Sprite produced by consecutive impulse charge transfers following a negative stroke: Observation and simulation

Gaopeng Lu1,2,3, Steven A. Cummer4, Ye Tian1,5, Hongbo Zhang1,5, Fanchao Lyu5, Tao Wang6,7, Mark A. Stanley6, Jing Yang1,2, and Walter A. Lyons9

1Key Laboratory of Middle Atmosphere and Global Environment Observation (LAGEO), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China, 2Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing, China, 3Key Laboratory of Meteorological Disaster of Ministry of Education, Nanjing University of Information Science and Technology, Nanjing, China, 4Electrical and Computer Engineering Department, Duke University, Durham, North Carolina, United States, 5University of Chinese Academy of Sciences, Beijing, China, 6Department of Atmospheric Sciences, Texas A&M University, College Station, Texas, United States, 7Now at Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, United States, 8Langmuir Laboratory, New Mexico Institute of Mining and Technology, Socorro, New Mexico, USA, 9FMA Research, Fort Collins, Colorado, United States

Abstract On the morning of 5 June 2013, two cameras of the SpriteCam network concurrently captured a red sprite with diffuse halo over a mesoscale convective system (MCS) passing the panhandle area of Oklahoma. This sprite was produced by a negative cloud-to-ground (CG) stroke with peak current of ~103 kA in a manner different from previous observations in several aspects. First of all, the causative stroke of sprite is located by the National Lightning Detection Network (NLDN) in the trailing stratiform of MCS, instead of the deep convection typically for negative sprites. Second, the sprite-producing stroke was likely the first stroke of a multistroke negative CG flash (with ≥6 CG strokes) whose evolution was mainly confined in the lower part of thunderstorm; although the parent flash of sprite might contain relatively long in-cloud evolution prior to the first stroke, there is no evidence that the negative leader had propagated into the upper positive region of thundercloud as typically observed for the sprite-producing/class negative CG strokes. Third, as shown by the simulation with a two-dimensional full-wave electrodynamic model, although the impulse charge moment change (~190 C km) produced by the main stroke was not sufficient to induce conventional breakdown in the mesosphere, a second impulse charge transfer occurred with ~2 ms delay to cause a substantial charge transfer (~290 C km) so that the overall charge moment change (~480 C km) exceeded the threshold for sprite production; this is a scenario different from the typical case discussed by Li et al. (2012). As for the source of the second current pulse that played a critical role to produce the sprite, it could be an M component whose charge source was at least 9 km horizontally displaced from the main stroke or a negative CG stroke (with weak peak current for the return stroke) that was not detected by the NLDN.

1. Introduction

Sprites are produced by tropospheric lightning strokes in the mesospheric environment through transient electric perturbation driven by substantial charge transfer from the in-cloud reservoir to ground [Posko et al., 1997; Cho and Rycroft, 1998; Qin et al., 2012; Wang et al., 2015]. The existing ground-based observations indicate that only a very small fraction (<1%) of sprites are produced by negative cloud-to-ground (CG) strokes [Williams et al., 2007, 2012; Li et al., 2012]. However, the rare observations of negative sprites indeed provide solid evidence that sprites are the consequence of lightning-induced conventional breakdown in the mesosphere [Taylor et al., 2008; Liu et al., 2009].

The examinations of a handful of ground observations reveal some features common to negative sprites. Their parent strokes usually generate vertical impulse charge moment change (ICMC, defined as the product of the transferred charge within 2 ms after the return stroke and its original height above the ground level) in excess of ~450 C km [Barrington-Leigh et al., 1999; Taylor et al., 2008; Li et al., 2012; Boggs et al., 2016]. Almost all the negative sprites documented in the literature are described as bright vertical columns embedded in an upper diffuse disk-shaped region (called “halo”), and the fainter downward branching tendrils are visible at
lower altitudes [Li et al., 2012]. The accompanying halo strongly suggests that negative sprites are generated with small lateral offset (<10 km) from the parent stroke, as usually observed for sprite halos provided by intense positive CG strokes [Wescott et al., 2001; Lu et al., 2013].

Negative sprites typically appear dimmer than their positive counterpart for parent strokes with comparable iCMC. For instance, bright sprites produced by positive strokes with iCMC in excess of +500 C km often excite a slow magnetic pulse measurable at thousands of kilometers as driven by the current along sprite bodies [Cummer et al., 1998; Pasko et al., 1998]; the similar magnetic pulse has not yet observed for negative sprites, even for events associated with iCMCs up to −1050 C km [Li et al., 2012]. As for the parent lightning of negative sprites, the multistroke negative CG flashes that mainly develop in the lower part of thunderclouds are not likely a major producer; instead, the parent strokes of negative sprites might be preceded by a substantial intracloud evolution in the upper part of thundercloud as observed for normal bilevel intracloud lightning [Lu et al., 2012; Boggs et al., 2016], which is similar to positive sprite-producing strokes [van der Velde et al., 2006; Lang et al., 2011; Lu et al., 2009, 2013], although it remains unclear as how a long intracloud evolution in the upper part of thundercloud would precondition a negative stroke with exceptionally large iCMC.

Nevertheless, it almost comes to a classical picture on the morphology and occurrence of rarely observed negative sprites as typically driven by a single stroke with a substantial iCMC [Li et al., 2012; Boggs et al., 2016]. In this paper, we report the observation of a very unusual sprite that was unambiguously produced by a negative CG stroke with a subcritical iCMC (about −190 C km), which would not have produced the sufficient electric field ($E_0$ field) change all by itself to induce mesospheric breakdown. However, the subsequent impulse charge transfer delayed by about 2 ms further enhanced the electric perturbation in the mesosphere so that the total lightning $E$ field exceeds the critical field for conventional breakdown ($E_k$), demonstrating a new scenario for the sprite production by negative CG strokes.

2. Observations and Data

Late on 4 June 2013, the convective cells scattered in southeast of Colorado moved eastward and merged into a mesoscale convective system (MCS) typical to the central plain of the United States with favorable conditions for sprite production [Boccippio et al., 1995; Lyons, 1996; Cummer and Lyons, 2004]. As shown in Figure 1a, two low-light-level video cameras (Watec 902H2 Ultimate) were operated at Lubbock and Hawley (Texas), respectively, to observe the red sprites produced over the thunderstorm, recording a total of 59 sprite events from 02:53 to 10:24 UTC on the morning of June 5.
In addition to the data of the U.S. National Lightning Detection Network (NLDN) that reports (with detection efficiency of 90–95% for CG strokes) the time, location (with median accuracy <500 m), polarity, and peak current of lightning discharges [Biagi et al., 2007; Cummins and Murphy, 2009; Nag et al., 2011; Mallick et al., 2014], we also examined the data from the lightning charge moment change network (CMCN) [Cummer et al., 2013], which estimates the vertical iCMC (with uncertainty up to 50% due to the automated processing) for the NLDN strokes through an automated version of the regularization-based method described by Cummer and Inan [2000]. Moreover, the wideband (~50 Hz to 30 kHz) magnetic sferics recorded near Duke University are used to estimate the iCMC of parent strokes more precisely for these sprites [e.g., Li et al., 2012], and the low-frequency (LF, 30–300 kHz) magnetic sferics were also recorded at several stations deployed in the continental United States [Lu et al., 2013, Figure 1], making it possible to investigate the intracloud discharges linked to the sprite-producing strokes.

The parent strokes (indicated by red open diamonds in Figure 1a) of 58 sprites are of positive polarity, and the CMCN system estimated the iCMC (ranging from +133 C km to +820 C km) for 14 sprites. The remaining sprite (black open diamond) was associated with a negative CG stroke (at 06:03:38.764 UTC) detected by NLDN with 50% geolocation error of 200 m at (36.909°N, −100.456°E), near the border of Oklahoma and Kansas; this stroke had a high peak current of −103 kA, and the CMCN system estimated the iCMC of this stroke to be −189 C km. We also investigated 45 negative strokes with peak current >−80 kA produced in the MCS and identified four negative strokes (between 06:20 and 08:00 UTC, indicated by black solid diamonds in Figure 1a) that generated higher iCMCs (between −194 C km and −282 C km). These strokes all occurred within the ideal range (<500 km) of sprite observation but without producing a sprite recorded at the sites. Therefore, although the minimum iCMC for initiating negative sprite could be as small as −300 C km under favorable conditions (e.g., high reference height of ionosphere and/or vertically elongated inhomogeneity in electron density) [Qin et al., 2012], this is not likely the case for the negative sprite examined in this paper. Apparently, the sprite-producing negative stroke of our interest seems to be characterized by something unique that merits a further investigation.

Figures 1b and 1c show the occurrence of lightning flashes during the lifetime of the MCS and the time-resolved ratio of +CG relative to the total CGs, respectively. A grouping procedure was applied to group strokes within 1 s time window and with lateral displacement ≤10 km into a single flash [e.g., Lang et al., 2013; Zoghzoghy et al., 2013]. In our analysis, we only examined NLDN-classified CG strokes with peak currents ≥15 kA since the NLDN discharges below this value are very likely intracloud discharges [Cummins et al., 1998]. Before 04:10 UTC when the trailing stratiform has not formed yet, the sprites were produced, while the ratio of positive CGs increased dramatically from ~10% to over 30% due to the increasing occurrence of positive CG flashes. The negative sprite was observed shortly after a 100 min interval (04:10 to 05:50 UTC) without sprite observation, when the average flash rate was ~60 flashes per minute and the ratio of negative CGs was ~80%. After 05:50 UTC, the sprites were produced as the percentage of +CGs gradually declined from 20% to 10%. Generally speaking, for the thunderstorm on 5 June 2013, the observed sprites were predominantly produced during the mature stage of the MCS.

3. Analysis and Results

In this section, we present a detailed analysis of the sprite based on the radar reflectivity of parent thunderstorm upon the sprite observation, the broadband magnetic fields recorded near Duke University, and the LF sferics at several stations in the continental United States. These data are examined to acquire the information on the morphology of sprite-producing flash and the feature of lightning charge transfer that might be crucial for the sprite production.

3.1. Location of Sprite-Producing Negative Stroke

The images of negative sprite recorded from Hawley and Lubbock are shown in Figures 2a and 2b, respectively. With time-stamped video images at two sites, the occurrence of negative sprite can only be constrained within 17 ms (roughly the exposure time of each video field) after the return stroke. This negative sprite is not considerably dimmer than previous observations. The halo feature is discernible in the video image captured at 391 km range from Lubbock. By using the image brightness at least twice the background noise level to define the altitude range of this halo-sprite event [e.g., Li et al., 2012], the halo region is estimated to be topped at 80 km (above mean sea level, msl), which is considerably lower than previous
observations (near 90 km) [Li et al., 2012]; there were several embedded sprite elements, and the streamer region of the brightest sprite element appeared to descend below 66 km (msl). Here we have assumed that the center of halo region is located right above the causative stroke, and a 20 km lateral displacement will lead to 5 km uncertainty in the estimation of top height. As shown in the figure, the azimuthal location of parent stroke relative to the observation site in Lubbock and Hawley is consistent with that the sprites with halo feature, including negative sprites, are not considerably displaced azimuthally from the parent stroke [Wescott et al., 2001; Li et al., 2012].

By examining the NLDN discharges within 1 s before and after the sprite-producing stroke (at 38.764 s) and associated magnetic sferics, it is inferred that the sprite was produced by the first stroke of a negative CG flash with at least six discrete strokes, including a fifth stroke (with \(-55\) kA peak current) that reached ground 0.5 s later in the close proximity of the first stroke. The NLDN also detected a negative discharge at 38.088 s with 200 m uncertainty (located within 4 km of the first stroke) about 0.68 s prior to the sprite-producing stroke. Although the NLDN classified this discharge as a negative CG stroke with \(-17\) kA peak current, the associated sferics (with relatively short timescale \(<25\) μs, not shown) recorded at two LF stations (installed on the campus of Oklahoma University and Kansas State University, respectively) at the closest distance (332 km and 423 km, respectively) confirm it to be a vertical intracloud (IC) discharge of negative polarity [e.g., Wiens et al., 2008]; the sferic signals recorded at these two stations also suggest that there might be a few more IC discharges (with peak current below \(-10\) kA) during the 0.68 s interval. Hence, the parent flash of negative sprite likely developed fairly long in-cloud activity prior to the first stroke [e.g., Cummins and Murphy, 2009].

The sprite-producing negative stroke was 290 km from the origin of the Oklahoma Lightning Mapping Array (LMA), which did not detect very high-frequency (VHF) sources within 20 km of the stroke, providing further evidence that the parent lightning was likely a multistroke negative CG flash evolving mainly in the lower part (\(<10\) km) of trailing stratiform. In contrast, for a negative sprite-producing stroke at 260 km range examined by Lu et al. [2012, Figure 14], the Oklahoma LMA detected \(>50\) VHF sources above 10 km altitude prior to the sprite-producing stroke, indicating the evolution as bilevel intracloud lightning in the upper part of thunderstorm, which was also recently shown by Boggs et al. [2016] to be typical for sprite-producing negative strokes. Is it the case for the negative sprite reported in this paper?
By carefully inspecting the performance of Oklahoma LMA upon the observation of this negative sprite, we concluded that the absence of associated VHF sources from the parent flash was due to the lack of negative leader progression in the upper part of thundercloud. During the 10 min interval centered at the negative sprite observation, the LMA detected hundreds of VHF sources (mostly >10 km) from the small convective region (~340 km from the LMA origin) located in west of the MCS (see Figure 2b), demonstrating the capability of LMA to detect at least strong VHF radiation at the range of causative stroke of this negative sprite. In particular, for all the sprite-producing positive strokes (SP + CGs) shown in Figure 2c at the similar ranges, the LMA detected a considerable number of VHF sources predominantly over 10 km (msl) \cite{Lu et al., 2009, 2013; Lang et al., 2011}; furthermore, the examination of LMA data for one (at 06:29:18 UTC) of the aforementioned nonsprite-producing negative strokes with the largest iCMC (\textasciitilde 282 C km), which is also at the similar range (310 km from the LMA origin), indicates the progression of negative leader(s) prior to the stroke with >20 VHF sources above 10 km (msl). Therefore, the parent flash for our particular negative sprite probably did not develop into the upper positive charge region at all during its lifetime.

It is also possible that the NLDN discharge detected 0.68 s prior to the sprite-producing negative stroke occurred without any connection to the parent flash of negative sprite. This will not affect the conclusion regarding the absence of negative leader progression in the upper positive region.

In summary, all the data available are not in favor of the negative leader progression in the upper positive region of thunderstorm prior to the causative stroke as typically observed for negative sprite-producing strokes, although this scenario is not impossible for our event. Nevertheless, our analyses above at least raise the possibility that the negative sprite could be produced in association with a multistroke negative CG flash whose development is confined in the lower part of thunderclouds, probably due to the considerable distribution of positive charge near the bottom of stratiform \cite{Stolzenburg et al., 1998; Nag and Rakov, 2009}.

### 3.2. Charge Transfer of Sprite-Producing Stroke

The very low frequency (VLF, 50 Hz to 30 kHz) magnetic sferics recorded at 1908 km range (Figure 3a) indicates the presence of at least two major impulse charge transfers (as implied by the low-pass filtered signal) separated by about 2 ms within 5 ms after the onset of the sprite-producing stroke. This feature was not observed for other negative CG strokes in the MCS that produced higher iCMC but without sprite observation, and the relevant observation with remote sensing data has not been reported yet in the literature to our best knowledge.

As indicated in Figure 3a, the NLDN-registered stroke (at 38.764 s) was related to the return stroke phase of the first current pulse, and there was no NLDN detection associated with the subsequent main current...
pulse. It can be claimed that this subsequent current pulse was not associated with the current flowing along sprite bodies as observed for bright sprites produced by energetic CG strokes typically with iCMC greater than +500 C km [Cummer et al., 1998; Pasko et al., 1998]. As shown in the figure, the broadband VLF magnetic signal (red line in Figure 3a) of the subsequent current pulse contains some submillisecond variations that were not observed in previous measurements associated with sprite current [Stanley et al., 2000; Hu et al., 2002]. In addition, as indicated consistently by the LF sferics recorded at six stations ranging between 332 km and 2097 km (Figure 3b), the second current pulse was accompanied by a relatively long (~1.5 ms) burst of LF emissions (see the inset) that initiated 2.4 ms after the leading return stroke. The similar LF emission, which is usually attributed to K process (or propagation of negative leader along the existing lightning channel) in the interpretation of broadband sferics [van der Velde et al., 2006], has not been reported in association with sprite current.

Figure 4a shows the sferic data for the positive sprite-producing CG stroke at 06:01:59 UTC. For comparison, the sferics for the negative CG stroke at 06:29:18 UTC with iCMC of −282 C km (but no sprite was produced) are plotted in Figure 4b. Although the VLF signals of positive and negative CG strokes look very similar in the general waveform except for the opposite polarities, the associated LF sferics recorded at the similar distance show a significant difference in the LF emissions shortly after the return stroke. As shown in the inset of Figure 4a, the positive sprite-producing CG stroke is characterized by a trailing LF emission lasting ~1 ms, which is linked to the negative breakdown (initiated by return stroke) horizontally spreading along existing lightning channels in the cloud [Lu et al., 2009]; the negative CG strokes does not show this feature, and the associated LF emissions (with timescales >100 μs) usually only reflect the propagation of return stroke signal in the Earth-ionosphere waveguide.

Nevertheless, all the relevant sferic features suggest that the subsequent current pulse shown in Figure 3 is more likely connected to a cloud-to-ground discharging event in the source region of negative sprite-producing lightning, rather than from the sprite streamers. The associated LF emissions could be attributed to the in-cloud lightning activity related to the CG charge transfer. With the LF magnetic fields recorded at six stations, we can independently locate the source stroke of the first current pulse at a location (36.908°N, 100.447°E), which is consistent with the NLDN-reported location within 800 m. The same data are used to locate the source of LF emissions (open circle in Figure 2c), which is best constrained 9–17 km (using different features of the sferic waveform shown in the inset of Figure 3b) northwest of the main stroke, placing the origin of second current pulse further into the trailing stratiform.

Using the deconvolution method that has been applied extensively to estimate the iCMC of sprite-producing strokes [Cummer and Inan, 1997; Hu et al., 2002; Cummer and Lyons, 2004], we reconstructed the current moment waveform in the lightning source region based on the VLF sferics [Li et al., 2012] and the result is shown in Figure 5. Overall, the cumulative charge moment change (~190 C km) within 1 ms after the onset of stroke is in good agreement with the aforementioned CMCN estimate of iCMC (~189 C km) through an automated procedure. The current pulse of the main stroke lasted about 0.5 ms, which is consistent with
previous analyses of sprite-producing negative strokes [Li et al., 2012]. The subsequent current pulse indicated in Figure 3a lasted ~1.2 ms and contributed −290 C km charge moment change. Consequently, by the end of second impulse charge transfer, the total charge moment change accumulated to −480 C km, reaching the threshold for producing sprites under normal conditions [Qin et al., 2013].

3.3. Possible Source of Second Current Pulse

Apparently, the subsequent current pulse with 2 ms delay after the main stroke has played a significant role in the production of negative sprite reported in this paper. One possible source for this subsequent current pulse is a weak (in term of peak current for the return stroke) negative CG stroke that was not detected by the NLDN. Although the associated LF emissions are atypical for negative CG strokes, we cannot exclude this likelihood since there is no dedicated study yet regarding the waveform feature of LF sferics radiated by negative return strokes with small peak currents. For this reason, also because of the uncertainty in the existence of a long in-cloud evolution prior to the negative stroke, it is possible that the second current pulse was actually caused by a different negative CG stroke. If that is the case, the parent flash of sprite produced two strokes that were very close in time at two locations separated by at least 9 km, which is unusual.

In order to explore other plausible physical cause of the second current pulse, we refer to the work of Visacro et al. [2013], who examined the channel base current of 15 negative CG flashes, finding that a considerable fraction (~50%) of first negative strokes contained $M$ component within 3 ms after return stroke, rather than superimposed on the continuing current. As a characteristic process commonly observed during the continuing current of negative CGs [Rakov et al., 1992; Rakov and Uman, 2003], the $M$ component is usually attributed to charge transfer to ground, while the lightning channel of preceding return stroke is still active [Rakov et al., 1995].

Therefore, the burst of LF emissions linked to the subsequent current pulse was likely linked to the progression of retrograding negative breakdown (i.e., $K$ process) occurring, while the positive leader extended into negative cloud regions, which is actually similar to the mechanism for the LF emissions typically observed in association with sprite-producing positive CG strokes (see the inset of Figure 4a). As mentioned above, the parent flash of negative sprite might undergo a long duration (0.68 s) of in-cloud evolution prior to the first negative stroke, and thus it is very likely during this interval one of the positive leaders progressed horizontally (at a mean speed of $-1-3 \times 10^4$ m/s) to a stratiform region >10 km from the flash initiation region. Upon the occurrence of the first stroke, the potential difference between the stroke channel and the distant negative cloud region might drive a subsequent current pulse that traverses the in-cloud lightning channel to ground with appreciable delay (~2 ms) after the main stroke. With a horizontal displacement of 9–17 km from the main stroke and 1.5 ms duration of progression, the propagation velocity of current-carrying negative leader is estimated to be on the order of $10^6-10^7$ m/s, which falls in the typical range for the velocity of $K$-processes [Shao et al., 1995]. However, due to the lack of relevant observations in the literature, it remains intriguing as what situation can make an $M$ component to produce such an extraordinary vertical charge moment change (~290 C km), which is also very unusual.

4. Simulation of High-Altitude Electric Transient

To further understand the mechanism of sprite production by the negative CG stroke with subcritical iCMC followed by a second current pulse with substantial charge moment change, we applied the two-dimensional (2-D) finite-difference time-domain model of Zhang et al. [2014] to simulate the lightning-induced electromagnetic transients at high altitudes. In this model, the self-consistent response of the upper atmosphere to lightning $E$ fields is taken into account. That is, while the lightning $E$ field decays in the
A conductive upper atmosphere, it will alter the ambient conductivity (dominated by electrons above 60 km) through attachment and ionization that both depend on the strength of ambient electric field [Pasko et al., 1997; Cho and Rycroft, 1998]. In the simulation, the time-resolved current moment shown in Figure 4 is used as an input, and the original height of depleted charge source is set to be 6 km above the ground level, which is a typical value for multistroke negative CG flashes confined in the lower part of thunderstorms [e.g., Lu et al., 2012].

Figure 6a shows the lightning-induced vertical electric field change (ΔE) at 80 km altitude (the typical altitude for the center of halo formation [Wescott et al., 2001] and the initiation of negative sprites [Li et al., 2012]) directly above the stroke. The sprite occurrence can be determined by comparing the lightning-driven ΔE with the critical electric field of conventional breakdown (E_k ~ 48 V/m) at this altitude, where the relaxation time in the absence of electric field is about 0.1 ms. As shown in the figure, within 0.5 ms after the arrival of lightning perturbation when it is dominated by the electromagnetic effect of current pulse [Cho and Rycroft, 1998; Pasko et al., 1999], the electric transient reaches a level ~75% of the threshold of conventional breakdown, and thereafter the lightning E field caused by the main stroke decays slowly with a time scale substantially longer than the original relaxation time. The variation in the electric density at high altitudes is caused by the competition between attachment and ionization [Pasko et al., 1997]; in the subcritical E-field, because the attachment process dominates to reduce electron density and thus ambient conductivity, the lightning transient can retain a considerable level for several milliseconds.

Figure 6b shows the time-resolved evolution of normalized total electric field (ΔE/E_k) at different altitudes (from 40 km to 90 km) above the negative CG stroke [e.g., Li et al., 2012]. We can see that the electromagnetic effect of the main stroke played a major role above 76 km, while its associated ΔE is generally below the threshold of conventional breakdown. The second current pulse causes the overall lightning electric field to exceed the critical E field between 76 km and 82 km, roughly the altitude range of main halo emission shown in Figure 2b. According to the analyses of Li et al. [2012], the streamers of negative sprites are typically terminated at relatively high altitudes where the ambient electric field (formed by lightning) is about 0.2–0.3E_k. In our simulation, the lightning E field with strength in excess of 0.2E_k extends to an altitude as low as 61 km, which is consistent with the observation that the streamer of the brightest sprite element (see Figure 2b) could have descended to altitudes below 63 km.
5. Conclusions

Sprites produced by negative CGs are extremely rare (<1%) among the family of transient luminous events (TLEs) [Williams et al., 2007]. Here we examined the observation of a negative sprite whose appearance is generally in line with previous reports (e.g., halo feature and relatively high termination altitude of sprite streamers) [Li et al., 2012], but this particular event was unambiguously produced by a $-103 \text{kA}$ negative stroke detected by the National Lightning Detection Network (NLDN) that was followed by two consecutive impulse charge transfers (causing charge moment change of $-190 \text{C km}$ and $-290 \text{C km}$, respectively) separated by $\sim2\text{ ms}$, which is not typical for negative sprite-producing CG strokes [Li et al., 2012; Boggs et al., 2016].

The fact that other negative CG strokes with higher iCMC up to $-282 \text{ C km}$ in the same MCS did not produce sprites captured within the ideal range suggests that the second impulse current in the parent stroke of negative sprite was critical for the sprite production. Our numerical simulation using an electromagnetic code indicates that although the $E$ field transient caused by the main stroke is insufficient to cause conventional breakdown, it creates a favorable condition for sprite production by reducing the ambient conductivity so that the electric perturbation of main stroke will persist on a high level. As a consequence, the electric transient of the second impulse current can be superimposed to readily exceed the critical field for sprite production. The role of the main stroke is therefore similar to the long continuing current preceding the long-delayed sprites [Li et al., 2008]. Nevertheless, the analysis of this rare observation presents a new but uncommon scenario for the mesospheric breakdown by CG strokes, namely, consecutive impulse currents with subcritical strength for producing sprite could also cause conventional breakdown in the mesosphere if their high-altitude electric transients are efficiently superposed so that the overall effect meets the condition for sprite formation [Asano et al., 2009].

The examination of data from NLDN, Oklahoma LMA (lack of relevant observations), and LF sferics recorded at multiple stations provides more insights into the lightning morphology linked to this atypical sprite-producing charge transfer. The sprite-producing stroke was likely the first stroke of a multistroke negative CG flash whose evolution was mainly confined below 10 km in the trailing stratiform of a mesoscale convective system. Although the data we collected are not in favor of the propagation of a negative leader in the upper positive region of the thundercloud as typically observed for sprite-producing/class negative CG strokes [Lu et al., 2012; Boggs et al., 2016], this flash was indeed likely preceded by a long period (0.68 s) of in-cloud activity prior to the sprite observation. During this considerable long prestroke interval, the negative leader might have been trapped in a potential well of a large positive charge center on the bottom of trailing stratiform, which also makes it possible for the positive leader to extend to another negative charge region in the stratiform with considerable horizontal displacement from the flash initiation region.

Therefore, although previous work seems to derive some common features on the morphology of negative sprites as well as causative lightning, the complexity in the charge structure of parent thunderstorms and lightning evolution might still cause some variability in the charge transfer of causative strokes. It has been established that the sprites could be produced by very large impulse charge transfer during the return stroke (i.e., prompt sprites) [Hu et al., 2002; Lu et al., 2013] or by brief enhancement of continuing current (i.e., delayed sprites) as surges linked to $M$ components [Yashunin et al., 2007; Li et al., 2008; Asano et al., 2009]. The current surges, however, could also occur with short delays (a few milliseconds) after the major stroke, leading to the occurrence of “prompt sprites” in a different manner.

Regarding the nature of the second current pulse, from the LF sferics recorded at six stations, it was likely an $M$ component caused by the interception of recoil leader with the existing stroke channel, and the origin of this recoil leader was at least 9 km from the stroke. What is remarkable is the substantial charge moment change ($-290 \text{ C km}$) caused by the $M$ component, which was rarely reported in the literature. Hence, it is desirable to investigate the magnitude (in term of charge moment change) of $M$ components on a statistical basis, especially those with short delays after return stroke [e.g., Visacro et al., 2013]. On the other hand, we cannot exclude the possibility that the second current pulse was caused by a negative CG not detected by the NLDN due to a weak peak current for the return stroke. More insights into the nature of the subsequent impulse charge transfer could be obtained by examining a sufficiently large dataset of broadband sferics with similar waveform feature from negative CG strokes located within the ideal detection range of Lightning Mapping Arrays.
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