF emissions in a longer post-stroke interval of 20 ms to confine the region hosting the charge transfer by impulse currents. The in-cloud lightning activities during the LCC are readily mapped by the LMA as they are mostly associated with negative breakdown into pristine air.

3. Results and Discussion

[7] The main features of our flashes are akin to those reported by *Carey et al.* [2005] for a trailing-stratiform MCS in Texas. The comparison with radar data indicates that all the flashes initiated in the convective region near the southern edge of the storm and extended northeastward into the stratiform region, following a sloping path that decreased in altitude by 3–5 km over a horizontal range of 30 km. The subsequent lightning channel extension in the stratiform area was highly branched. To derive a scenario that depicts the main charge transfer in positive strokes, we first examine one flash with the strongest NLDN stroke. Other flashes are analyzed with the same method and the results are generalized to answer the questions regarding the charge source of impulse and long continuing current.

3.1. Case Study: Flash +CG_050203

[8] Figure 1 shows the LMA data and ULF waveform of a flash initiating at 05:02:03.901 UT. The LMA sources are shown in different colors for four consecutive intervals: prior to the NLDN stroke (grey dots), within 20 ms after the stroke (red "+"s), later during the LCC (blue dots), and the remainder of the flash (black dots) when the LCC has either shut off or fallen below the detectability threshold. The first LMA source indicated the initiation of a negative leader that propagated over 80 km prior to the stroke while descending from ~10 km (above the sea level, hereinafter) in the convection region to 6–8 km in the stratiform region. The NLDN stroke, with $I_p \sim +167$ kA, was located below the stratiform region, about 50 km from the flash origin. *Krehbiel* [1981] depicted how a +CG stroke strikes ground far from underneath the flash origin: when the negatively charged horizontal channels become "cutoff" due to the inherent instability, new positive leaders are launched from the opposite end of the progressing negative leader and head for ground, producing a +CG stroke away from the origin. Note that the in-cloud negative leader passed over and ~20 km beyond the eventual +CG stroke (Figure 1c). The sequence of post-stroke LMA sources, particularly those earlier along the lightning channel above the stroke and later near the channel ends, implied a negative breakdown that initiated from ground, propagated into the existing lightning channel, and extended the channel into virgin air. It is noticed that VHF emissions were detected from both branches formed before the return stroke.

[9] The ULF measurement (Figure 1b) indicated a post-stroke impulse current and a subsequent LCC of ~180 ms. This stroke caused a large iΔM_q of +800 C·km within 2 ms, sufficient for producing a prompt nighttime sprite [*Cummer and Lyons*, 2005]. The subsequent LCC caused an additional charge moment change of +2400 C·km, and thus the total ΔM_q was significantly larger than the +2000 C·km minimum reported for sprites with >120 ms delays [*Li et al.*, 2008]. Although no simultaneous video observations were made, this flash is typical of the kind that produces sprites, and we treat it as such here.

[10] The LMA observation of this flash has several implications concerning the charge transfer during the impulse and long continuing current. First of all, the main charge removal altitude was between 6 and 8 km in stratiform region, >1 km above the 0°C isotherm. This is discussed later on the basis of the results for other flashes. Secondly, the post-stroke (20 ms) LMA sources suggested that the impulse charge removal was from or near the existing channels in the stratiform area; the geometric center of charge distribution, which is circled by a dotted line in Figure 1c, was about 10 km horizontally displaced from the stroke. The LCC, in contrast, was associated with highly branched negative leader expansion into the stratiform region, indicative of a concurrent positive charge transfer (to ground) originating in the regions of new breakdown. When the LCC appeared to shut down and thus the connection to ground has been terminated, there were still many new VHF emissions in the stratiform region during the post-continuing current period which, however, did not significantly expand the horizontal scale of the flash.

3.2. Implications on Impulse Charge Transfer

[11] The results for other flashes are generally consistent with the implications from the analysis with respect to Flash +CG_050203. In Figure 2 we show another four flashes to demonstrate the tight correlation between the pre-stroke lightning development and charge transfer in impulse currents by comparing the pre-stroke flash evolution with the post-stroke LMA sources within 20 ms. The post-stroke LMA sources were consistent with that the positive stroke initiated a negative breakdown propagating along the lightning channel that had already existed prior to the stroke. This is shown most plainly in Figure 2c, where such a breakdown was mapped with LMA sources along the tortuous channel and later near the channel end, adding new channel sections. From the timing of these sources, we estimate the mean speed of this breakdown to be well above 10^6 m/s, in comparison with the typical speed of $1–2 \times 10^5$ m/s for negative stepped leaders [*Shao and Krehbiel*, 1996].

[12] Through a positive stroke the in-cloud lightning channel gains more negative charge. In five of the eight flashes the first stroke was located under the stratiform area despite the origination in the convective core. For these flashes (e.g., Figures 2a and 2c), the lightning channel extending from higher in the convective region probably has been cutoff, as indicated by the absence of post-stroke

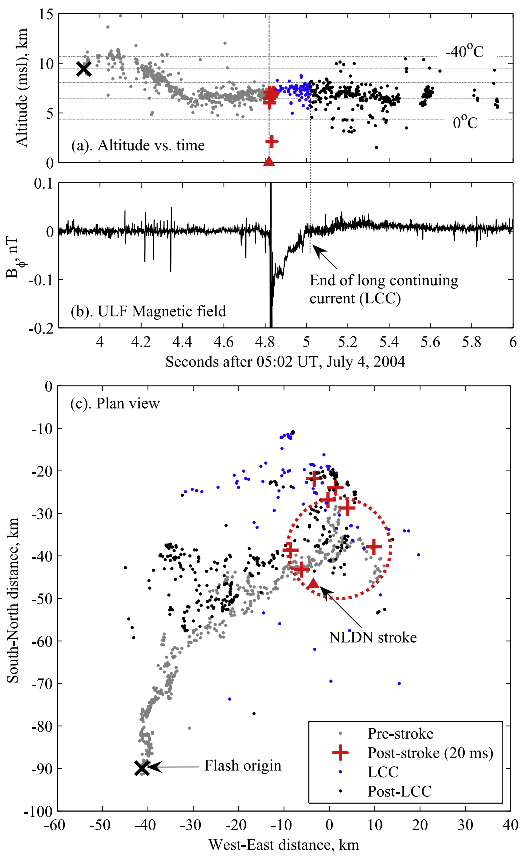

Figure 1. (a) LMA observation and magnetic field measurement of Flash +CG_050203. (b) The ULF data are intentionally clipped to show the magnetic field of the LCC. LMA sources are plotted in different colors to show the flash development (see text for details). Temperature levels plotted at 10°C intervals in Figure 1a use the balloon sounding on the morning of July 4, 2007 from the Shelby County Airport, Alabama. (c) The origin is at 34.7558°N and −86.6678°W.

VHF emissions there. Therefore, the newly transferred negative charge (into thunderclouds) was deposited along the channels in the stratiform region. For those with strokes nearly below the flash origin (e.g., Figures 2b and 2d), the new charge transfer might be distributed extensively along lightning channels in both convective and stratiform region, while the latter was likely the main source of impulse charge transfer because the pre-stroke lightning channel was mainly in the stratiform region.

[13] In summary, the post-stroke VHF emissions suggested that the primary charge source of impulse current was the lightning channel developed prior to the stroke. Most of the charge transfer was likely deposited along the existing channels in stratiform region, consistent with the observation that short-delayed sprites usually appear above the peripheral regions of flash development within 200–300 ms prior to the stroke [*Stanley*, 2000]. As indicated in Figure 2, the NLDN strokes were usually not located under the geometric center of this charge distribution, explaining the typical horizontal displacement of ∼15 km between short-delayed sprites and causative strokes [*Wescott et al.*, 2001].

3.3. Charge Transfer in Long Continuing Currents

[14] As illustrated with Flash +CG_050203, the LCC was correlated with the progression of multiple negative leaders in the stratiform region. This is true for other flashes, where the first strokes occurred at 160–730 ms after the flash onset and were followed by 130–280 ms LCC, producing total ΔM_q of 1500–3200 C·km.

[15] Figure 3 shows the altitudes of LMA sources in five flashes that were separated in time by 6–10 minutes, in comparison with the environmental temperature levels plotted in Figure 1c. It is seen that in these flashes the altitude of negative leader extension in the stratiform region dropped gradually from 8 to 5 km as the storm evolved, indicative of a systematic lowering of the positive charge region that usually traps negative leaders [*Coleman et al.*, 2003]. In the conceptual model of charge structure in the stratiform region of MCSs [*Stolzenburg et al.*, 1998, Figure 9], there are two positive charge layers centered at 4 km (near 0°C) and 8 km (−20°C), respectively. The slanted path of negative leader while it propagated from the convective to the stratiform region indicated that the higher one, which appeared to be contiguous to the upper positive charge in the convective region, more likely trapped the negative leader. The VHF observations of +CG flashes in a MCS over central Florida also indicated that the sprite-producing strokes removed charge from the upper positive layer in the stratiform region [*Stanley*, 2000]. The altitude of this layer in the Florida observations, however, exhibited small variations between 7 and 8 km, probably because all the strokes analyzed by *Stanley* [2000] occurred within 14 minutes after the first sprite occurrence, during the late mature stage of the storm. For the MCS examined here, the negative leader extension in the stratiform region before the dissipation stage was at 6–8 km altitudes (Figures 3a and 3b), slightly higher than those later in the storm (Figures 3d and 3e).

[16] *Williams* [1998] suggested that the lower positive charge in the MCS stratiform region is the main charge reservoir responsible for sprites, based upon the dominance of a positive charge layer near the 0°C isotherm [*Marshall*

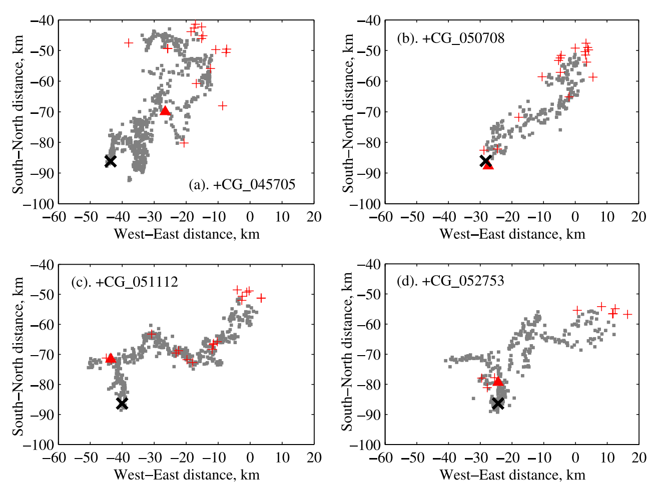

Figure 2. LMA sources during the pre-stroke (grey dots) and post-stroke (within 20 ms, red "+"s) intervals in four +CG flashes. The first LMA source is indicated with a "×" and the first NLDN stroke with a red triangle.

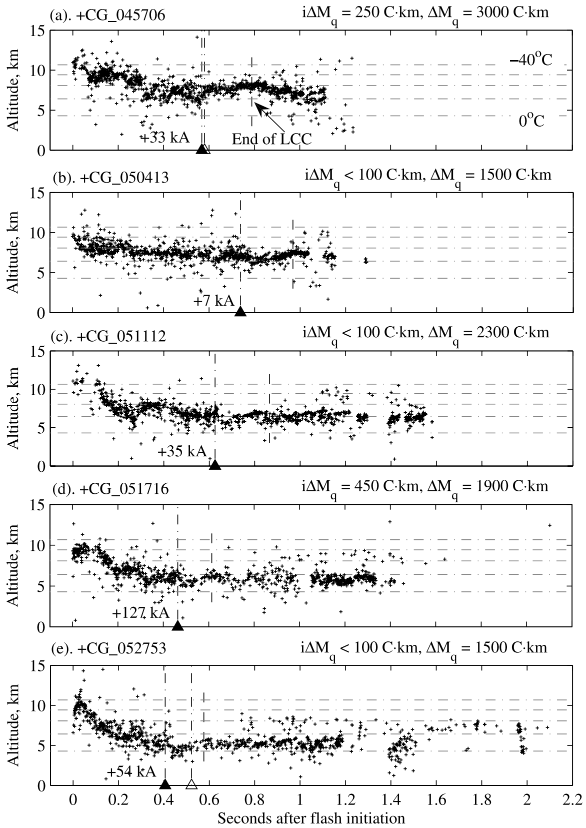

Figure 3. Altitude of individual LMA sources in five +CG flashes. The first and the second stroke, if present, are indicated by a solid and an open triangle, respectively. NLDN peak current for the first stroke, impulse charge moment change (iΔM_q) within 2 ms after the (first) stroke and overall charge moment change (ΔM_q) are shown for each flash.

and Rust, 1993] and the occurrence of "spider" lightning as evidence of a positive charge removal from this layer. In fact, *Mazur et al.* [1998, Figure 3] show that the altitude of recurring "spider" lightning in the storm dropped from ~7 km to 4 km within ~30 minutes, and thus the "spider" lightning occurred before it was visible below the cloud base. Of the eight flashes analyzed, most appeared to exhibit low altitude (e.g., <5 km) LMA sources only after the LCC has shut off; the one shown in Figure 3e is exceptional by exhibiting brief negative leader propagation below the 0°C isotherm during the LCC, while the major development was still above 5 km. This suggests that in these flashes the negative breakdown extended into the lower positive charge layer only after the charge transfer to ground was completed, and visual "spider" lightning may not always reflect charge removal from the lowest altitudes during the LCC.

[17] Our results also show that the charge source of LCC was more dispersed than that of impulse current due to multi-branched extensions, as also seen in negative CG flashes [*Proctor et al.*, 1988]. Usually it was further into the stratiform region from the stroke. Therefore, presuming sprites initiate at the maximum quasi-electrostatic field above the center of charge transfer, long-delayed sprites more likely have larger horizontal displacements (>40 km) from causative strokes [e.g., *Füllekrug et al.*, 2001].

4. Conclusions

[18] The joint analyses of VHF and ULF measurements of eight +CG flashes in a mesoscale convective system over north Alabama show that in strokes with $\Delta M_q > 1500$ C·km positive charge was first removed from the existing channel during the impulse current and later from an extensive stratiform area explored by multiple negative leaders during the long continuing current.

[19] All these flashes originated in the convective region and propagated horizontally over several tens of km into the stratiform region, and positive strokes could occur either under the convective or under the stratiform. However, in both cases the charge transferred to ground was mainly from the stratiform region. Moreover, source altitude descended from 8 to 5 km in 30 minutes as the storm developed, and environmental temperatures indicated that this was the upper positive charge region in the stratiform. The lower positive charge region only participated significantly in these flashes after the continuing current has already shut off.

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