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Implications of lightning charge moment changes for sprite initiation

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[1] We report impulse lightning charge moment changes (defined as occurring in the first 2 ms after return stroke onset) in all cloud-to-ground lightning strokes detected by the National Lightning Detection Network in three storms during which above-thunderstorm sprite video was recorded. After analyzing strokes that both did and did not produce sprites and carefully accounting for lightning-sprite delay times, we found that sprite initiation on all three nights is consistent with a sharp charge moment threshold; essentially, all charge moment changes above and none below this threshold produced sprites with short delays (<5 ms) from the source lightning. On two nights this threshold was approximately 600 C km and on the other it was approximately 350 C km. This internight variability is probably due to expected variability in the nighttime mesospheric conductivity, and the thresholds themselves are consistent with predictions of conventional breakdown theory. Additionally, we found only one negative polarity lightning stroke from all three storms that exceeded this threshold, indicating that the rarity of documented sprites produced by negative strokes may be largely explained by the lack of sufficiently big negative strokes in the U.S. High Plains.

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1. Introduction

[2] Understanding the characteristics of lightning responsible for generating transient luminous events (TLEs) in the mesosphere has been one of the main goals of the field since the documented discovery of sprites [*Franz et al.*, 1990]. This is a necessary step toward the larger goal of understanding the local and global effects and implications of TLEs because the lightning controls the electric field, which in turn controls the mesospheric electrodynamic and chemical processes that occur inside them. Accurate measurements of the driving lightning can be used as inputs into models of these processes and can also test theoretical models of their initiation and behavior.

[3] We focus here on the best-documented class of TLE, the sprite. It is well known experimentally that sprite-producing lightning transfers substantial charge to ground [*Boccippio et al.*, 1995; *Reising et al.*, 1996; *Cummer and Inan*, 1997]. This, combined with the streamer-based morphology of sprites [*Gerken and Inan*, 2003], supports the conventional breakdown sprite generation model, in which a large lightning charge moment change creates a large quasi-static electric field at mesospheric altitudes, which in turn creates electric breakdown [*Pasko et al.*, 1997b] and bright optical emissions. The lightning parameter that is almost directly proportional to this mesospheric field is charge moment change [*Pasko et al.*, 1997b], i.e., the product of the charge transfer and the lightning channel length. Experimentally measured statistical distributions of lightning charge moment changes at the time sprite initiation [*Hu et al.*, 2002] are consistent with predictions from this model. Runaway breakdown of relativistic electrons has also been proposed to explain the optical emissions from sprites [*Roussel-Dupré and Gurevich*, 1996; *Lehtinen et al.*, 1999]. Despite some attractive properties, particularly regarding the generation of terrestrial gamma ray flashes [*Fishman et al.*, 1994], the current experimental evidence favors conventional breakdown as the main source of sprite optical emissions.

[4] However, there are some experimental observations that suggest there may be some missing elements in the conventional breakdown model. Some sprites are generated by apparently small ($\sim$100–200 C km) charge moment change lightning strokes [*Hu et al.*, 2002] that most of the time do not produce a sprite. Sprites are also very rarely made by negative cloud-to-ground lightning strokes ($-$CGs) [*Barrington-Leigh et al.*, 1999], despite global observations showing that large charge moment $-$CGs and +CGs are equally frequent [*Sato and Fukunishi*, 2003; *Füllekrug et al.*, 2002] (although *Füllekrug et al.* [2002] notes that the large $-$CGs occur preferentially over oceans) and conventional breakdown theory does not suggest a strong polarity asymmetry [*Pasko et al.*, 1998a]. Sprites are sometimes laterally displaced from the source

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lightning and coincident halo [*Moudry et al.*, 2003] in a way that suggests that sprites may not always initiate in the region of highest electric field. Also, some sprites contain their own substantial electric current; strong evidence for this comes from carefully aligned electromagnetic and optical measurements [*Cummer et al.*, 1998] and the detection of a significant lateral displacement between the lightning and sprite currents [*Füllekrug et al.*, 2001]. *Pasko et al.* [1998b] showed that sprite currents like those observed would occur if the sprite significantly enhanced the mesospheric electrical conductivity. However, it is not understood why only a small fraction of sprites (~10%) appear to contain significant sprite currents [*Cummer*, 2003]. All of these open questions pertain at some level to sprite microphysics, i.e., the processes that initiate and drive a sprite. Until those processes are reasonably well understood, it will be difficult to determine how sprites might be significant at a local or global level.

[5] Our goal is to answer two specific questions and therefore move toward an understanding of potential larger-scale TLE effects, through a careful analysis of charge moment changes in lightning strokes that both do and do not generate sprites. The first is whether a sharp threshold of lightning charge moment change explains sprite initiation or if there is significant threshold variability that suggests that other processes may play a significant role. Previous statistical analyses of only sprite-producing lightning from many nights [*Huang et al.*, 1999; *Hu et al.*, 2002] have found a somewhat broad charge moment change threshold; this may reflect a threshold that varies from event to event, or it may be simply a consequence of mesospheric conductivity variability from night to night. Consequently, we focus here on charge moment change thresholds for individual nights to minimize the effect of conductivity variability. We also search for the largest lightning charge moment changes that did not produce sprites; these have not been studied previously but are an essential part of a possible sharp charge moment threshold for sprite initiation. The second question is whether the lack of sprites produced by −CGs is due to a lack of high charge moment change −CGs or if there is a quantifiable polarity asymmetry in the initiation of mesospheric breakdown. To answer this, we searched for high charge moment change −CGs that occurred within the field of view of the sprite video.

[6] After carefully accounting for lightning-to-sprite delays and the limitations in the ability of our instrumentation to sense long continuing currents that are responsible for some sprites [*Cummer and Füllekrug*, 2001], we find that the data are consistent with a sharp lightning charge moment change threshold for sprite initiation that varies from night to night, between 350 and 600 C km on the three nights analyzed. These data and instrument limitations prevent a truly definitive determination of the sharpness of the threshold, but the data strongly support the existence of a sharp threshold over an event-to-event variable threshold. Although charge moment change is not a widely measured parameter, this threshold is substantially larger than typical stroke charge moment changes in −CGs, which are on the order of 5–50 C km [*Brook et al.*, 1962; *Berger et al.*, 1975; *Krehbiel et al.*, 1979; *Cummer and Lyons*, 2004]. Numerically, these threshold are consistent with predictions from conventional breakdown theory, and the apparent sharpness of the threshold indicates that other factors, such as atmospheric pressure depletions generated by gravity waves, have either a spatially homogeneous or only minor effect on sprite initiation. We also found only two negative cloud-to-ground lightning strokes out of thousands in the analyzed storms that barely exceeded the apparent charge moment change threshold. Although these two strokes did not generate sprites or halos, two events are not strong evidence of a field polarity asymmetry in sprite generation. It thus appears that the main reason so few sprites from negative lightning strokes have been observed is that high charge moment change −CGs are very uncommon in the U.S. High Plains.

2. Instruments, Data, and Analysis Techniques

[7] We report data recorded during the summer of 2000 during the Severe Thunderstorm Electrification and Precipitation Study (STEPS). Approximately 4 months of continuous ELF/VLF magnetic field data were recorded at a field site near Duke University (35.975°N, −79.100°E). The effective sensor bandwidth covered approximately 30 Hz (where the signal-to-noise ratio (SNR) was typically around unity) to 6 kHz (the cutoff frequency of our antialiasing filter). This sensor recorded the magnetic field radiated by essentially every cloud-to-ground lightning stroke in the United States. The very smallest and most distant strokes can occasionally be masked by noise. Simultaneously, intensified normal speed video (16.7 ms time integration per video field) acquired with multiple cameras at Yucca Ridge Field Station (YFRS, 40.67°N, −105.94°E) recorded optical emissions from sprites on nights when viewing was clear and thunderstorms were present. The distance between Duke and YFRS is 2387 km, and the distance between Duke and most of the analyzed lightning strokes is 1800–2000 km.

[8] We used the video to positively identify lightning strokes that did and did not produce sprites. We identified three nights with good sprite viewing conditions near Yucca Ridge and relatively low magnetic field noise at Duke: 25 June, 4 July, and 10 August. National Lightning Detection Network (NLDN) data were used to identify all detected cloud-to-ground lightning strokes that occurred within the video viewing area. Because all data were recorded with GPS-based timing, the ELF magnetic field waveform radiated by each of these strokes could be identified and analyzed. Specifically, we measure the charge moment change (ΔM_q) during the first 2 ms of the lightning stroke, which is essentially the return stroke, using the technique described by *Cummer and Inan* [2000]. We call this quantity the impulse charge moment change ($i\Delta M_q$) (after *Berger et al.* [1975]). Direct measurements of lightning currents have shown that even in positive strokes, the bulk of the return stroke current flows in the first 2 ms of the stroke (and often less, especially in −CG strokes) [*Uman*, 1987, p. 199]. Moreover, continuing currents are usually not big enough to transfer substantial charge in 2 ms [*Uman*, 1987, p. 196]. Thus in most strokes the $i\Delta M_q$ will be closely related to the return stroke charge moment change.

[9] Longer-duration currents (i.e., longer than 2 ms) associated with big return strokes can be also reliably measured from remote low-frequency fields if the longer

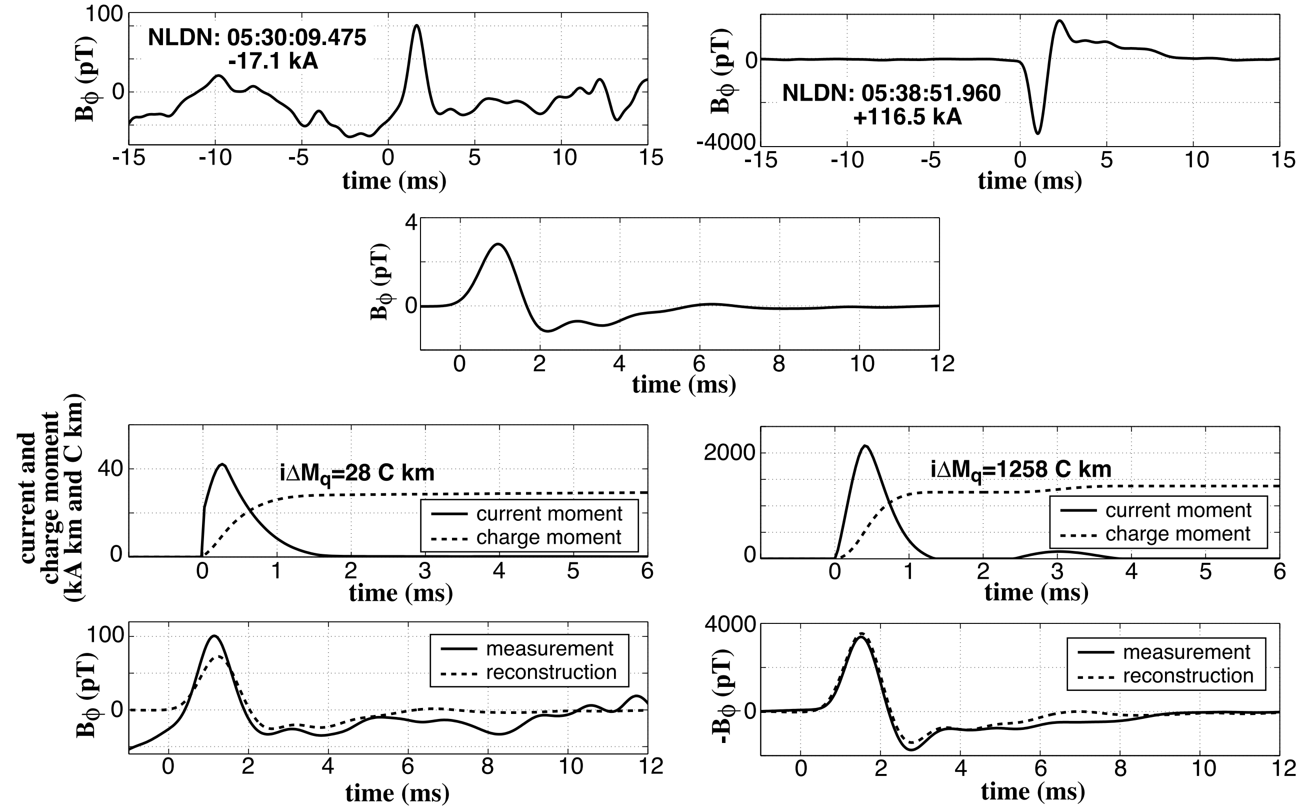

Figure 1. Two examples of current and charge moment measurement from distant magnetic fields. (top row) Magnetic field waveforms recorded from small and large CG strokes. (second row) The assumed 1 C km propagation impulse response computed from a combination of measurement and modeling. (third row) The extracted current moment and charge moment change waveforms for each stroke. (bottom row) The agreement between the measured and reconstructed field waveforms validates the measurement procedure.

currents are big enough or the source-receiver distance is sufficiently short. However, our goal is to compare every NLDN-detected stroke in the video field of view, which requires that many small strokes be measured, and only the $i\Delta M_q$ can be reliably measured for all strokes at the distances (roughly 2000 km) involved. We emphasize that our measurements are of physical ΔM_q, i.e., the total charge moved times the channel length from cloud to ground.

[10] The absolute accuracy of the reported measurements depends on the absolute calibration of the sensor and of the assumed propagation impulse response. There is an absolute error in all the reported measurements estimated to be −33%/+50% at worst, based on unpublished initial comparisons of this data set with other measurements and techniques. The relative error between all of the measurements on a single night (i.e., measurement precision) is much smaller (±10%) because the calibration and propagation uncertainty errors are systematic and thus identical in all signals. Therefore the conclusions drawn regarding the sharpness of sprite initiation thresholds are robust, while there is some uncertainty in the exact value of the threshold. These absolute and relative uncertainties apply to all numerical charge moment changes given in this paper.

[11] Figure 1 shows an example of the data and analyzed results from two lightning strokes, one small and one large, on 4 July 2000. The top row shows two calibrated magnetic field waveforms received at Duke from NLDN-detected lightning strokes after 60 Hz powerline noise removal. The signals from the known lightning discharges are the pulses starting at t = 0. Note that simple scaling of the received field amplitude suggests the large discharge is at least 30 times larger in charge moment change than the small one. The second row shows the modeled propagation impulse response, which is the magnetic field waveform that would be received by the sensor (including its frequency response) from a 1 C km impulsive CG discharge. Impulsive is defined as occurring on timescales shorter than the bandwidth of the receiving system, which in this case means faster than approximately 0.5 ms. This waveform is computed via a method described in the following paragraph. The third row shows the source current moment and charge moment change waveforms extracted from the data using the deconvolution technique described by *Cummer and Inan* [2000]. We find $i\Delta M_q$ of 28 and 1258 C km for these two strokes. The fourth row shows the agreement between measured field waveforms and the reconstructed field waveforms, which are computed by convolving the extracted source waveform and the modeled impulse response. The good agreement between these two waveforms shows that the extracted source current moment is consistent with the data, thus validating the measurement. The not-quite-perfect agreement reflects both noise in the

measured signal and the uncertainty in the modeled impulse response. Imperfect agreement is necessary for accurate interpretation of smaller signals where the signal-to-noise ratio is not particularly high. After fitting a source to a section containing signal and noise and subtracting this fit from the data, what remains should be pure noise. Although we do not know the actual noise waveform, we do know the statistical properties of the noise because the majority of the recorded data falls between the impulsive signals of interest and is thus simply noise. We thus require the remaining data (or residual) to be consistent with the known properties of the background noise. For example, overfitting a small signal, which generally leads to erroneously large current moment waveforms, will result in a nearly zero residual which is clearly not consistent with the measured noise. We attempt to extract the source current moment waveform with the smallest impulse charge moment change that leaves the residual statistically consistent with the known noise.

[12] We compute the modeled impulse response in a different way than the purely simulation approach described by *Cummer and Inan* [2000]. To minimize mismatch caused by differences between the actual and assumed ionospheric electron density profiles, we compute an uncalibrated impulse response by summing the waveforms received by most of the −CG strokes in the storm in order to average down the background noise. For this to accurately represent the propagation impulse response, we implicitly assume that all of these −CG strokes transfer their charge in less than $\sim$0.5 ms. Those strokes with especially poor SNR or those that do not appear impulsive are excluded from the sum. This impulsiveness is reflected in the bipolarity of the ELF ($\lesssim$1 kHz) component of the signal. If we assume that the source current waveform is strictly positive or strictly negative and is nonoscillatory, then the spectrum of the source must peak at zero frequency and be constant (if the source is impulsive) or monotonically decreasing. Consequently, impulsive strokes contain the maximum possible energy at higher frequencies (here $\sim$1 kHz) for a fixed lower-frequency energy (here $\sim$100 Hz), which in turn creates a more bipolar distant ELF signal, as can be seen by comparing the impulsive waveforms in Figure 6 with the less impulsive ones in Figure 7. This average waveform must then be calibrated to a known impulsive source strength, which we take to be 1 C km. This is done by linearly scaling the measured waveform to match, in a least squares sense, an ensemble of waveforms simulated using a variety of representative nighttime ionospheres. The shape of the resulting waveform thus matches the shape of the actual, ionosphere-dependent propagation impulse response, and its calibrated amplitude matches as well as possible what is expected for a reasonable set of nighttime ionospheres. We find the $i\Delta M_q$ measured with this hybrid data/simulation method agrees well (generally <10% difference) with that measured using a purely simulated propagation impulse response and, by matching the data more closely, also results in more realistic current moment waveforms with smaller nonphysical oscillations.

[13] Because regular speed video does not enable precise sprite timing, we cannot always tightly bound the lightning ΔM_q at the time of sprite initiation. However, the lightning-to-sprite delay can often be bounded better than 16.7 ms (one video field) because the stroke normally occurs later than the start of the video field integration period [*Hu et al.*, 2002]. We thus classify the observed sprites as short-delayed sprites if they positively occurred within 5 ms of the lightning, as possibly short-delayed sprites if they might have occurred within 5 ms of the lightning, and as long-delayed sprites if they definitely occurred more than 5 ms after the lightning.

[14] We focus primarily on the short-delayed sprites, thereby ensuring that the 2 ms $i\Delta M_q$ is as close as possible to the ΔM_q at the time of sprite initiation. If the sprite initiation time is at least 5 ms or more after the lightning stroke, then continuing currents may contribute substantially more ΔM_q than the measured $i\Delta M_q$ [*Cummer and Füllekrug*, 2001], leading to significant uncertainty in the initiation ΔM_q. Given that we are measuring the 2 ms $i\Delta M_q$, it would be ideal if the analysis could be limited to sprites delayed less than 2 ms from the source stroke. However, the 5 ms criterion is necessary to have enough events for significant results. If significant lightning charge transfer occurred between 2 and 5 ms, then the $i\Delta M_q$ may underestimate the sprite initiation charge moment threshold, but in most cases this is not significant and the $i\Delta M_q$ is an accurate measure of the ΔM_q responsible for short-delayed sprite initiation.

3. Data From 25 June 2000

[15] On 25 June 2000, scattered convection over the Colorado, Nebraska, and Kansas High Plains produced an area of scattered multicellular convective storms, plus one isolated and intense storm which frequently exhibited supercellular characteristics. The sprite video field of view covered the supercell and one other storm cell, and in the 0300–0600 UT viewing time these two cells contained 90 −CGs and 95 +CGs detected by the NLDN. These strokes were contained in the area defined by latitude 39.4° to 40.7°N and longitude −103.0° to −100.5°E. The NLDN-determined polarity of 5 −CGs and one +CG were incorrect based on the unambiguous polarity of the received ELF waveforms, indicating that these strokes were probably ionospheric reflections misidentified as lightning strokes (K. Cummins, personal communication, 2002). These were excluded from the set of analyzed strokes. Most NLDN-detected +CGs with peak current $\leq$10 kA are thought to be cloud discharges misidentified as CGs [*Cummins et al.*, 1998] and should be excluded, but there was none on this night. The resulting data set thus contained 85 −CGs and 94 +CGs.

[16] After a careful search of the video, five sprites were found, all of which were produced by +CG strokes in the supercell. The $i\Delta M_q$ in the 85 −CGs ranged from less than 5 C km to 59 C km (see *Cummer and Lyons* [2004] for a complete distribution and analysis). In light of theory [*Pasko et al.*, 1997b] and past measurements [*Cummer and Inan*, 1997; *Huang et al.*, 1999; *Hu et al.*, 2002] showing that ΔM_q in the hundreds of C km is usually required to make a sprite, it is not surprising that none was generated by these −CGs.

[17] The ΔM_qs in the +CGs are substantially larger. Figure 2 shows a histogram of the $i\Delta M_q$ of the 94 +CGs. The strokes that produced the five observed sprites are

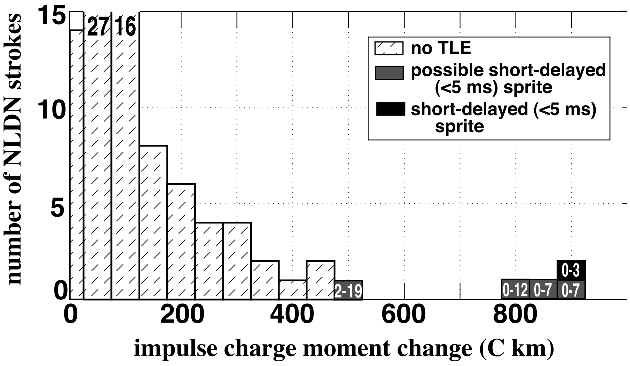

Figure 2. Histograms of impulse (in 2 ms) charge moment changes in 94 +CG strokes during 3 hours (0300–0600 UT)of transient luminous event (TLE) video observation on 25 June 2000. The presence of a sprite in response to a given stroke and the range of possible lightning-to-sprite delay in milliseconds is noted for each stroke.

marked with ranges of possible lightning-to-sprite delays in milliseconds. All five sprites were either short-delayed or possibly short-delayed, and thus the measured $i\Delta M_q$ is closely related to that required for sprite initiation. The five sprites were produced by the strokes with the five biggest impulse charge moment changes. The four biggest, which are separated somewhat from the rest of the distribution, produced bright sprites, while the one with significantly smaller charge moment change produced a fairly small and dim sprite. Only one faint halo and no elves were found in the video for these strokes, although both TLE classes can be hard to find in regular-speed video [*Bering et al.*, 2004]. We conclude that the 25 June 2000 data are completely consistent with a sharp ΔM_q threshold for sprite initiation of about 600 C km. All strokes above this threshold made short-delayed or possibly short-delayed sprites, all below did not, and the one near the threshold made only a small and dim sprite. This threshold is close to the 600–1000 C km statistical charge moment change threshold for which sprites are generated by 50% of strokes of that magnitude [*Hu et al.*, 2002]. Note that this statistical threshold was derived by assuming a charge moment change distribution for non-sprite-producing lightning strokes, rather than measuring them as is done here. We cannot address whether there is any electric field polarity asymmetry in the sprite initiation process with data from this night because none of the −CGs is within a factor of 10 of this apparent threshold.

4. Data From 10 August 2000

[18] On 10 August 2000, sprites were observed over a single storm cell in the area bounded by latitude 41.0° to 43.5°N and longitude −104.5° to −101.5°E between 0400 and 0500 UT under clear viewing conditions. A total of 13 TLEs (12 sprites and one halo or elve) were recorded on video, 11 of which corresponded to NLDN-detected strokes and were thus analyzed. After removing probable ionospheric reflections, we found a total of 46 +CG and 42 −CG NLDN-detected strokes in this space and time window.

[19] We found that all 42 −CG strokes contained an $i\Delta M_q$ of less than 90 C km, which is consistent with past measurements of −CGs [*Brook et al.*, 1962; *Berger et al.*, 1975; *Krehbiel et al.*, 1979]. Not surprisingly, none of these generated visible TLEs. Figure 3 shows the distribution of the $i\Delta M_q$ in the 46 +CG strokes along with a classification of any associated TLE. The largest stroke (420 C km) produced the only confirmable short-delayed sprite. Of the other eight strokes above 225 C km, four produced possibly short-delayed sprites, one produced a long-delayed sprite, one produced a halo or elve (labeled "H or E" in the figure), and two did not produce detectable TLEs. Four long-delayed sprites were also produced by even smaller $i\Delta M_q$ strokes.

[20] Accounting for the possibly larger ΔM_q at the time of sprite initiation in the possibly short-delayed sprites, this distribution is also consistent with a sharp ΔM_q threshold for sprite initiation of about 350 C km. All CG strokes above 350 C km produced sprites or probable halos, and no CG strokes smaller than 350 C km produced confirmably short-delayed sprites. Moreover, the long-delayed and possibly short-delayed sprites were produced by smaller 200–300 C km $i\Delta M_q$ strokes, which is consistent with charge transfer from continuing current pushing them above the apparent initiation threshold.

5. Data From 4 July 2000

[21] The 4 July 2000 storms we analyze consisted of two very large mesoscale convective systems (MCSs) which propagated eastward through Kansas and Nebraska. Continuous above-thunderstorm video was recorded from approximately 0300 to 0800 UT, and the geographic area inside the video field of view was 38.5° to 42.0°N latitude and −100° to −96.5°E longitude. More than 70 TLEs (almost all sprites) were observed between 0330 and 0730 UT. Given the large number of sprites and CG strokes (more than 10^4) in the video field view during this period, we analyzed subsets of the total lightning. We

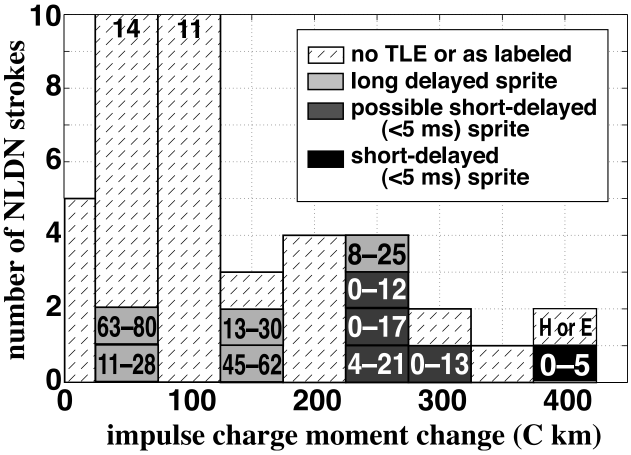

Figure 3. Histograms of impulse (in 2 ms) charge moment changes in 46 +CG strokes during 60 min (0400–0500 UT) of TLE video observation on 10 August 2000. The presence of a TLE in response to a given stroke and a classification based on lightning-TLE delay is noted for each stroke.

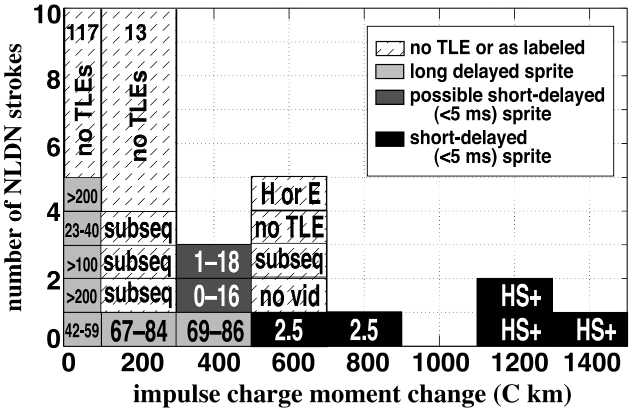

Figure 4. Histograms of impulse (in 2 ms) charge moment changes in 142 +CG strokes during 30 min (0530–0600 UT) of TLE video observation on 04 July 2000. The presence of a TLE in response to a given stroke and a classification (fully explained in the text) is noted for each stroke.

analyzed all NLDN-recorded −CG strokes in the target area in the 0530–0531 UT and 0559–0600 UT time periods. After removing six probable ionospheric reflections, 350 −CGs remained. Impulse ΔM_q in these strokes varied from less than 5 to 183 C km. Careful examination of the video during the larger of these events revealed no TLEs. As for 25 June 2000, the lack of TLEs from these −CGs is not surprising given their relatively small magnitude.

[22] We also analyzed all of the NLDN-recorded +CG strokes in the target area in the entire 0530–0600 UT time period. The polarity of the ELF waveforms indicated that 24 of these +CGs were probable ionospheric reflections, and these were removed from the data set. We also removed 56 +CGs with peak current ≤10 kA (probable intercloud strokes [*Cummins et al.*, 1998]), leaving 142 +CGs for complete analysis. A careful search of the video from multiple cameras revealed 18 sprites and one isolated halo or elve generated by this set of +CGs.

[23] Figure 4 shows a histogram of the $i\Delta M_q$ of these 142 +CGs. Most of the strokes had small impulse charge moment changes (see *Cummer and Lyons* [2004] for a detailed analysis of this distribution) and produced no TLEs. Some produced long-delayed sprites or sprites that followed closely (<1 s) after a sprite in the same area. We call these subsequent sprites and label them "subseq" on the figure. We exclude these subsequent sprites from our threshold analysis because of the possibility that the initiation threshold was altered by the previous sprite in the same area. *Stenbaek-Nielsen et al.* [2000] observed the influence of previous sprites on subsequent ones, and our data suggest, albeit inconclusively, that the initiation threshold may be lowered for subsequent sprites. We also exclude the long-delayed sprites from ΔM_q threshold analysis because they were likely aided by continuing current charge transfer [*Cummer and Füllekrug*, 2001] that cannot be reliably measured with the instruments used for this work; this explains the relatively small $i\Delta M_q$ in these sprite-producing strokes.

[24] The remaining TLEs are all short-delayed (<5 ms), probably short-delayed (based on the images showing a large and bright sprite and halo combination, which typically follows a big discharge by only a few milliseconds), or possibly short-delayed. Thus their $i\Delta M_q$ is a reasonable estimate of the threshold for sprite initiation. As on 25 June, these sprite-producing strokes are completely consistent with a sharp ΔM_q threshold for sprite initiation of 600 C km. Essentially, all strokes greater than this magnitude produced sprites, and, equally importantly, no stroke smaller than 600 C km made any visible short-delayed sprite or halo. We note that the video during one of these strokes was blinded by car headlights; this event is marked "no vid" in the figure. And there seems again to be a connection between sprite size and ΔM_q; the five biggest strokes (all >1150 C km) produced bright and large sprite/halo combinations.

[25] To widen our search for −CGs with large ΔM_q, we also analyzed the 459 NLDN-detected −CG strokes with peak current >50 kA inside the geographic and time window of the video observation. It is well known that peak current is not necessarily an indicator of large ΔM_q, but this criterion was an efficient one for gathering a manageable number of large strokes. Figure 5 shows the distribution of $i\Delta M_q$ for these 459 strokes. The only TLEs observed in this subset were two probable elves in response to the two highest peak current strokes (−156 and −181 kA), which is consistent with elves being generated through nonlinear processes driven by high peak wave electric fields [*Barrington-Leigh and Inan*, 1999]. Even in a large subset of powerful peak current −CGs, the $i\Delta M_q$ exceeded 600 C km in only two out of 459 strokes. These two strokes are likely the only >600 C km −CGs in the entire 4-hour window; in contrast, the 1-hour period of this storm analyzed by *Cummer and Lyons* [2004] contained approximately 15 >600 C km +CGs. Consequently, in this storm, above sprite threshold +CGs outnumber −CGs by roughly 30 to 1.

[26] More high ΔM_q −CGs with above-thunderstorm video will need to be found and analyzed to produce

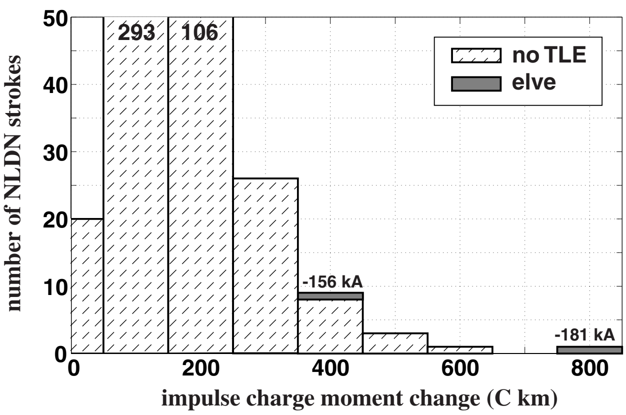

Figure 5. Histograms of impulse (in 2 ms) charge moment changes in all 459 National Lightning Detection Network (NLDN)-recorded >50 kA −CG strokes during 4 hours of TLE video observation on 04 July 2000. The only TLEs observed were two probable elves in response to the two strokes with the largest peak currents.

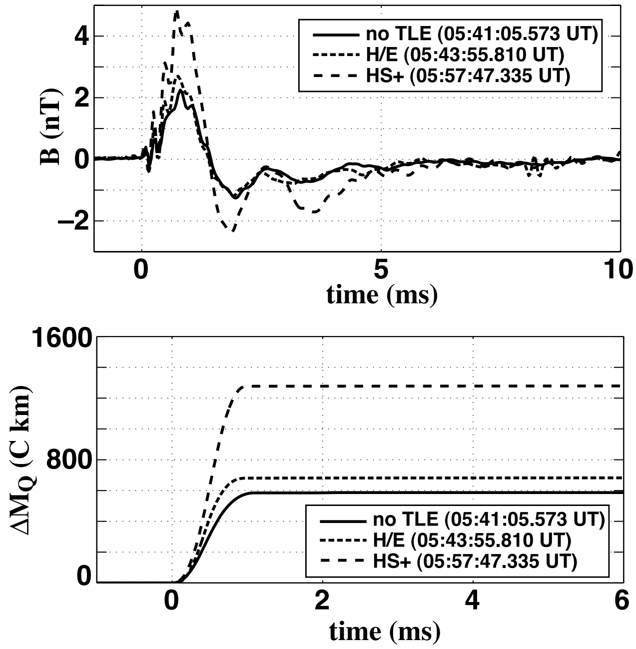

Figure 6. A detailed look at three similarly impulsive +CGs on 4 July 2000 that both demonstrate and confirm the consistency of the measurements with a sharp sprite initiation threshold. (top) The measured magnetic field waveforms from these three strokes. (bottom) The measured $\Delta M_q(t)$ waveforms for each stroke.

significant experimental evidence regarding a possible lightning and field polarity asymmetry in sprite generation. It is intriguing that a 791 C km −CG produced only an elve (no halo or sprite) while a smaller 681 C km +CG produced a likely halo, since the conventional breakdown process responsible for halos [*Barrington-Leigh et al.*, 2001] is not thought to have any polarity asymmetry. These and other near-threshold strokes are examined more closely in the following section.

6. Close Examination of 4 July 2000 Strokes

[27] The number of sprites recorded on 4 July 2000 is large enough that a closer, event-by-event examination of some lightning strokes may reveal additional information about the sharpness and polarity asymmetry of the 600 C km threshold on this day. We first show three +CG strokes; one contains the largest $i\Delta M_q$ that did not create a detectable TLE, one generated a halo or elve, and one generated a large halo-sprite combination. Figure 6 shows the calibrated magnetic field waveforms radiated by these strokes (top) and the extracted $\Delta M_q(t)$ waveforms for each (bottom). The NLDN peak current for the no TLE stroke (+87.4 kA) is greater than that for the halo or elve stroke (+75 kA); it is thus likely that the observed TLE was a halo. This is also supported by the measured ΔM_q. The no TLE stroke ΔM_q of 587 C km is slightly smaller than the halo/elve stroke ΔM_q of 681 C km. The radiated magnetic field waveforms are almost identical in shape and the only difference is this ~20% magnitude difference. This is further evidence in favor of a sharp ΔM_q threshold for sprite and halo production around 600 C km on this night. The stroke that produced the large halo-sprite combination also has almost exactly the same waveform shape but is even bigger with a safely above-threshold ΔM_q of 1277 C km.

[28] We also examine in detail the two biggest (in ΔM_q) −CGs in the 4 July 2000 storm and compare them to the halo-producing +CG from above. The top of Figure 7 shows the calibrated magnetic field waveforms radiated by these strokes, while the bottom shows the extracted $\Delta M_q(t)$ waveforms for each. The smaller −CG is very similar in magnitude and timescale to the halo-producing +CG, but it is slightly smaller (641 C km versus 681 C km) and, given that it is so close to the apparent 600 C km threshold, it is not a complete surprise that it did not generate a halo. However, the waveforms show that the larger −CG is clearly bigger than the halo-producing +CG and it contained an significantly larger $i\Delta M_q$ (791 C km versus 681 C km). This large −CG did produce an elve that was identified by its large horizontal extent, which is not surprising in light of its large −180.7 kA NLDN peak current, but it did not produce visible optical emissions from lower-altitude conventional breakdown in the form of a halo or sprite. Although this event hints at a possible polarity asymmetry, it is likely the only −CG in the entire storm that substantially exceeded the 600 C km threshold, and it is impossible to draw firm conclusions from a single event. It is worth noting that the large −CG $i\Delta M_q$ occurred over a faster timescale than the other two in Figure 7 (note the faster return to zero in that magnetic field waveform).

7. Summary and Conclusions

[29] To investigate whether factors other than lightning charge moment change, which drives the quasi-static mesospheric electric field thought to produce sprites,

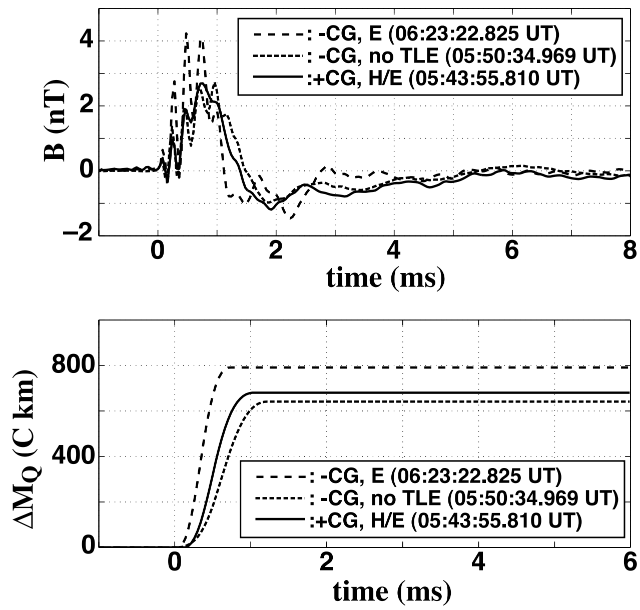

Figure 7. A detailed look at three near-threshold 4 July 2000 lightning strokes (2 −CGs and 1 +CG). (top) The measured magnetic field waveforms from these three strokes. (bottom) The measured $\Delta M_q(t)$ waveforms for each stroke. Only the +CG produced a halo or sprite.

contribute to sprite initiation, we carefully analyzed the 2 ms $i\Delta M_q$ in hundreds of CG lightning strokes in three different storms during which sprite video observations could confirm whether specific strokes did or did not produce sprites. In all three storms the distribution of ΔM_q and sprite occurrence is consistent with a sharp threshold in the ΔM_q required for sprite initiation that does not vary with time for an individual storm. The data and instrument limitations prevent a truly definitive determination of the sharpness of the threshold, but the data strongly support the existence of a sharp threshold over an event-to-event variable threshold. After accounting for lightning-to-sprite delays and the limitations of our 2 ms $i\Delta M_q$ measurements, we found that essentially all +CG strokes above the nightly threshold produced short-delayed sprites and, equally importantly, all below the nightly threshold did not. Moreover, all of the delayed sprites followed below-threshold $i\Delta M_q$ lightning strokes, which is consistent with subsequent continuing current contributing further charge transfer to exceed the initiation threshold.

[30] These data support the hypothesis that lightning charge moment change is the dominant factor involved generating sprites, as expected from the generally accepted conventional breakdown theory [*Pasko et al.*, 1997b]. We also find that the ΔM_q threshold for short-delayed sprites is spatially (on the scale of individual storms) and temporally (on the scale of a few hours) uniform. If neutral density depletions produced by gravity waves played a major role in sprite initiation [*Rowland et al.*, 1996; *Pasko et al.*, 1997a], then we might expect that in some regions at certain times the sprite initiation ΔM_q threshold would be lowered. This would manifest itself as a wider spread in the apparent threshold that is not supported by these data.

[31] On two of the nights analyzed, this threshold was 600 C km, while on the other it was 350 C km. Direct comparison of this threshold with theory is difficult because the threshold depends very strongly on the variable and poorly known conductivity profile in the mesosphere. However, this threshold is consistent with rough estimates of the conventional breakdown threshold [*Huang et al.*, 1999] at typical sprite initiation altitudes of roughly 75 km [*Stanley et al.*, 1999]. On the three nights examined, the threshold does not appear be lowered significantly below expectation by some other factor such as field amplification by meteoritic dust particles [*Zabotin and Wright*, 2001]. Some threshold variation across nights is also expected from background *D* region ionospheric conductivity variability [*Pasko et al.*, 1997b], although confirming that the observed variations are caused by this requires independent ionospheric measurements.

[32] The search for evidence of any field polarity asymmetry in sprite initiation that could explain the lack of sprites produced by −CG strokes proved challenging. In the U.S. High Plains storms analyzed, there were very few −CG strokes with $i\Delta M_q$ larger than a few hundred C km. Only one −CG stroke significantly exceeded the apparent sprite initiation threshold and, interestingly, it produced an elve but not a halo or sprite. More large −CG strokes must be found during above-thunderstorm optical measurements before strong conclusions regarding polarity asymmetry can be drawn.

[33] Although the measurements presented here are consistent with a sharp ΔM_q sprite initiation threshold corresponding to conventional breakdown in the mesosphere, there are observations of short-delayed sprites produced by ΔM_q < 200 C km [*Hu et al.*, 2002] that suggest other factors may at times play a role. A combination of high time resolution sprite video and longer-time, continuing current measurements [e.g., *Cummer and Füllekrug*, 2001] will enable a more precise measurement of sprite initiation ΔM_q thresholds that would enable a more rigorous comparison of theory and measurement.

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