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Rare measurements of a sprite with halo event driven by a negative lightning discharge over Argentina

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[1] As part of a collaborative campaign to investigate Transient Luminous Events (TLEs) over South America, coordinated optical, ELF/VLF, and lightning measurements were made of a mesoscale thunderstorm observed on February 22–23, 2006 over northern Argentina that produced 445 TLEs within a $\sim$6 hour period. Here, we report comprehensive measurements of one of these events, a sprite with halo that was unambiguously associated with a large negative cloud-to-ground (CG) lightning discharge with an impulsive vertical charge moment change (ΔM_{Qv}) of -503 C.km. This event was similar in its location, morphology and duration to other positive TLEs observed from this storm. However, the downward extent of the negative streamers was limited to 25 km, and their apparent brightness was lower than that of a comparable positive event. Observations of negative CG events are rare, and these measurements provide further evidence that sprites can be driven by upward as well as downward electric fields, as predicted by the conventional breakdown mechanism.

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1. Introduction

[2] Sprites are the most prominent members of an extraordinary family of Transient Luminous Events (TLEs) which include elves, halos and jets. Sprites originate in the middle atmosphere in association with severe thunderstorms and often appear as clusters of bright column or carrot-like structures extending near-vertically from the mesosphere into the stratosphere ($\sim$40–90 km). Since their scientific discovery in the late 1980's [*Franz et al.*, 1990] thousands of sprites have been imaged, and much is now known about their characteristics and underlying physical processes. In particular, high resolution [*Gerken and Inan*, 2003], and high speed [e.g., *McHarg et al.*, 2007] measurements have shown that sprites are composed of individual streamers produced by a strong quasi-electrostatic field following cloud-to-ground (CG) lightning strokes [e.g., *Pasko et al.*, 1997] with large charge transfer. Sprites have a duration of a few to several 10s of milliseconds. In comparison, halos sometimes precede sprite formation, occurring within a few milliseconds of the parent CG, and appear as a faint, diffuse, disk-shaped emission from which structured sprites may develop [e.g., *Stenbaek-Nielsen et al.*, 2000; *Barrington-Leigh et al.*, 2001].

[3] To date, the overwhelming association of sprites with positive CG events [e.g., *Lyons*, 1996] is enigmatic as the conventional quasi-static breakdown mechanism does not depend on the polarity of the parent CG discharge [*Pasko et al.*, 1997]. Of the several thousand sprites reported in the literature only two events have been unambiguously associated with negative CG discharges [*Barrington-Leigh et al.*, 1999]. Although there have been several other reports of sprites associated with negative CG discharges, *Williams et al.* [2007] have recently questioned their validity, due primarily to large timing discrepancies, and concluded that the ratio of positive to negative sprite production is at least 1000:1. In contrast, investigations of halos, although relatively few [e.g., *Wescott et al.*, 2001], have revealed their association with both positive and negative CG discharges, with a clear predominance for negative CG halos to occur over open water [e.g., *Frey et al.*, 2007].

[4] Due to their rarity, observations of sprites triggered by negative CGs are of great interest and the measurements of *Barrington-Leigh et al.* [1999] remain exceptional to date. They reported high-speed photometric and ELF/VLF data on two discrete sprite events observed over the Gulf of California, Mexico, that were closely associated (within 5 ms) with two large negative CG lightning strokes. Coincident low-light video data showed clear evidence of sprites with vertical (columnar) structure.

[5] Here we report new evidence of a well-formed sprite with halo event (hereafter termed a sprite-halo), and establish its temporal and spatial association with a large negative CG discharge. The measurements were made from southern Brazil as part of a joint US-Brazil campaign and provide novel measurements of the spatial structure, altitudinal extent and relative brightness of this event and its associated electromagnetic properties.

2. Instrumentation

[6] Ground-based measurements were made from the Southern Space Observatory (SSO) at Sao Martinho da Serra (29.4°S, 53.8°W, 480 m) near Santa Maria, Rio Grande do Sul, Brazil. The isolated location of this facility

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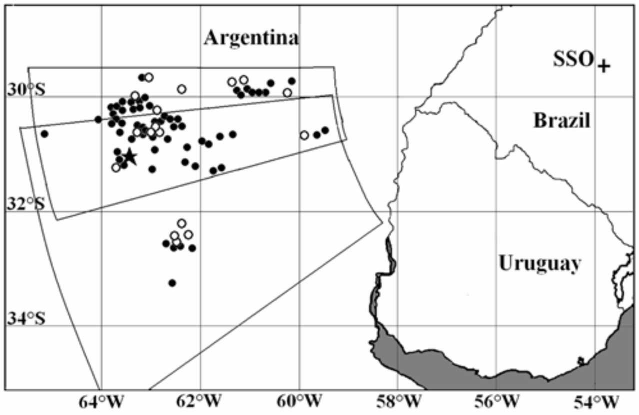

Figure 1. Map showing locations of 81 TLEs observed from 05–06:00 UT. Open circles denote 18 WWLLN events. Solid circles depict estimated locations of remaining events. The star locates the negative sprite-halo.

enabled high-quality observations of TLEs at large ranges, up to ~1000 km. Instrumentation comprised two intensified Xybion CCD cameras from Utah State University and a compact broadband ELF/VLF sensor system from Duke University. Both cameras were operated in manual gain and field mode (60 Hz) resulting in a 16.7 ms exposure time. GPS timing (accurate to 1 ms) was encoded onto each video data stream.

[7] The Duke University electromagnetic sensors comprised one pair of magnetic field coils to measure the vector horizontal magnetic field and one vertical AC electric field sensor (provided by Quasar Federal Systems, Inc) continuously sampled at 100 kHz. The electric and magnetic sensors had flat pass bands from 2 Hz to 25 kHz and 5 Hz to 25 kHz, respectively. Absolute timing using GPS was validated to better than 20 μs prior to deployment in Brazil using U.S. National Lightning Detection Network data. Cross calibration ensured that the impulsive ΔM_{Qv} results are directly comparable with recent measurements using sensors at Duke University [e.g., *Cummer and Lyons*, 2005]. VLF-based measurements of the azimuth to the lightning source have an uncertainty of ~2°.

[8] In parallel with these measurements, data from the World Wide Lightning Location Network (WWLLN, see http://wwlln.net) were used to identify the timing and geographic location of the lightning discharges. The WWLLN provided real-time lightning locations globally by measuring very low frequency (VLF) radiation (3–30 kHz) from lightning. The timing, position and efficiency of WWLLN have been estimated for several key regions, including South America, by comparison with local ground-based lightning detection systems [e.g., *Lay et al.*, 2004]. WWLLN is most sensitive to the largest lightning strokes and it is estimated that ~15–20% of all cloud-to-ground lightning discharges within South America are located with a spatial accuracy of ~10 km and a timing uncertainty of <30 μs.

3. Observations

[9] On 22 February, 2006 a large mesoscale convective system (MCS) developed over northern Argentina. During the night the storm complex lay almost due west of SSO at a range of ~500–900 km and grew to an area of about 550,000 km^2 [*Thomas et al.*, 2007]. Sprites were first detected around 02:30 UT February 23 (23:30 LT) and continued until dawn (~08:30 UT) resulting in 445 TLEs during ~6-hrs of observations, making it the third most active spriting storm on record. The majority of the TLEs (~60%) comprised sprite clusters, with numerous halos (62 events) and sprite-halos (121 events).

[10] Figure 1 shows the viewing geometry from 05–06:00 UT encompassing the negative event. Two cameras were aimed W–SW with fields of view of ~15° and ~30° that overlapped by ~5°. The circles show the locations of 81 TLEs imaged during this 1-hour interval, all of which were associated with positive CGs. WWLLN lightning locations and rainfall data from the Tropical Rainfall Measuring Mission (TRMM) satellite indicate that these events occurred predominantly above the stratiform region of the MCS, rather than the convective core regions. Furthermore, WWLLN identified 18 of these events (open circles) providing additional information on their location. The positions of the remaining TLEs (solid circles) were estimated from their central azimuth and elevation in image data assuming an altitude of 86 km (the mean of over 100 sprites identified by WWLLN during this night). The resultant uncertainty in the location of these events is ~10–15 km, and has minimal effect on their overall spatial distribution. The star indicates the WWLLN location of the negative event (31.039°S, 63.457°W), which occurred at ~05:29:33 UT and was detected by both cameras and the ELF/VLF sensors.

[11] Figure 2a shows an enlarged (6° × 4°) image of this event as captured by the narrow angle camera at 05:29:33.522 UT. A well-developed sprite-halo is evident exhibiting a characteristic upper diffuse horizontal disk with several embedded, bright columnar forms and fainter tendrils extending downwards and branching at lower elevations. In the wider field image this event was observed in a single video field (16.7 ms duration) at 05:29:33.535 UT, whereas the narrow angle data (Figure 2) show development of the sprite-halo over two consecutive video fields. Together these data limit the sprite initiation time to between 05:29:33.515 – 519 UT (taking into account the ~3 ms propagation time to SSO), with a maximum duration of <17 ms, which is in excellent agreement with the WWLLN time of 05:29:33.5162 UT.

[12] Coincident ELF/VLF measurements from SSO have been used to determine the polarity, current, and charge characteristics of the causative lightning stroke. Figure 2b shows its ELF/VLF azimuthal magnetic field ($B\varphi$) waveform. The sferic onset time of 05:29:33.5193 UT matches the WWLLN data within 0.1 ms (taking the 3 ms travel time into account). The large upward pulse unmistakably shows that this TLE was produced by a negative CG discharge with associated downward net charge transfer. In comparison, Figure 2c shows $B\varphi$ for a similar sprite-halo that occurred at the same azimuth (255.4°) ~1 hour earlier. The sharp downward pulse is typical for a TLE produced by a positive CG (these two events are compared further later). The ΔM_{Qv} (first 2 ms) for the −CG (method of *Cummer and Inan* [2000]) was determined to be −503 C.km. Confirmation of the negative polarity of this event was

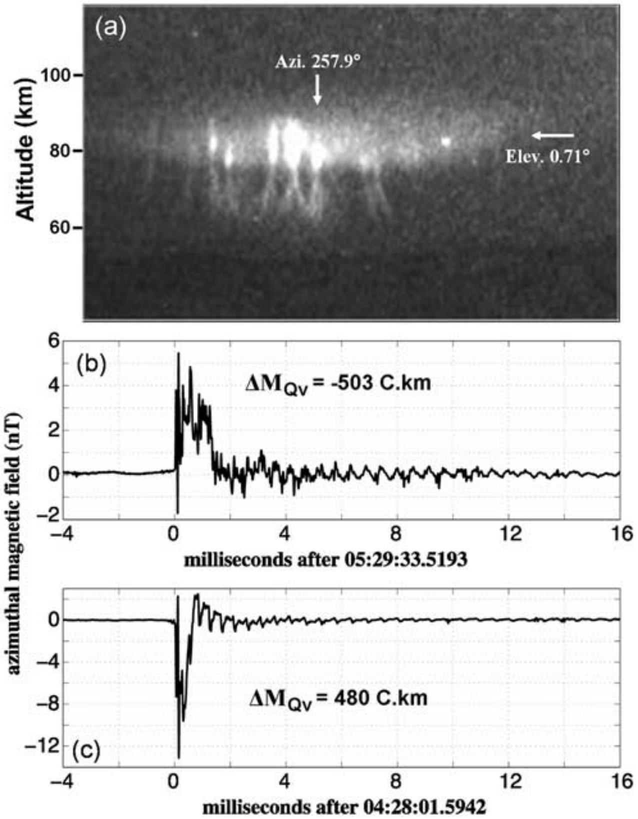

Figure 2. (a) Enlarged (6° × 4°) image of the negative event at 05:29:33.522 UT showing a well developed sprite-halo with streamers. (b) The ELF/VLF azimuthal magnetic field ($B\varphi$) waveform associated with this event. (c) The $B\varphi$ waveform of a sprite-halo (Figure 3c) produced by a positive CG of similar ΔM_{Qv}.

provided by simultaneous vertical electric field data from SSO (not shown), and by Y. Yair (University of Tel Aviv, private communication, 2006) using ELF measurements from Israel and Hungary.

[13] Combining the WWLLN location of the negative event with its measured azimuth and elevation from the image data (determined using standard star field calibration and taking full account of refraction effects), the altitude of the halo center was determined to be 83 ± 1 km, and its diameter 89 ± 5 km.

4. Discussion

[14] Here we report observations of a single sprite-halo event that was unambiguously associated with a negative CG, occurring within 3 ms of the parent lightning stroke. Previously, only two negative events have been substantiated, exhibiting exceptionally large ΔM_{Qv} (-1380 and -1550 C.km) as measured within the first 5 ms of the sferic (both observed over the Gulf of California). However, their video signatures were partially obscured by cloud and no estimates of their vertical extent were made [*Barrington-Leigh et al.*, 1999]. The parent storm was unusual as the sprites were produced from a region overly dominated by $-$CG lightning, with very few ($\sim$1.5%) +CG discharges detected during its lifetime, compared with the surrounding MCS that exhibited positive CG occurrence rate of $\sim$6% which is more typical of a sprite-producing storm. In contrast, the negative event reported here originated from a large MCS over the pampas of Argentina ($\sim$600 km to the nearest open water), that produced numerous TLEs (at least 445), within the stratiform region in close proximity to the observed negative event (Figure 1). The ΔM_{Qv} (-503 C.km in 2 ms) associated with this event was at least 30% larger than other TLEs observed within ±10 min and 100 km radius (total 6 events), all of which were positive and had ΔM_{Qv} ranging from +32 to +383 C.km. For direct comparison with *Barrington-Leigh et al.*'s [1999] results we have further evaluated the ΔM_{Qv} of our negative event yielding -822 C.km (over a 5 ms interval) with a total of -843 C.km over the 8 ms duration of the charge moment change as determined from the sferic data. As were the negative events reported by *Barrington-Leigh et al.* [1999], these are larger than the 2 ms charge moment changes in typical positive CGs that produced short-delayed sprites (350–600 C.km) [*Cummer and Lyons*, 2005].

[15] The conventional breakdown mechanism for initiating sprites and halos is largely independent of the electric field direction, and thus the lightning polarity [*Pasko et al.*, 1997]. However, the critical field needed to maintain streamer propagation is approximately a factor of two larger for negative streamers when the field and propagation direction are anti-parallel [*Pasko et al.*, 2000; *Bazelyan and Raizer*, 2000]. Simulations [*Pasko et al.*, 2000] predict that although positive and negative sprites should be morphologically similar, positive sprites should extend approximately 10 km lower in altitude under otherwise identical conditions (e.g., charge moment change and atmospheric conductivity). To investigate this, Figures 3a and 3b show the development of the negative sprite-halo as recorded by the narrow field camera over two consecutive video fields (total duration 33 ms). As the halo (center altitude 83 km ± 1 km) faded during this interval, the sprite evolved with additional streamers and some limited downward development of existing streamers. Using the WWLLN location, the lowest visible border of the streamers was determined to be $\sim$63 km for the first field and $\sim$61 km for a small part of the second field. However, the base of the streamers clearly remained above the horizon at SSO (as shown by the horizontal line). This indicates a relatively short vertical extent ($\sim$25 km) for the negative sprite with no obvious streamer penetration into the stratosphere. Figure 3c shows the optical signature of a sprite-halo that was produced by a positive CG with a similar ΔM_{Qv} (480 C.km, shown in Figure 2c) to that of the negative event. This TLE was imaged by the narrow field camera at approximately the same azimuth (255.4°) as the negative event, but $\sim$1-hour earlier (04:28:01 UT). The video data also show that it occurred at almost the same geographic location as the negative sprite-halo (within 30 km) and exhibited a similar halo diameter (85 ± 5 km), assuming a central altitude of 83 km. The tendrils appear to be cut-off at the horizon (horizontal line) suggesting they extended to lower altitudes than $\sim$60 km. Comparing these two events of different polarity suggests that the positive sprite-halo exhibited streamers that were significantly longer, in agreement with predictions of *Pasko et al.* [2000].

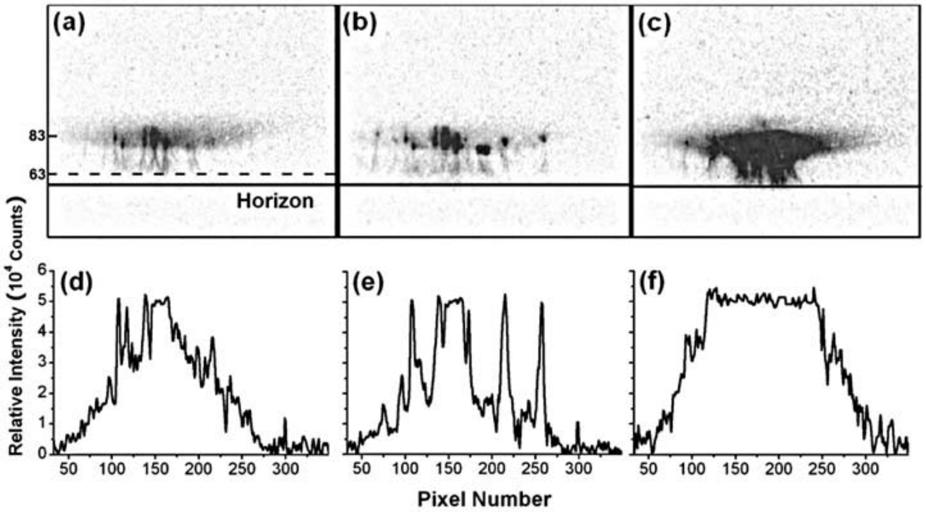

Figure 3. (a and b) Downward development of the negative event over two video fields (duration 33 ms). The data are shown as "negative" images, after background subtraction, to enhance the sprite structures (lower visible border ~61 km). (c) Positive sprite-halo, which occurred at approximately the same location 1-hr earlier. (d, e, and f) Horizontal cross-sections of the relative intensity of the negative and positive events.

[16] As the Xybion camera was operated at the same electronic gain throughout the night we can also investigate changes in relative brightness of the negative event as it developed. This is shown in Figures 3d and 3e which plot the relative brightness of the sprite-halo as determined from a horizontal "intensity scan" through the middle of the halo centered at 83 km altitude. Significant development of both halo and sprite emissions are evident from one field (17 ms duration) to the next. Initially, several narrow sprite structures are evident (Figure 3d) imbedded in the diffuse halo emission, which appears as a large symmetric bulge of peak relative brightness ~30,000 counts (or ~60% of maximum signal level). The subsequent field shows further intensification of the sprite's columnar-like structures (close to the video saturation level) and a significant decrease in the relative brightness of the halo emission by ~50%. Figure 3f shows a relative intensity scan through the halo region of the positive event, which exhibited comparable spatial dimensions to the negative event (but was only evident in one video field). Although the basic shape of the plot is similar the combined sprite and halo emissions saturated the camera and the imbedded sprite structures are not discernable.

[17] Together these results suggest that both the length and the apparent brightness of the downward negative streamers are more limited for this negative driven sprite-halo as compared with a positive event of similar location, morphology and ΔM_{Qv}. The shorter negative streamer lengths are consistent with the need for larger critical fields to maintain downward streamer propagation [*Bazelyan and Raizer*, 2000]. Furthermore, *Liu and Pasko* [2004] have shown that under identical conditions, positive sprite streamers would appear brighter due to the larger expansion of their streamer heads and higher electron densities and electric fields in their heads, as compared with negative streamers, which would appear dimmer when propagating downward over the same distance. However, we appreciate that there are many factors which ultimately control the development of a sprite, and the widely used phrase that "no two sprites are the same", underlines the inherent difficulties of performing such a comparison. This said, these data have provided us with the best opportunity to date to study a well-defined negative sprite event and to compare its optical properties with those of a similar sprite-halo generated by a positive CG.

5. Summary

[18] Of the many thousands of sprites reported in the literature, clear images of a negative polarity sprite are extremely rare. Here we report detailed measurement of a sprite-halo event that was unambiguously produced by a −CG lightning stroke originating from an MCS over Argentina. The identification of this TLE was made using a combination of simultaneous video, ELF/VLF radio measurements, and WWLLN lightning data and provides further proof that sprites can be driven by upward as well as downward electric fields, as predicted by the conventional breakdown mechanism [e.g., *Pasko et al.*, 1997]. The negative event was similar in its morphology and duration to other positive polarity TLEs observed from this storm. However, its apparent brightness was lower than that of a similarly located positive event of comparable ΔM_{Qv}, and the vertical extent of the downward negative streamers was limited to ~25 km. Such morphological differences are important for constraining effects of streamers on the mesosphere.

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