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Key Points:
- First observation of a negative halo/sprite event with the signature of sprite current in the concurrent very-low-frequency sferic waveform
- This unusual negative sprite is produced by an impulse charge moment change (approximately −520 C·km) barely enough for producing a sprite
- The occurrence of this event is likely caused by an extraordinarily long duration of charge transfer to ground following the return stroke

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Space-Based Observation of a Negative Sprite With an Unusual Signature of Associated Sprite Current

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Abstract We report the first observation of an unusual red sprite produced by negative cloud-to-ground (CG) lightning from the Imager of Sprites and Upper Atmospheric Lightning (ISUAL) in Colombia on August 15, 2012. The impulse charge moment change for this event is approximately −520 C·km, barely reaching the threshold for negative sprite production. However, different from all previously reported observations, this negative sprite contains a distinct "sprite current" feature that is unambiguously identified in the very-low-frequency magnetic field recorded at the 3,387 km range in Duke Forest. There is no evidence that this feature was produced by a fast discharging process associated with the causative CG stroke. Instead, the sprite current signal corresponds well to high-altitude optical emissions associated with the charge flow in the sprite body. The charge moment change caused by the charge transfer in the sprite region was estimated to be about −460 C·km. We attempt to reveal the possible causes of this atypical event from the perspective of the parent thunderstorm and the local ionosphere irregularities, whereas we believe that the most possible reason remains to lie in an extraordinarily long duration (more than 5 ms) of charge transfer to ground following the return stroke.

Plain Language Summary Although the sprite observations associated with negative cloud-to-ground (CG) strokes are very rare, the analyses on limited cases still yield a consensus on the typical features of negative sprites. Negative sprites have not yet been reported to contain the "sprite current" signature usually detected in bright positive sprites. With the dataset provided by the Imager of Sprites and Upper Atmospheric Lightning, we found an extremely rare case of negative sprite. The associated broadband magnetic field clearly shows the characteristic waveform indicative of sprite current, despite the impulse charge moment change (about −520 C·km) barely exceeding the critical strength for producing negative sprites. Our analyses exclude the possibility that this sprite current signature was produced by the low-altitude lightning discharges; instead, the absence of low-frequency emissions during the occurrence of the suspected sprite current strongly suggests that the second slow magnetic pulse was driven by the charge transfer associated with the high-altitude optical emissions. This exceptional observation implies that there could be some situations (such as local plasma irregularities) hidden in the mesosphere. However, the most likely cause seems to be a particularly long charge transfer time (more than 5 ms) after the return stroke of the parent CG flash.

1. Introduction

Red sprites are produced by the transient electric field (*E*-field) perturbation caused by the substantial charge transfer during tropospheric cloud-to-ground (CG) lightning (Lyons et al., 2003; Pasko et al., 1997). For the red sprites observed over continental thunderstorms, the vast majority are produced by positive CG strokes (e.g., Li et al., 2012), and those events appearing to be particularly bright could drive a remarkable signature called "sprite current" in sprite-associated broadband lightning sferics (Cummer et al., 1998; Hager et al., 2012). Ground-based observations show that Only a very small fraction (less than 1%) is generated by negative lightning strokes (Lu et al., 2013; Williams et al., 2012), while the observations of the Imager of Sprites and Upper Atmospheric Lightning (ISUAL) aboard the FORMOSAT-2 satellite indicate that the proportion can reach up to nearly 20% over oceanic thunderstorms (Chen et al., 2019; Lu et al., 2017).

Although rarely documented, the sprites produced by negative CG strokes bear some common features including: (1) A relatively large charge moment change (usually >−500 C·km) in a short period of time (typically <1 ms); (2) An accompanying halo feature on the top of the sprite; and (3) A relatively small lateral offset between the sprite region and the parent stroke (Boggs et al., 2016; Li et al., 2012; Taylor et al., 2008; Wescott et al., 2001). The sprite current signature has not yet been reported for sprites produced by negative CG strokes, even for events associated with impulse charge moment changes (iCMC) in excess of −1000 C·km (Lu et al., 2017). When including the negative sprites over oceanic thunderstorms, their morphological characteristics remain the same. The studies over the past 2 decades almost reach a classical image of negative sprites, at least revealing an absence of sprite current signature.

In this study, we report the observation of a particular negative sprite among the ISUAL dataset above a mesoscale convection system (MCS) in South America. The morphological features of this event are basically in line with previous reports, namely the negative sprite consists of a few vertical elements that contain bright cores as well as filamentary streamers (Li et al., 2012; Taylor et al., 2008). Notably, its brightness was higher in visual perception than that reported in previous studies (e.g., Frey et al., 2007; Lu et al, 2017. As a matter of fact, the event in Figure 2 examined by Frey et al., 2007 could also be classified as a halo-sprite event due to the existence of two tiny streamer features). Similar to the case examined by Lu et al. (2016), the broadband magnetic sferics associated with this event contain two pulses, while the second pulse is inferred to be generated by the current along the sprite body. Therefore, the atypical event composes the first case of the negative sprite with the sprite current signal discerned in the concurrent broadband lightning sferics. The possible reason leading to the occurrence of this unusual event is discussed.

2. Observations and Data

The sprite of our particular interest was captured by ISUAL at 0437:38.048 UTC (Coordinated Universal Time, ISUAL triggering time with approximately ±5 ms uncertainty) on August 15, 2012. The sprite location provided by the space-borne platform showed that the event is near the northern border of Bogotá, Colombia (Figure 1a, 5.21°N, 76.10°W), about 100 km east of the location (5.23°N, 77.15°W) reported by the World-Wide Lightning Location Network (WWLLN; Abarca et al., 2010). In our analysis, we assumed that the sprite was located above the causative CG stroke, since the sprites accompanied with halos are typically centered within 10 km of their corresponding parent strokes based on the previous studies (e.g., Miyasato et al., 2002). As shown in the left inset of Figure 1a, the sprite contains multiple elements as well as a distinctive halo feature, whose lateral scale is estimated to be >60 km. The top diffuse glow reaches an altitude of about 87 km; the lowest altitude of downward streamers is about 50 km, which is lower than all cases examined by Li et al. (2012). The real altitude range of the sprite structure may be larger due to the atmospheric attenuation (Frey et al., 2016).

Figure 1b shows the very-low-frequency (VLF, 50 Hz–30 kHz) sferics of the sprite-producing CG stroke recorded at 3,387 km range in Duke Forest (35.98°N, 79.10°W), with a negative polarity. The parent stroke lacked a sustained current component in contrast to typical positive sprite-producing strokes, and a pulse waveform suspected to be the sprite current signature starts at about 1 ms after the stroke. The charge transfer duration of the parent stroke is longer than that of the negative sprite-producing strokes described by Li et al. (2012). The long persistence *E*-field is favorable for the plasma in the sprite streamer channel to propagate into the non-ionized medium. This may explain why a significant fraction of negative strokes with sprite-producing iCMCs only produced pure halos, rather than sprites (Li et al., 2012; Lu et al., 2018).

We have known that the optical characteristics of sprites are mainly from the N_2 first positive band ($1PN_2$, 478–2,000 nm), the N_2 second positive band ($2PN_2$, 270–470 nm), the N_2 Lyman-Birge-Hopfield (LBH) band (100–260 nm), the N_2^+ first negative band ($1NN_2^+$, 320–1,600 nm), and the N_2^+ Meinel band (550–1,600 nm; Kuo et al., 2011). ISUAL measured the precise spectral characteristics of sprites as well as lightning. To examine the relationship between the suspected sprite current and the optical emissions, we use the coordinated measurements of sferic and ISUAL data to determine the source of the second current pulse. This

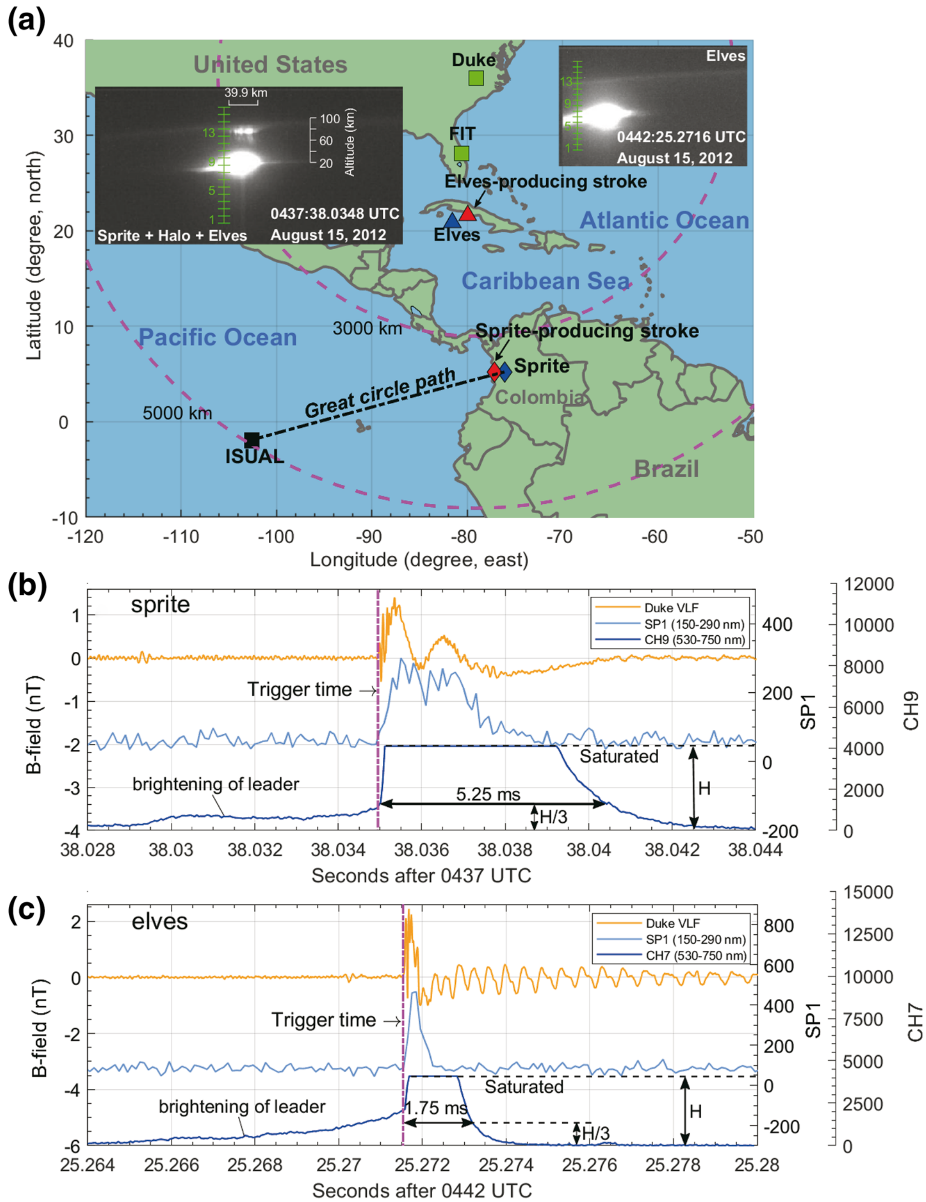

Figure 1. Panel (a) red sprite recorded by ISUAL on August 15, 2012 near Colombia. The blue diamond and triangle mark the ISUAL-determined sprite and elves location, respectively; the red diamond and triangle mark the parent stroke location of two events detected by the World-Wide Lightning Location Network (WWLLN), respectively. Panels (b & c) optical emissions and VLF sferics associated with two events. The time axis is corrected by the propagation delay. ISUAL, Imager of Sprites and Upper Atmospheric Lightning; VLF, very-low-frequency; WWLLN, World-Wide Lightning Location Network.

study adopts the absolute time of the lightning onset to plot the measured signals. The small timing errors may be due to the uncertainty in the ISUAL time.

Figure 1b also shows the optical signal for the event of channel 9 (corresponding to the lightning altitude) among Array Photometer (AP) installed on ISUAL for the event. The AP includes two wavelength channels (blue: 350–470 nm and red: 530–750 nm), and each channel has 16 vertically stacked strip anodes. The channel signal has a three-step brightness signature (namely, initial brightening, slow brightness decrease, and strong brightening) in the photometer trace (the characteristics of the waveform signal may not be significant due to the short time window; see Figure 2 and Figure 3 of Frey et al., 2005 for detailed features). Frey et al. (2005) showed that the brightness variation is caused by the initial breakdown with a β-type stepped leader, followed by a return stroke. To ensure the validity of sferic measurements, we also examined other transient luminous events (TLEs) observed by ISUAL in Central America on August 15, 2012 (see Table 1). The results showed that all of them were elves (emission of light and VLF perturbations due to electromagnetic pulse sources) caused by negative CG strokes. The appearance of elves is the consequence of electrons being accelerated by lightning discharges (Fukunishi et al., 1996) and they are almost always caused by negative CG strokes (Barrington-Leigh & Inan, 1999). Therefore, the special case in this study is not signal misjudgment. This also supports that the parent lightning of this event should be a negative CG flash.

In the absence of radar reflectivity data to examine the evolution of the parent thunderstorm, we refer to the cloud-top brightness temperature (equivalent blackbody temperatures with a spatial resolution of 4×4 km) merged from the geostationary satellites of European, Japanese, and U.S. (e.g., GOES-8/9, METEOSAT-5/7, and GMS-5/MTSat-1R) to analyze the morphology and development of the parent thunderstorm. In addition, we also tried to investigate the available occultation and sounding data to further understand whether the electromagnetic environment and the parent thunderstorm of this particular event is different from the typical sprite-producing environment as well as the thunderstorm in more detail. It is a pity that no corresponding data were found at the event time.

3. Analysis and Results

The observation of this intriguing event undoubtedly enriches our understanding on the phenomenology of sprites produced by negative CG strokes. Further analyses are desired to be made from the perspective of parent thunderstorm and causative CG stroke to reveal the possible reasons that could lead to the occurrence of this unusual event.

3.1. Implications on the Parent Thunderstorm

Lang et al. (2013) indicated that negative sprite-parent strokes typically occur in precipitation systems of similar size and intensity to the positive counterpart as well as they usually appear in the convective region rather than the stratiform precipitation region. The sprite-parent thunderstorm examined here was a mesoscale convective system (MCS) with a life span of more than one day and a maximum horizontal range of more than 200 km. The parent thunderstorm began with several small convective cells at about 23 UTC on August 14, and then kept growing to agglomerate into a relatively larger convective core near the northern border of Bogotá, Colombia. Since 03 UTC on August 15, the boundary of the convection system became gradually distinct as well as the bright temperature area below 210 K also gradually expanded. Accompanied with low-pressure centers, the convective system moved from northwestern Colombia to the eastern Pacific Ocean and evolved into a MCS at around 04 UTC, which is a typical mesoscale convective process observed in the Central America region. Under the influence of wind shear, the trailing stratiform region spread to the southwest, giving the MCS an asymmetric structure. The MCS eventually dissipated at about 16 UTC.

Figure 2 shows the distribution of WWLLN CG strokes (within 20-minute interval centered at 05 UTC) overlaid on the cloud-top brightness temperature. To facilitate the observation of the thunderstorm morphology, we only show the area below 250 K of brightness temperature in Figure 2. CG strokes are mainly distributed in lower temperature regions (<230 K) as well as the lightning frequency is positively correlated with the convection intensity. The sprite-producing stroke is located in the relatively cold region (about 210 K). During the sprite generation period, the thunderstorm became more organized and the border of the stratiform region developed clearer. After the active convection region of the parent thunderstorm, there is an extensive stratiform region. This is consistent with previous studies that the parent lightning of negative sprites occur mainly in or near intense, deep convection region and the parent systems are usually of MCS scale (Lang et al., 2013; Soula et al., 2009; Taylor et al., 2008). Overall, the parent thunderstorm appeared to be an ordinary sprite-producing thunderstorm.

Table 1
List of Transient Luminous Events Observed by ISUAL in Central America on August 15, 2012

Time (UTC)	Type	Location (estimated by ISUAL)		Location (detected by WWLLN)	
August 15, 2012 0255:36.136	Elves	5.49°N	−59.75°E	5.55°N	−60.107°E
August 15, 2012 0437:38.048	sprite + halo + elves	5.21°N	−76.10°E	5.233°N	−77.150°E
August 15, 2012 0441:07.383	Elves	13.04°N	−83.62°E	13.125°N	−88.394°E
August 15, 2012 0441:19.551	Elves	11.42°N	−85.53°E	11.501°N	−86.138°E
August 15, 2012 0442:25.285	Elves	20.86°N	−81.57°E	21.604°N	−79.955°E
August 15, 2012 0443:12.411	Elves	22.87°N	−84.56°E	23.362°N	−83.653°E
August 15, 2012 0626:00.821	Elves	21.87°N	−106.78°E	22.278°N	−106.571°E
August 15, 2012 0627:32.777	Elves	21.70°N	−104.82°E	22.102°N	−106.244°E

Abbreviations: ISUAL, Imager of Sprites and Upper Atmospheric Lightning; UTC, Coordinated Universal Time; WWLLN, World-Wide Lightning Location Network.

Tropospheric disturbances such as deep convection can generate atmospheric gravity waves (GWs; Dewan et al., 1998; Taylor & Hapgood, 1988). Rowland et al. (1996) indicated that the ionization rate υ_i is dependent on N/E, where E is the electric field and N is the neutral air density. Therefore, the variation of the neutral air density caused by GWs over intense thunderstorms could induce mesospheric perturbations, that is, the neutral density perturbation can modulate the coefficient (υ_i) of the electron impact ionization driven by electric field, thereby affecting the location and morphology of sprites (e.g., Lay & Shao, 2011; Liu et al., 2015, 2016; Shao et al., 2013). Siefring et al. (2010) reported a clear correlation between airglow and sprites, that is, the tops of extended sprite elements appear to align with the gravity wave trough in the 80–95 km altitude region. Yue and Lyons (2015) proposed that GWs can modulate the optical brightness of elves. Whether this will also affect the brightness of negative sprites remains to be further investigated. The occurrence region of the event is located in the equatorial area that effectively generates a large number of strong convection systems as well as collectively controlled by the North Atlantic Subtropical High, the South Pacific Subtropical High, and the Equatorial Low. Therefore, we examined relevant satellite datasets, but found no available data at the event time, so it is impossible to determine whether the appearance of the unusual sprite is related to the modulation of GWs.

3.2. Analysis of Sferic and ISUAL Data

Figure 3a shows the ISUAL optical image of the negative sprite examined in this study. As shown in the figure, there was another lightning about 800 km to the south of the event of our interest. Was the subsequent magnetic pulse produced by the fast discharge process in this flash? We examined the sferic data associated with the distant lightning flash, whereas no CG lightning signal has been found. The detection results of WWLLN for the distant lightning were not found too. Therefore, we believe that this discharge process was an intra-cloud (IC) lightning.

Figure 3b shows the luminosity for this event detected by the 150–290 nm channel (SP1) and the 774–785 nm channel (SP5) of the 6-channel spectrophotometer. The luminosity waveform exhibits two peaks in the SP1 channel. Since lightning occur at altitudes of about 10 km or lower as well as the 150–290 nm band is strongly absorbed by O_2 and O_3 below 60 km altitude (Chang et al., 2010; Orville, 1977), the SP1 channel can effectively display the emissions of TLEs occurring at high altitudes. The luminosity waveform in the SP5 channel has only one peak. The 777.4 nm emissions mainly originate from the dissociation of O_2 in lightning at low altitudes as well as the concentration of oxygen atoms between 60 and 100 km is very low (Chang et al., 2010; Cummer et al., 2006), thus the peak value of the SP5 channel is primarily produced by the low-altitude lightning emission. Blue light is absorbed more strongly, so the noise in the SP1 channel is higher than that of the SP5. Other spectrophotometer channels (not shown) are saturated for this event. In addition, optical signals of AP channel 13 (CH13) covering 530–750 nm (red) along with channel 29 (CH29) in the 350–470 nm (blue) exhibit significant enhancement at the high-altitude during the second magnetic

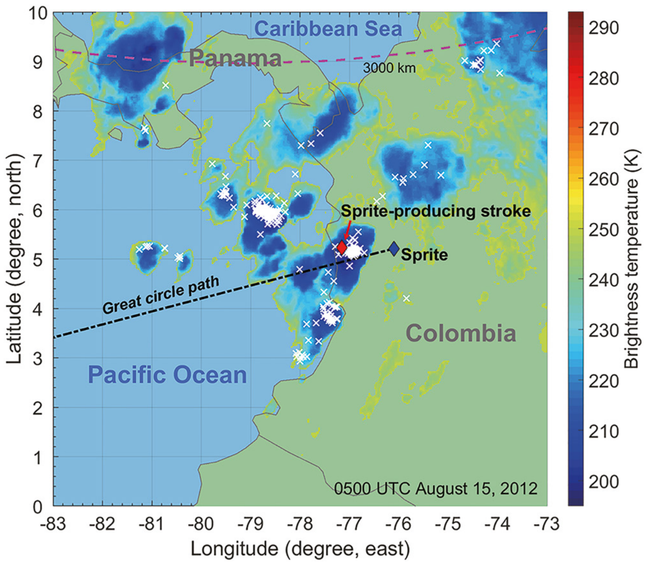

Figure 2. Cloud-top brightness temperature at 0500 UTC on August 15, 2012. White "×"s mark lightning discharges detected by WWLLN (within 20-minute interval centered at 0500 UTC). The blue and red diamonds mark the ISUAL-reported location of the sprite and the WWLLN-reported location of the sprite-producing stroke, respectively. ISUAL, Imager of Sprites and Upper Atmospheric Lightning; UTC, Coordinated Universal Time; WWLLN, World-Wide Lightning Location Network.

pulse, but there is no intensification of optical signals from CH6 (red) and CH22 (blue) corresponding to the low-altitude emissions (Figures 3c and 3d). Therefore, we can conclude that the first current pulse was from the low-altitude lightning emissions, while the second current pulse was primarily caused by the sprite emission at high altitudes.

The subsequent current pulse was also possible to be an *M*-component or a *K*-process (Lu et al., 2016), rather than originating in the sprite region. In the case examined by Lu et al. (2016), the corresponding low-frequency (LF, 30–300 kHz) emission was obvious during the second current pulse. The LF magnetic sferics associated with our event were recorded at 1,598 km range on the campus of Florida Institute of Technology (FIT, 28.06°N, 80.62°W). As shown in Figure 3e, the magnetic signals of the subsequent current pulse do not contain noticeable LF emissions. LF sferic data acquired in FIT provide further evidences that the second magnetic field pulse was not produced by tropospheric lightning discharges; instead, it was most likely generated by the vertical flow of charge along the sprite. In addition, Liu et al. (2016) also reported a negative sprite with a similar impulse charge moment change feature (see Figure 2 of Liu et al., 2016), but it is a pity that they did not investigate the source of the second increase feature. However, it is still reasonable to speculate that a negative sprite with sprite current characteristics are most likely not be unique.

The sprite current is typically observed in bright sprite events (with a relatively large vertical scale) produced by energetic positive CG strokes associated with iCMC more than +500 C·km (Lu et al., 2017). Is the presence of sprite current caused by intense CG strokes? Based on the VLF sferics of sprite-producing CG flashes, we reconstructed the current moment waveform of the lightning source, and calculated the iCMC (e.g., Lu et al., 2016). Figure 3f shows the iCMC waveform and the current moment waveform of the parent CG stroke. The iCMC waveform of the case contains two step-like enhancement. The first step-like increase corresponds to the return stroke stage and reaches about −520 C·km, which is barely sufficient to produce sprites (Li et al., 2012). The arithmetic mean and median of iCMC associated with negative sprite-producing strokes observed by ISUAL near North America are −644 C·km and −691 C·km, respectively (Lu et al., 2017). The sprite-parent CG stroke examined here is not substantially intense in comparison with normal negative sprite-producing strokes. The second step-like enhancement was produced by the sprite current flowing along the sprite body. The charge moment change caused by the charge transfer in the sprite region was estimated to be about −460 C·km. It is noteworthy that the time difference between the two peaks shown by the VLF sferics (shown in Figure 3e) is slightly longer (by about 0.3 ms) than the peaks exhibited by the retrieved current moment waveform (Figure 3f). This may be due to that the excitation source in the model is set at the height of normal CG lightning (e.g., Lu et al., 2016), which is much lower than the height of the actual sprite current.

4. Discussions

As mentioned above, the features of sprite current/remarkable brightness of the case examined in this study appear to be unrelated to an atypical structure of thunderstorms and energetic CG lightning. Previous studies focused almost exclusively on the characteristics of sprite-producing peak current and charge transfer (e.g., Boggs et al., 2016; Cummer & Lyons, 2004; Li et al., 2012; Lu et al., 2017; Taylor et al., 2008). However, the effect of charge transfer duration of lightning on the morphology of sprites is rarely reported. Consequently, we analyzed all the negative sprites examined by Lu et al. (2017) after excluding the events that were contaminated by other lightning or occurred behind the horizon (so that the sprite-producing lightning could not be reliably examined). If the maximum measurable luminosity has been reached at the triggering time, the pulse width is from the triggering time to one third of the amplitude between the

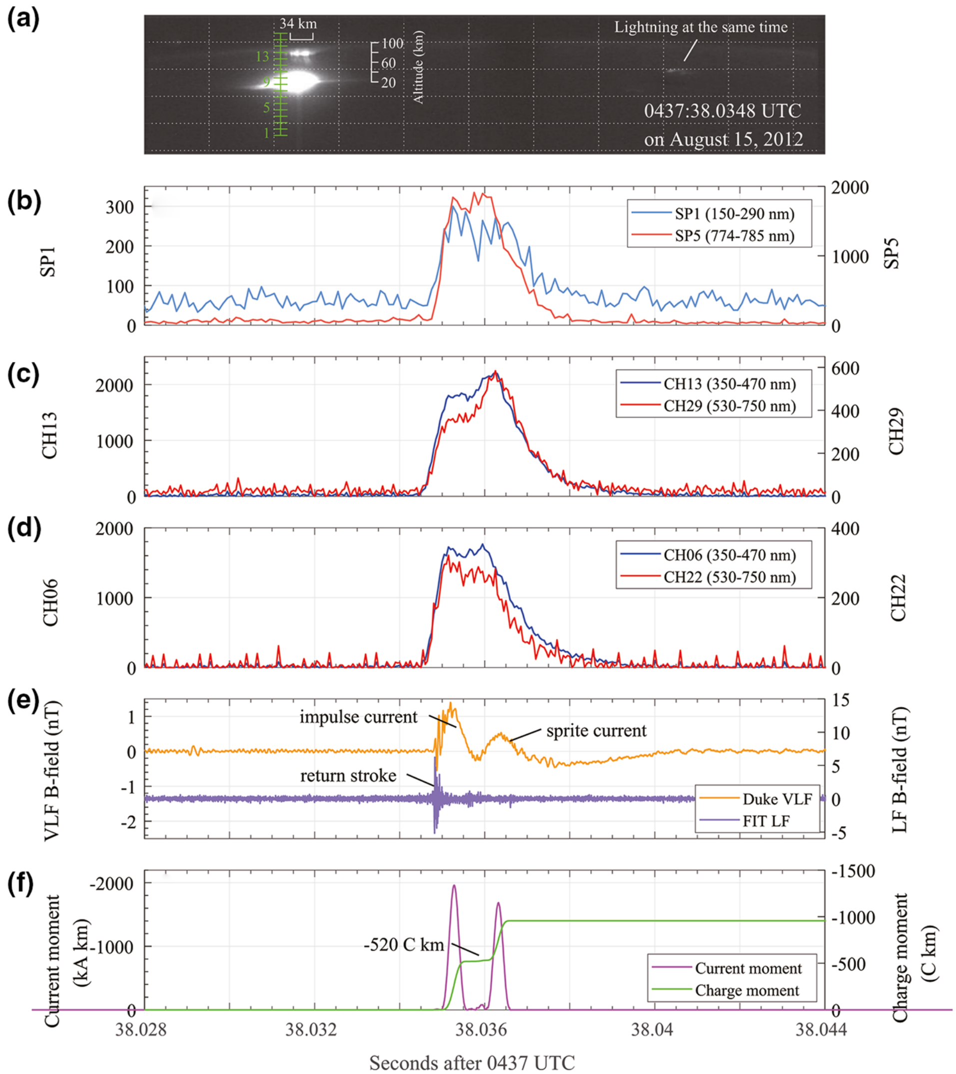

Figure 3. Panel (a) Sprite image recorded by ISUAL at 0437:0348 UTC on August 15, 2012. The green scale represents the corresponding height of the array photometer on ISUAL. Panel (b) Optical measurements of channels 1 and 5 of spectrophotometer installed on ISUAL for the same event. Panels (c & d) Optical measurements of the channel 6, 13, 22, and 29 of array photometer aboard ISUAL. Panel (e) VLF sferics recorded in Duke Forest and LF sferics recorded on the campus of Florida Institute of Technology. Panel (f) Current moment and impulse charge moment change extracted from the VLF magnetic field. The time axis is corrected by the propagation delay and the plotted signals are shifted vertically to avoid the overlap. CM, current moment; iCMC, impulse charge moment changes; ISUAL, Imager of Sprites and Upper Atmospheric Lightning; UTC, Coordinated Universal Time; VLF, very-low-frequency; WWLLN, World-Wide Lightning Location Network.

maximum value and the background noise; if the maximum measurable value is not reached at the triggering time, the pulse width is only taken as the time interval between one third of the amplitude (see in Figure 4b). The results showed the arithmetic mean and median of the charge transfer duration for the normal negative sprites are 2.72 and 2.70 ms, respectively. However, the duration of our case lasted 5.25 ms (Figure 1b), which suggests that the extraordinarily long charge transfer time could be the possible reason for the sprite current signature.

For comparison, we take a typical case of negative sprite recorded by ISUAL on September 16, 2008 as an example. The lightning distribution of WWLLN (within 20 min interval centered at 0445 UTC) display that the lightning activity mainly occurred in the convective region (Figure 4a) and that the sprite-parent stroke of the event is located in the relatively cold cloud region where the cloud-top brightness temperature was

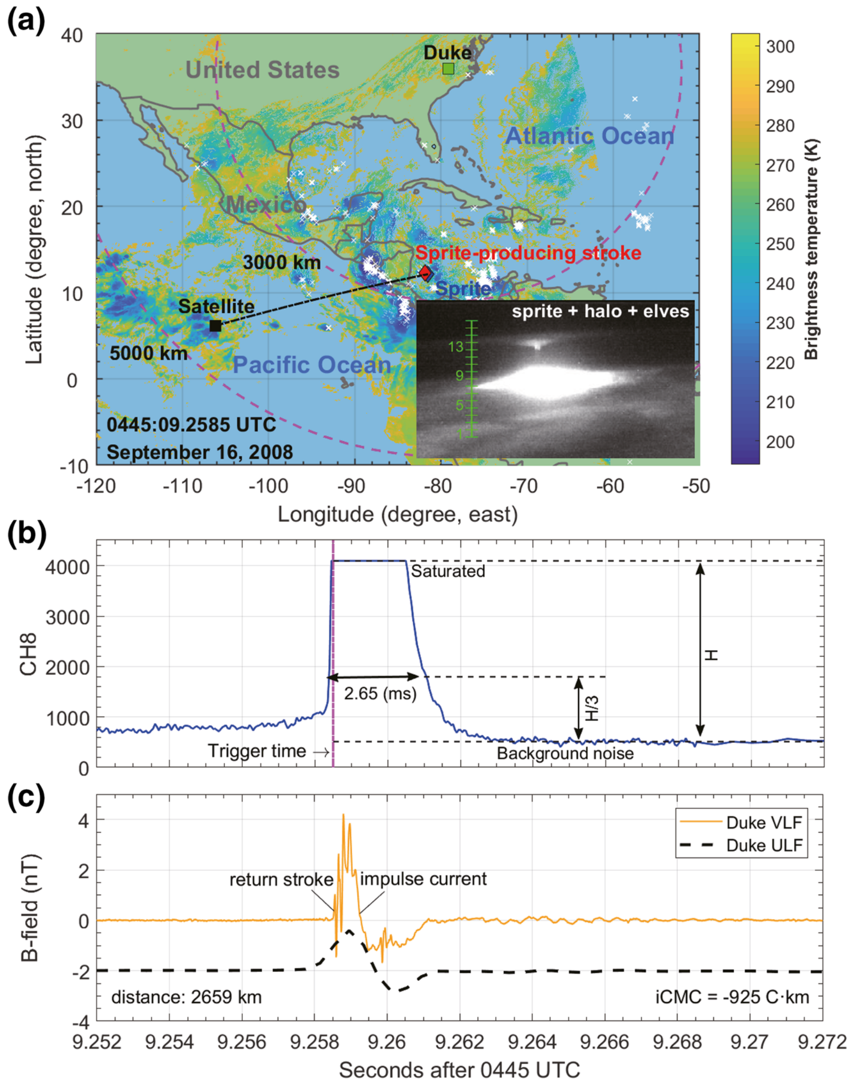

Figure 4. Panel (a) Example of a negative sprite recorded by ISUAL on September 16, 2008. The blue and red diamonds mark the ISUAL-reported location of the sprite and the WWLLN-reported location of the sprite-producing stroke, respectively. White "×"s mark CG strokes detected by WWLLN (within 20 min interval centered at 0445 UTC). Panel (b) Array photometer signal of ISUAL associated with the negative sprite at 0445:09.2585 UTC on September 16. Panel (c) Broadband magnetic lightning sferics (VLF: 50 Hz to 30 kHz; ULF: <1 Hz–400 Hz) recorded in Duke Forest for the case. The time axis is corrected by the propagation delay and the plotted signals are shifted vertically to avoid the overlap. ISUAL, Imager of Sprites and Upper Atmospheric Lightning; UTC, Coordinated Universal Time; VLF, very-low-frequency; WWLLN, World-Wide Lightning Location Network.

below 220K (for ease of observation, only showing temperature below 280K). Figures 4b and 4c show the optical signals detected by ISUAL and the sferic signals measured at about 2,600 km range in Duke Forest. The estimated iCMC (−925 C·km) of the sprite-parent stroke is almost twice as large as our particular event. The persistence luminosity in CH8 (corresponding to lightning altitude) is 2.65 ms, which is much shorter than our particular case. The lightning electric field decays in the conductive upper atmosphere and alters the ambient conductivity (dominated by electrons above 60 km) through attachment and ionization (Cho & Rycroft, 1998; Pasko et al., 1997). It is speculated that the charge transfer after the immediate impulse current of sprite production plays a role to produce a favorable condition for reducing the self-consistent response of the upper atmosphere to lightning electric fields. The electric field change caused by the subsequent charge transfer is superimposed on that caused by the return stroke, making that the charge in the sprite body is further driven to produce a slow electromagnetic signals. Based on the discussion above, we can see that the charge transfer in the existing lightning channel is beneficial to the streamer development of sprites, as well as is a profound effect on the formation of a sprite current signature, which typically occurs in positive strokes with a brief enhanced long sustained current.

In addition, it is reasonable to believe that such an unusual sprite may also be the result of plasma irregularities in the mesosphere (Qin et al., 2014). We suggest that the spatial structure of plasma irregularities may be vertically elongated and they are likely to exist in the low-altitude region with the high electron density, which makes sprites easier to be "illuminated" by the lightning-induced electric field (Kosar et al., 2012; Qin et al., 2014). The electron density in the sprite body is more than two orders of magnitude higher than the ambient electron density. Excess ambient electron density will lead to simple collective multiplication of electrons (i.e., electron avalanches overlap) and release energy in the form of large-scale ionization waves (e.g., diffuse glow). It is speculated that the electron density in the atypical sprite body is the maximum value that allows the development of streamers prior to the relaxation of the lightning-induced electric field. As a result, the event has a very strong current in its body, resulting in a slow electromagnetic signal. Except for the modulation of GWs mentioned in Section 3.1, plasma irregularities generated by sprites occurring earlier in the same region increase the probability of subsequent events (e.g., Stenbaek-Nielsen et al., 2000). Besides, the low ionospheric inhomogeneities also are likely caused by the ionization from inelastic collisions between vaporized meteor atoms and air molecules in low-altitude meteor trails (Suszcynsky et al., 1999). Certainly, these situations are quite accidental, and therefore, it is hoped that more long-term ground-based observations will be performed in future work to supplement our understanding on the phenomenology of negative sprites.

5. Conclusions

With coordinated observations of multispectral optical and ground-based magnetic sferic measurements, we report a very extraordinary sprite event produced by a negative CG stroke. The observation shows that the first current pulse corresponds to low-altitude optical emissions from the sprite-producing CG stroke; the subsequent current pulse is related to high-altitude optical emissions associated with the sprite current. Furthermore, the second current pulse does not contain a burst of LF emissions, which suggests that the second pulse was not radiated by a CG stroke or other IC lightning processes. Therefore, we can be sure that the source current responsible for the subsequent pulse is not in the low-altitude lightning channel, but in the sprite itself at mesospheric altitudes.

Interestingly, negative sprites previously reported are usually relatively dim (e.g., Li et al., 2012), so the remarkable brightness of this event almost declares that it was most likely a sprite event produced by an energetic positive CG stroke. However, the broadband magnetic field of this event clearly indicates that it was produced by a negative CG stroke. The iCMC of the parent CG stroke is estimated to be approximately −520 C·km, which is not particularly intense in comparison with negative sprite-producing strokes reported by previous studies. Moreover, the cloud-top brightness temperature image and the magnetic field waveform both indicate that this is a very normal CG stroke. The study suggests that the extraordinarily long charge transfer after the parent negative CG stroke might play a critical role in the formation of the intense sprite current. In addition, the formation condition of the unusual sprite may also be attributed to the plasma irregularities in the mesosphere, whereas this needs to be examined with further observations of local mesospheric conditions. More insights into the nature of the current signal in the negative sprite body need to be obtained by examining a sufficiently large dataset in future work.

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Data Availability Statement

The data examined in this study are available at https://zenodo.org/record/3897944#.Xvq0a-e-taQ

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