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Statistical analysis of space–time relationships between sprites and lightning

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Abstract

We present a detailed statistical analysis of the association of 40 sprite events with lightning from the parent thunderstorm. Both temporal and spatial criteria were used to identify the parent cloud-to-ground (CG) lightning. Sprite images were GPS time stamped and their locations triangulated. In contrast to previous reports of nearly one-to-one association of sprites with positive cloud-to-ground (+CG) lightning, 11 events (27%) did not have a +CG recorded by the National Lightning Detection Network (NLDN), and 7 events (17%) had neither NLDN nor very low frequency (VLF) signatures associated with them. A negative cloud-to-ground (−CG) preceded one of these events by 9 ms. As expected for ∼16.7 ms integrated images, none of the sprites without a +CG had any discernible visual characteristic that would distinguish them from "regular positive sprites". We have calculated the distribution of time intervals ($\Delta t = t_{\mathrm{sprite}} - t_{\mathrm{lightning}}$) for the sprites that had a parent +CG flash registered by the NLDN or VLF systems, and the distribution of distances between the sprite nadir positions and the flash locations registered by the NLDN. The time interval (Δt) distribution had a peak around 10–20 ms and a mean of 30 ms (total). This distribution is broadly consistent with the characteristic single electron avalanche time scale associated with streamer growth between ∼70 and 85 km. The distribution of the distances (Δs) between the nadir point of sprites and the parent +CGs showed that approximately two-thirds of the sprites occurred within 50 km lateral displacement from the parent +CG. The parent +CG peak current distribution had a maximum at 40–50 kA and mean of 60 kA, suggesting that high peak currents ($I \geqslant 75$ kA) are not a necessary prerequisite for sprites. The peak current distribution for all +CGs of the storm, with a maximum around 10–20 kA and mean of 27 kA, exhibits a qualitatively different form from the peak current distribution of the parent +CGs producing sprites.

Keywords: Sprites; Lightning; Relationships; Triangulation; Statistics

1. Introduction

Sprites are luminous mesospheric/D region emissions generally associated with positive cloud-to-ground lightning (+CGs). Their duration can vary from a few ms to a few hundred ms. Sprites were initially reported to extend from 40 to 90 km altitude and possess lateral dimensions of 5–30 km (Sentman et al., 1995). More recent observations have shown that some sprites appear to extend down to the top of the clouds (Siefring et al., 1999), and that their horizontal extent within the mesosphere ranges from ∼10 m, for the small column sprites and fine structure within sprites (Gerken et al., 2000), to ∼40 km for fully developed single sprites (Stenbaek-Nielsen et al., 2000), and a few hundred of km for sprite clusters. Sprites are predominantly red in color and the dominant emissions are found to be from the

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first positive bands of N_2 (Mende et al., 1995; Hampton et al., 1996; Heavner et al., 2000). Evidence for ionization has been reported in the form of weak red N_2^+ Meinel emissions (Bucsela et al., 1998; Morrill et al., 1998) and transient blue N_2^+ 1NG emissions (Armstrong et al., 1998; Suszcynsky et al., 1998; Takahashi et al., 1998; Armstrong et al., 2000).

Boccippio et al. (1995) first established that a +CG lightning precedes most sprites by approximately 20–30 ms. In their study, totals of 42 and 55 sprites observed in July 12 and September 7, 1994, respectively, were analyzed. Approximately 86% and 82% of the sprites each night, respectively, were preceded by a +CG recorded by the NLDN, and 95% and 78% were preceded by a Q-burst (large excitation of the normal modes of the Earth-ionosphere cavity in the extremely low frequency (ELF) Schumann resonance band), recorded by an ELF sensor. Subsequent studies have reported results that are generally consistent with these observations (Lyons, 1996; Cummer and Inan, 1997; Bell et al., 1998).

Based on observations showing evidence that sprites are strongly associated with positive cloud-to-ground lightning, several mechanisms have been proposed to explain the sprite generation process (Boccippio et al., 1995; Pasko et al., 1997; Bell et al., 1995; Roussel-Dupré and Gurevich, 1996; Taranenko and Roussel-Dupré, 1996). A widely accepted model (Pasko et al., 1997) uses a quasi-electrostatic approach in which a transient electric field generated by a +CG is the dominant trigger mechanism for sprites. Because of the higher altitude of the positive charge center inside the thunderstorm assumed in this model and the higher incidence of continuing current among +CGs when compared to other types of lightning, the charge moment of +CGs is on average greater than other types of flashes, making +CGs more effective at generating sprites than other types of lightning. However, the model does not rule out occasional −CGs and intracloud discharges (ICs) with a large enough charge moment to generate a breakdown electric field in the mesosphere and produce a sprite.

Using an extensive set of low-light TV data from the summer of 1996, São Sabbas (1999) analyzed 746 sprites from 7 different nights and found that only 65% of sprites were associated with +CG recorded by the NLDN, suggesting that other types of lightning besides +CGs could be generating sprites. About 11% of sprites were found to be immediately preceded by a −CG, and 24% of sprites were not associated with a CG registered by the NLDN. At the time this study was performed no association between sprites and −CG had been reported. In an independent study, Barrington-Leigh et al. (1999) subsequently reported observations of 2 sprites that had a −CG VLF signature associated with them. Those results support São Sabbas (1999) suggestion that +CGs are not the only type of lightning that can generate sprites.

In this paper, we report results of a detailed statistical study of the space–time association of sprites with positive and negative CGs. In most previous studies of the association of sprites with lightning, sprites were assumed to be centered above the causative +CGs, which were identified based on timing proximity (Lyons, 1996; Cummer and Inan, 1997; Bell et al., 1998). Lyons (1996), using 7 events, and Wescott et al. (1998; 2001), using 20 events, have triangulated the location of sprites showing that they are actually laterally displaced from the +CGs on average ∼50 km. In the present study we investigated the association of sprites with ±CGs preceding the sprites based on time and distance. We calculated the distribution of distances and time differences between the parent +CG and the sprite, and the peak current distribution of the sprite-associated +CGs. The results obtained here were compared with four previous observational studies. We also discuss a definition for an "independent sprite event" based on the time interval and distance between the sprite and the parent +CG, as well as considerations about the physical process involved in initiating a sprite.

2. Observations

We studied a set of 40 sprite events recorded on July 22, 1996, during the Sprites96 Campaign, conducted in the central United States. The location of cloud-to-ground lightning discharges of the sprite producing thunderstorm, recorded by the NLDN between 00:00 and 14:00 UT, are shown in Fig. 1 together with locations of CGs from other thunderstorms. Sprites were documented above the mesoscale convective storm (MCS) over Kansas.

The location of the sprites was triangulated, with an accuracy of a few to a few tens of km, from images simultaneously obtained by University of Alaska (UAF) and Utah State University (USU) located at different ground optical sites. Simultaneously recorded sprites were easily identified by comparing their time and visual characteristics in the images recorded by UAF and USU. The UAF observations were made from the Wyoming Infra-Red Observatory (WIRO, 41.098°N, 105.997°E, 2.943 km alt.), on Jelm Mountain, Wyoming, using an unfiltered intensified (∼600–800 nm BW) CCD video camera with ∼17° FOV operating at 30 frames/s (fps). A GPS clock was coupled to the camera system to provide time stamped images (TV fields) with a resolution of ∼16.7 ms (1 field), and an absolute scan line accuracy of 1 μs. The GPS time stamped onto the image (t_{field}) corresponded to the very last scan line of each field, and was used as the sprite time (t_{sprite}).

The USU observations were obtained from Yucca Ridge Field Station (YRFS, 40.669°N, 104.939°E, 1.6 km alt.), located 20 km northeast of Ft. Collins, Colorado. Sprites were recorded at 25 frames/s (fps) using an Isocon camera with ∼22° field-of-view (FOV). The camera was fitted with a 665 nm interference filter to image sprites in the N_2 first positive system, and each video field was uniquely time stamped using a crystal clock oscillator with a drift of

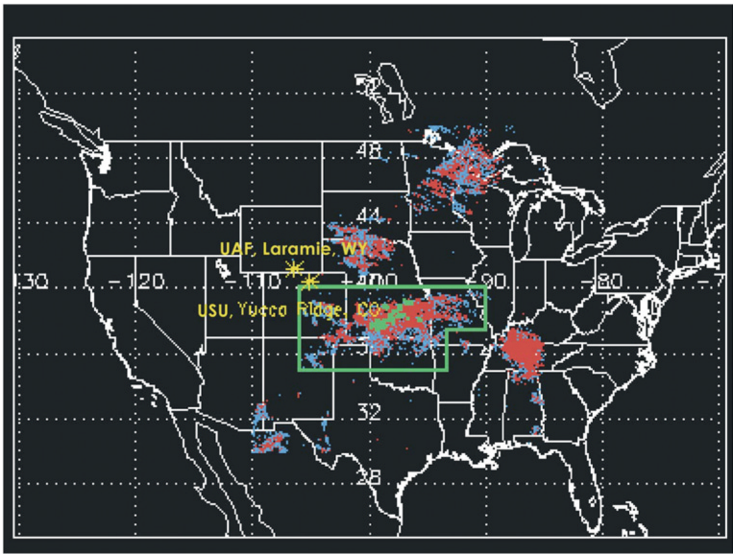

Fig. 1. Map of United States showing location of +CGs (red), −CGs (blue) and +CGs possibly associated with sprites (green), occurred between 0 and 14 UT, on July 22, 1996. The lightning from the sprite producing storm is within the green rectangular region. Yellow asterisks indicate the locations of the 2 ground observation sites.

$\sim$2 s/day assumed to be linear. The clock was set manually at the start of each night to an accuracy of better than 1 s (see Armstrong et al., 1998 for details).

The lightning information was provided by the NLDN (Cummins et al., 1998). Broadband electric field data (between $\sim$200 Hz and $\sim$200 kHz) recorded from the Langmuir Laboratory, New Mexico (Stanley et al., 2000), were examined to look for very low frequency (VLF) signatures (3–30 kHz) of CGs flashes in the cases for which NLDN did not record a lightning signature.

3. Results and discussion

3.1. Identification of sprite independent events

Initially, we visually identified 47 sprites recorded from both ground sites that could be triangulated. To be identified as an independent event, a sprite had to have occurred with a time separation of at least 1 video field ($\sim$16.7 ms) and be spatially distinct from any sprite occurring in the previous field. The spatial displacement requirement prevented counting a re-brightening or the continuity of previous processes as distinct events. Individual events could be single "sprite units" (Sentman et al., 1995) or what we defined as "sprite spatial groups", i.e., a group of units that occurred simultaneously, within a single video field (e.g. Figs. 9a and b).

This preliminary definition, based solely on video images, proved not to be completely unambiguous in the case of complex events when a single lightning discharge generates consecutive sprites. Hence, we constructed a statistic based on both the time interval between a sprite and its nearest preceding (parent) +CG and on triangulation. The parent CG candidates, positive or negative, were initially screened by requiring the CG to have occurred in a space–time vicinity of the sprite defined as a square region of 400 km on a side, centered on the sprite, and within a 1 s window preceding the sprite. Cloud-to-ground lightning registered by NLDN, occurring closest in time preceding the sprite and closest in space were selected as being the parent CG. For CGs with a VLF signature and no NLDN signature, only the time criterion was applied. Negative CGs were selected only if neither the NLDN nor the Broad band electric field sensor recorded a positive CG. To calculate the time interval between sprites and parent +CGs ($\Delta t = t_{\text{sprite}} - t_{\text{lightning}}$) the GPS time tag of the video field (t_{field}) in which the sprite first appeared was used as t_{sprite} (Fig. 2).

In the video systems used in this study the time stamp on each image field refers to the end of the video field. Each video field has a duration of $\sim$16.7 ms, so the start of the image is at $t_{\text{field}} - 16.7$ ms and the end is at t_{field} ($= t_{\text{sprite}}$ when a sprite is present). Hence, the sprite could have occurred at any instant in the interval $t_{\text{sprite}} - 16.7$ ms to t_{sprite}, and 16.7 ms is the maximum uncertainty in the sprite time. In the cases when the parent lightning occurs within the interval of the video field containing the sprite, Δt may be less than 16.7 ms, since causality requires the sprite to have occurred some time after the lightning but before the end of the video field. The sprite must be constrained to this interval. When $\Delta t < 16.7$ ms, the uncertainty in the sprite time is equal to Δt.

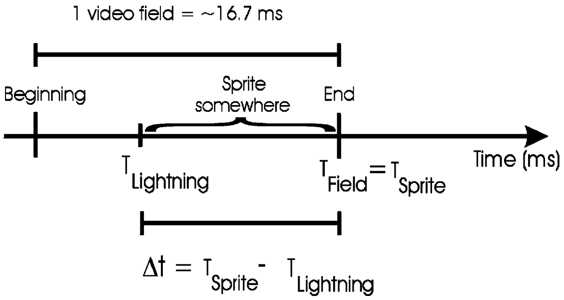

Fig. 2. Diagram showing how Δt can be < 16.7 ms. The lightning occurs before the sprite and the GPS time stamped at the end of the field is assigned as t_{sprite}. Due to causality the sprite must have occurred some time after the lightning but before the end of the video field.

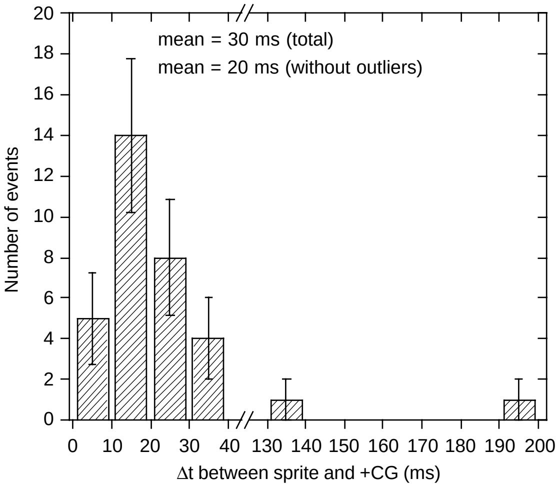

Fig. 3. Distribution of the time difference between the sprite and parent +CG flashes within the sprite's space–time vicinity, binned in intervals of 10 ms. The error bars are the statistical errors, i.e. the square root of the number of events in each bin.

Fig. 3 shows the distribution of time intervals between sprites and parent +CGs. The first bin ($0 \leqslant \Delta t < 10$ ms) and part of the second bin ($10 \leqslant \Delta t < 20$ ms) represent the cases in which the parent lightning occurs within the interval of the video field containing the sprite, discussed in the previous paragraph. The time-interval distribution peaks around 10–20 ms and possesses a mean value of 30 ms (20 ms if we exclude the 2 outlying events). This distribution agrees with results reported by Bell et al. (1998).

Bell et al. (1998) suggested that the longest delays observed in their study were associated with small sprites for which horizontal intracloud discharges removed the amount of charge necessary to generate them. Furthermore, Δt would vary from 0 to 15 ms for the larger events to 100 ms to the smallest events. We grouped the sprites analyzed here in three categories with respect to visual size and brightness: small, medium and large. The three groups were statistically consistent with each other (graph not shown). We did not observe any consistent visual distinction between sprites with short and long Δt: in fact, the two events with largest Δt (outliers) were very bright (large) sprites. We suggest that the time delay between lightning and sprites characterizes the time scale of the duration of the physical process (or processes) that is responsible for the sprite initiation, and takes place once the transient electric field is established in the mesosphere. This process is discussed in recent models based on streamer physics (Pasko et al., 1998; Raizer et al., 1998) that explain in detail how the fine structure observed in high-speed (Stanley et al., 1999; Stenbaek-Nielsen et al., 2000) and telescopic (Gerken et al., 2000) images of sprites develop.

The process that originates a streamer can be triggered from an avalanche initiated by a single electron. The avalanche creates a local charge separation, and the streamer develops when the electric field of the space charge equals the external transient electric field in the mesosphere generated by the CG. Pasko et al. (1998) have modeled the characteristic time of this process as $t_z = z_s/v_d$, where $z_s = (1/\alpha)\ln(4\pi\varepsilon_0 r_s^2 E_k/e)$ is the distance over which the avalanche generates a space charge field comparable to the ambient electric field, taken to be the breakdown field $\sim E_k$. Here, $\alpha = (v_i - v_a)/v_d$, where v_i is the ionization rate, v_a is the electron attachment rate, v_d is the electron drift speed, and the space charge is assumed to be concentrated in a sphere of radius $\sim r_s$. Fig. 1 of Pasko et al. (1998) shows the altitude profile of the modeled t_z. The distribution of Δt between the sprite and parent +CG shown in Fig. 3 is consistent with the characteristic time scale for the development of an individual electron avalanche into a streamer between ~70 and 85 km altitude modeled by Pasko et al. (1998).

Fig. 4 shows the distribution of distances (Δs) between the triangulated nadir point (latitude and longitude) of sprite events and the location of parent +CGs. The distances between sprite events and parent +CGs were calculated for the +CGs detected by the NLDN only. When the sprite events were "spatial groups" an average nadir point was calculated using the triangulated nadir points of each "sprite unit". The distribution displayed in Fig. 4 shows that approximately two thirds of sprites occurred within 50 km from the parent +CG, in agreement with Lyons (1996) and Wescott et al. (1998). The maximum distance observed was ~82 km. Since "spider" discharges extending for ~100 km have been previously observed (Lyons, 1996), all +CGs in the present study were consistent with previous results, and no further spatial selection criteria were applied to identify independent events.

We also plotted the time intervals versus the distance (Fig. 5) and there was no correlation between the two quantities, i.e. sprites further away from the +CG do not appear to have longer delays.

Most sprites (~95 ± 15%) that were associated with +CGs occurred within 40 ms after the parent +CG. Only

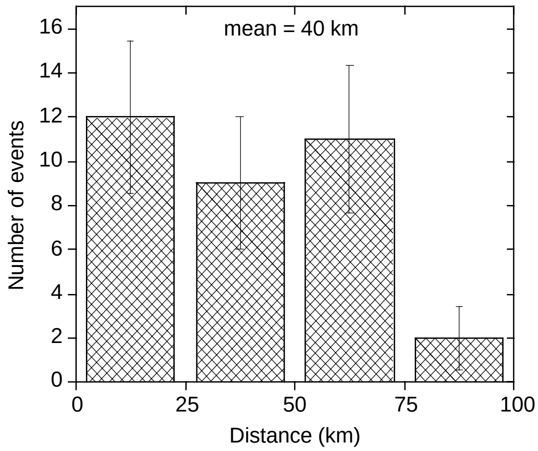

Fig. 4. Distribution of the distances between sprites events and parent +CG flashes within the sprite's space–time vicinity. The events were binned in intervals of 25 km, and the "error bars" are the statistical errors.

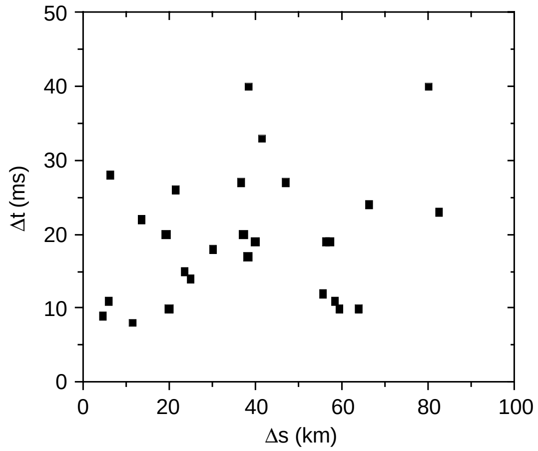

Fig. 5. Time interval between sprites and associated +CGs versus the distance between them. The two outliers, one with $\Delta t = 140$ ms and $\Delta s = 51$ km, and the other with $\Delta t = 197$ ms and $\Delta s = 75$ km, are not shown.

two events occurred with a Δt greater than 40 ms after the +CG. Given the large time interval that those sprites had from their parent +CG (140 and 197 ms) it is possible that closer +CGs had occurred but were not registered by either NLDN or the Broadband electric field sensor.

Except for the two outlying events, the analysis of Fig. 3 suggests 40 ms as an effective upper limit for the delay between the parent +CG flash and the sprites observed during this night. The 40 ms delay exceeds the timing uncertainty of ~16.7 ms by a factor of ~2.5, and is therefore a robust result. Based on this result, consecutive sprites that had a minimum time separation of ~16.7 ms from each other and a maximum time interval of 40 ms from the parent CG were grouped into a "sprite time group", similar to the manner in which individual strokes are grouped into flashes (Cummins et al., 1998). The individual "sprite units" or "sprite spatial groups" were called "sprite time units". Seven sprites that did not have a +CG registered by any system, and which had been initially considered to be independent events were reclassified to be "time units" forming a single "time group" event. The hypothesis used here is that if the electron avalanche can take up to 40 ms to develop into a streamer in a particular location, multiple "sprite time units" could be produced by the same CG at different locations, with a varying duration for the streamer development, probably influenced by the local characteristics, within a maximum Δt of 40 ms from the CG. The total number of sprite events was thereby reduced from 47 to 40, 7 events being "time groups" with 2 "time units" each.

The definition of what an independent sprite event might be has been extensively but informally discussed within the sprite community; the topic has not yet been approached in scientific papers. There is no established definition of "independent sprite event." This is an important issue since any analysis of the temporal and spatial relationship between sprites and lightning based on observational data is affected by how and if sprites are grouped into "independent events", i.e., by the definition used. For the sprites occurring on July 22, 1996, analyzed in this paper, the maximum Δt observed, excluding the 2 outliers, was 40 ms. However this could be a particularity of this specific night, resulting from a combination of the characteristics of the thunderstorm, lightning activity and local mesospheric conditions. For example, applying the same selection criteria for parent +CGs (closest in time preceding the sprite and closest in space), a preliminary analysis of 69 triangulated sprites from July 24, 1996, resulted in only 58 ± 9% sprites occurring within 40 ms after the parent +CG (not shown). That illustrates the necessity of a detailed statistical study of a large data set of triangulated sprites with GPS timing from a variety of storms and locations to establish a definition of "independent sprite event" with bounded variances that can be widely adopted. Such a study is been currently developed as a continuation of the analysis reported herein.

3.2. Sprites' association with lightning and comparison with other studies

Working with the redefined data set of 40 sprite events, we found that about 73 ± 13% of the sprites were associated with a +CG recorded by the NLDN. This percentage increased to 82 ± 14% when we considered VLF signatures for +CGs not detected by the NLDN. NLDN has detection efficiency around 90% for −CGs (Cummins et al., 1998). The detection efficiency of +CGs has not been documented, but may be assumed to be similar to this. The 10% increase in the number of sprites associated with +CGs when VLF data is considered supports this assumption.

Table 1
Comparison of reports of the percentage of sprites associated with +CGs

Study	Dates	Report	Total number of sprites	Percentage of sprites with +CGs detected by the NLDN (%)
1	July 12, 1994	Boccippio et al. (1995)	42	86 ± 14
2	September 7, 1994	Boccippio et al. (1995)	55	82 ± 12
3	August 6, 1994	Lyons (1996)	36	94 ± 16
4	July 6, 7, 11, 19, 21, 22, 24, 1996	São Sabbas (1999)	746	65 ± 3
5	July 22, 1996	This study	40	73 ± 13

We have compared the percentage of sprites associated with lightning calculated in this work with values reported by Boccippio et al. (1995), Lyons (1996) and São Sabbas (1999). Boccippio et al. (1995) compared the time of occurrence of sprites, recorded in GPS time-stamped low-light-level video images, with the time of lightning discharges from the associated thunderstorms recorded by the National Lightning Detection Network (NLDN), as well as with electromagnetic "Q-bursts" events. The ELF data was time-tagged with an internal PC clock that drifted ~13 s/day. The drift was assumed to be linear. An algorithm generated by comparing the recorded onset times with the GPS-timed sprite events corrected the drift. The sprites occurred above thunderstorms over the central US and were observed from Yucca Ridge. The identification of the parent +CGs of the sprites was based mainly on timing. Sprite locations were not triangulated, and the spatial requirement was that NLDN and/or ELF signatures must have originated from the same thunderstorm that generated the sprites.

Lyons (1996) studied 36 sprites recorded in GPS time stamped images from Yucca Ridge, during a 2 h interval. The sprites occurred above a mesoscale convective system (MCS) over Nebraska on August 6, 1994. Lyons (1996) reported that 94% of sprites were preceded by +CGs registered by the NLDN. Seven sprites were triangulated and the location of the other sprites was estimated based on the location of the parent +CG, which was identified based on the timing.

São Sabbas (1999) analyzed 746 sprites from 7 different nights in 1996, recorded from Yucca Ridge by Utah State University. The sprites occurred above thunderstorms over the central US on July 6, 7, 11, 19, 21, 22 and 24, 1996, and were image using the same system describe in the Section 2. To compensate for the time uncertainty of this system, a selection window with Δt of 360 ms before the sprite and 60 ms (3 fields at 25 fps) afterwards was adopted in identifying the parent +CG. Sprites were not triangulated in this study, so to be considered a possible parent the +CG had to be inside the field of view of the camera. With this approach several +CGs that were not associated with sprites may have been incorrectly tagged as the possible parents of sprites. Nevertheless, only 65 ± 3% of the sprites were associated with a +CG signature registered by the NLDN. The same criteria were used to look for a possible association of sprites with −CGs when there was no +CG. Table 1 summarizes these results.

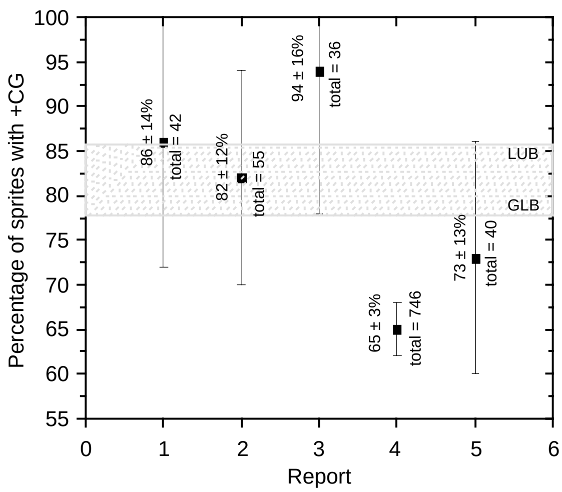

Fig. 6. Comparison between various statistical studies of percentages of sprites associated with +CGs detected by the NLDN. The region between the least upper bound (LUB) and the greatest lower bound (GLB) is highlighted.

The definitions of "sprite independent event" utilized for studies 1–3 were not available, in study 4 all "sprite time units" were considered to be "independent events." The statistical uncertainties ("error bars") of these percentages were estimated using $\Delta x = x/(N\sqrt{x})$, where x is the number of events relative to the percentage (x/N) and N is the total number of events, and are included in Table 1. These results, including the estimated uncertainties, are plotted in Fig. 6. The figure also shows the least upper bound (LUB) and the greatest lower bound (GLB) of the uncertainties for studies 1, 2, 3 and 5. When these uncertainties are taken into account, studies 1, 2, 3 and 5 are statistically consistent among themselves within the region bounded by the LUB and GLB. Report number 4, however, is statistically distinct from the other reports, since its error bars do not fall

Table 2
Lightning and sprite related data (São Sabbas, 1999)

July, 1996	Percentage of +CGs relative to total	Percentage of −CGs relative to total	Total number of CGs	Number of sprites	Duration of sprite period
6	10.9% (2652)	89.1% (21740)	24 392	36	2 h 34 m
7	14.1% (1367)	85.9% (8318)	9685	88	4 h 22 m
11	10.7% (1928)	89.3% (16129)	18 057	38	1 h 32 m
19	7.3% (1086)	92.7% (13714)	14 800	83	3 h 05 m
21	17.0% (1504)	83.0% (7327)	8831	212	3 h 27 m
22	10.9% (4412)	89.1% (36193)	40 605	84	4 h 07 m
24	9.0% (5088)	89.0% (51446)	56 534	205	5 h 20 m

within their LUB and GLB. The low percentage (65 ± 3%) of sprites associated with +CGs was obtained using a large time selection window, and a data set on average 17 times larger than the data sets utilized in the other studies. Even adjusting upwards by 10%, to approximately compensate for the 90% detection efficiency of NLDN, 25 ± 2% of sprites remain without +CGs. São Sabbas (1999) suggested that −CGs and intracloud discharges were generating the sprites without +CGs that could not be explained by NLDN detection efficiency.

Table 2 shows the percentage of positive and negative lightning relative to the total lightning (positive + negative) for the sprite producing thunderstorm of July 22, 1996 analyzed here, together with percentages for other nights analyzed by São Sabbas (1999). The table also shows the number of sprites observed and duration of the sprite production period for comparison. All storms had small percentages of +CGs (from 7.3% to 10.9%), showing that the production of a large percentage of +CGs by the thunderstorm is neither a necessary condition for sprite occurrence nor a determining factor for the number of sprites produced.

Fig. 7 shows a relationship between the onset of sprite production and growth in the rate of occurrence of the storm's +CG for all peak current ranges. Of the seven days in 1996 studied by São Sabbas (1999), July 21, 1996, is the only day for which the onset of the sprite occurrence might have been observed, since the observations for this day started before lightning activity. In all other days, lightning activity had already commenced before observations began. On July 21, 1996, sprites were observed to commence after a continuous growth in the occurrence rate of storm's +CGs, for all peak currents ranges. All other days had similar growths and peaks in the +CG occurrence rate of storm's +CG before the beginning of the observation period (not shown).

3.3. Negative sprites and sprites without a CG

Approximately 27 ± 8% of sprites did not have a parent +CG recorded by the NLDN, and 17 ± 7% had neither NLDN nor VLF signatures. Two of the seven sprite events

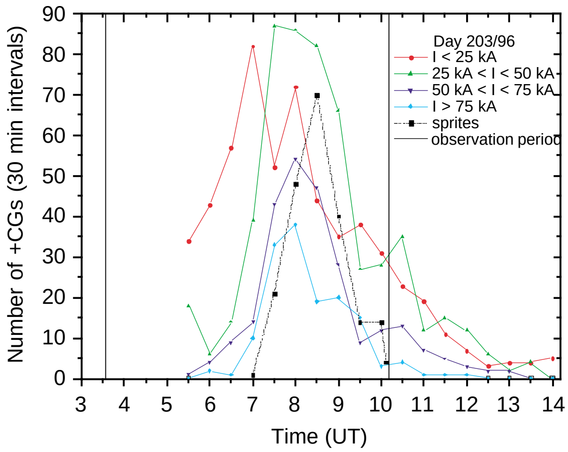

Fig. 7. Time distribution of the number of positive lightning in 30-min intervals, for different peak current ranges, day 203/96 (São Sabbas, 1999). The vertical black line delimitate the observation period. Sprites started to occur at 6:40 UT.

that had neither a NLDN nor VLF +CG signature were preceded by a −CG (Figs. 8a and 9a). Fig. 8 shows three consecutive independent sprite events. The time separation between the first and second event is 50 ms, and between the second and third is 117 ms. The first event (Fig. 8a) was preceded by a negative CG with $\Delta t = 9$ ms. This flash was not registered by the NLDN, but it was registered by the New Mexico Tech VLF system. Due to its small Δt it is very likely that this −CG, in fact, generated the sprite. The second sprite (Fig. 8b), considered as an independent event here (occurred 59 ms from the −CG associated with the first sprite), was not associated with any detected CG, positive or negative.

The third event (Fig. 8c) had both NLDN and VLF +CG signatures preceding it by 17 ms. The +CG had a peak current of 48 kA and occurred ~78 km from the sprite. The discharge had a slow tail in VLF that lasted ~0.5 ms. It was followed, ~4 ms afterwards, by a slow energetic field change, possibly due to the sprite, that lasted ~1 ms (not shown). The "positive sprite" (Fig. 8c) was the brightest of

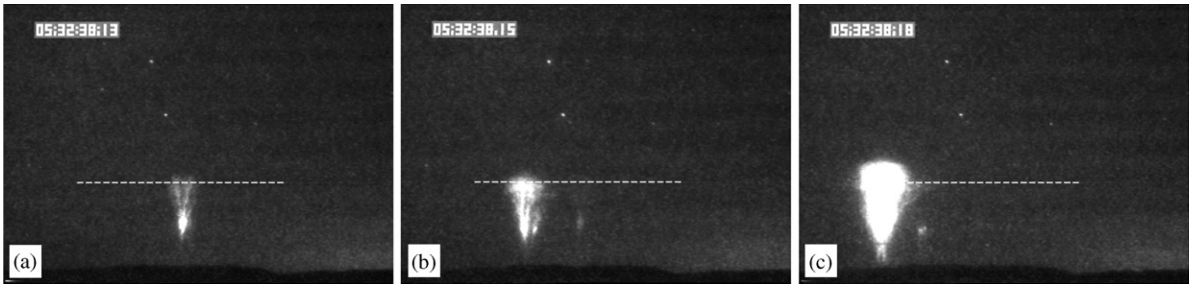

Fig. 8. Three consecutive independent sprite events separated by 50 (a and b) and 117 ms (b and c), respectively. The first sprite (a) was preceded by a −CG recorded by the Broad band electric field sensor (no NLDN), $\Delta t = 9$ ms. The second sprite (b) had no CG signature associated with it in either NLDN or VLF, and the third (c) was preceded by 48 kA +CG recorded by both systems, $\Delta t = 17$ ms and $\Delta s = 78$ km. The images shown were obtained by UAF.

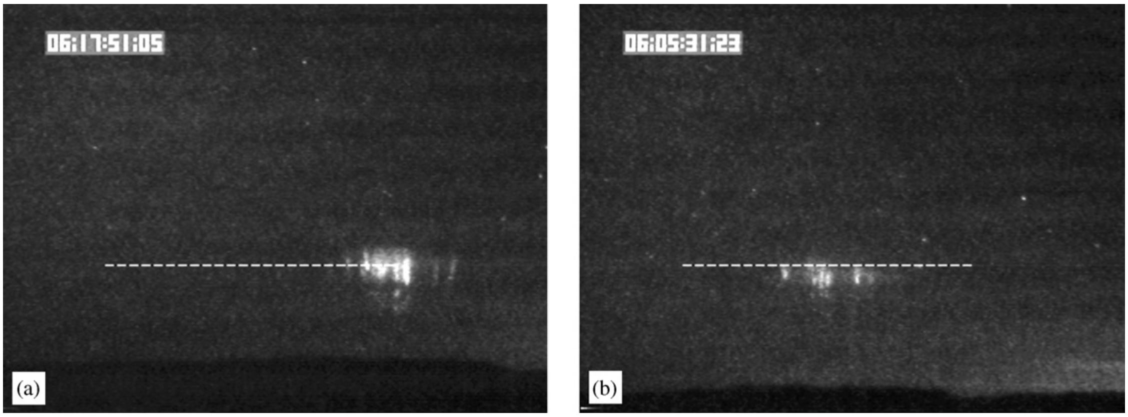

Fig. 9. The first image (a) shows a sprite preceded by a 22 kA − CG recorded by both NLDN and VLF systems, $\Delta t = 146$ ms and $\Delta s = 201$ ms. The second (b) shows a similar type of sprite event that was preceded by a 47 kA +CG, $\Delta t = 28$ ms and $\Delta s = 9$ km. The images shown were obtained by UAF.

these three consecutive events, but there were other "positive sprites" that occurred during the night of the study that were much smaller and dimmer than the possible "negative event" (a) displayed in Fig. 8a. The variation of brightness of the sprites with respect to underlying lightning characteristics is not yet well understood.

The second sprite preceded by a −CG detected in this study is shown in Fig. 9a, together with a "positive sprite" (Fig. 9b) for comparison of visual characteristics. The −CG was recorded by the NLDN and VLF system 146 ms before the sprite, had a peak current of 22 kA and occurred at ∼201 km from the event. Because of the large Δt and distance between this sprite and the −CG, it is possible that both NLDN and VLF systems missed a +CG (or −CG) that would have a better association with this event. The "units" of this sprite, shown in Fig. 9a, were slightly brighter and larger than the "units" of the "positive sprite" of Fig. 9b. The sprite in Fig. 9b was preceded by a +CG with a Δt equal to 28 ms. The +CG peak current was 47 kA and it occurred ∼9 km from the sprite.

None of the sprites without +CGs had any particular characteristics that would visually distinguish them from the positive sprites. An upward–downward difference in the branch orientation might conceivably be expected for sprites generated by lightning of different polarities. However, we do not expect this difference to appear in a 16.7 ms integration image; it is more likely to show on 1 ms images from high-speed cameras (e.g., Stanley et al., 1999; Stenbaek-Nielsen et al., 2000). Comparatively, the percentage of "bright" and "small" events was about the same for positive and negative sprites.

There are two possible interpretations for the sprites without a +CG. The first is that they were preceded by positive strokes undetected by either the NLDN or the VLF systems. An alternate interpretation is that other types of lightning besides +CGs, e.g., negative CGs and intracloud discharges, may also generate sprites. This interpretation is supported by the São Sabbas (1999) study, and is not ruled out by Pasko et al. (1997) quasi-electrostatic model, or the Pasko et al. (1998) and Raizer et al. (1998) streamer models. Sprites

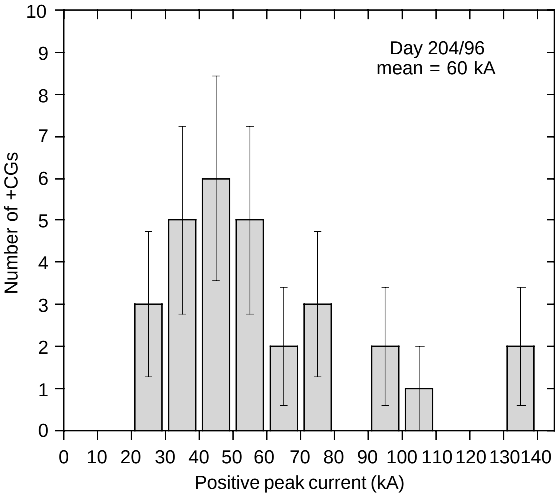

Fig. 10. Peak current distribution of the parent +CG flashes within the sprite's space–time vicinity. The +CGs are binned in intervals of 10 kA. Error bars are the statistical errors.

generated by other types of lightning besides +CGs would represent a smaller portion of the total, such as we may have observed here. Furthermore, according to Dejnakarintra and Park (1974), and Baginski et al. (1988), vertical intracloud discharges that annihilate positive charge at the top of the clouds and negative charges at the bottom can both generate large electric fields in the upper atmosphere, also supporting this interpretation.

3.4. *Peak current distribution of parent +CGs*

Fig. 10 shows the peak current distribution of the sprite's associated +CG. The distribution exhibits a maximum for peak current between 40 and 50 kA. Five out of the 29 (17 ± 7%) +CG flashes preceding sprites had high peak currents (> 75 kA). The average peak current of 60 kA in the present study agrees with the 52 kA reported by Bell et al. (1998), and supports results showing that the peak currents of +CGs producing sprites span a large range of values.

Fig. 11a shows that the peak current distribution of sprite's associated +CGs in the 7 storms studied in São Sabbas (1999) also has a maximum around 40–50 kA, and is statistically consistent with the one reported here (Fig. 10). Both distributions are different from the distribution for all +CGs in the 7 storms (Fig. 11b), which peaked at 10–20 kA and had a mean value of 27 kA. This difference in distributions is one of the principal characteristics that appear to distinguish the lightning population associated with sprites from those not associated with sprites. The peak current distribution of the −CG candidates found in the São Sabbas (1999) study and the totality of −CGs of the storm are quite similar to each other; both are centered at 10–20 kA (not shown).

4. Conclusions

We performed a detailed statistical analysis of the space–time relationships between sprites and the associated lightning characteristics. The results of this study can be summarized as follows:

1. A set of 40 sprite events from the Sprites96 campaign was analyzed. Seven of the events (17%) did not have a parent +CG registered by either NLDN or VLF sensors. Images of these events revealed no particular visual characteristics that distinguished them from positive sprites, and such differences are not expected at 16.7 ms integration. Two of the sprites without +CGs were preceded by a −CG, one of them was very likely to be associated with the −CG, which was registered by the VLF system 9 ms before the sprite.

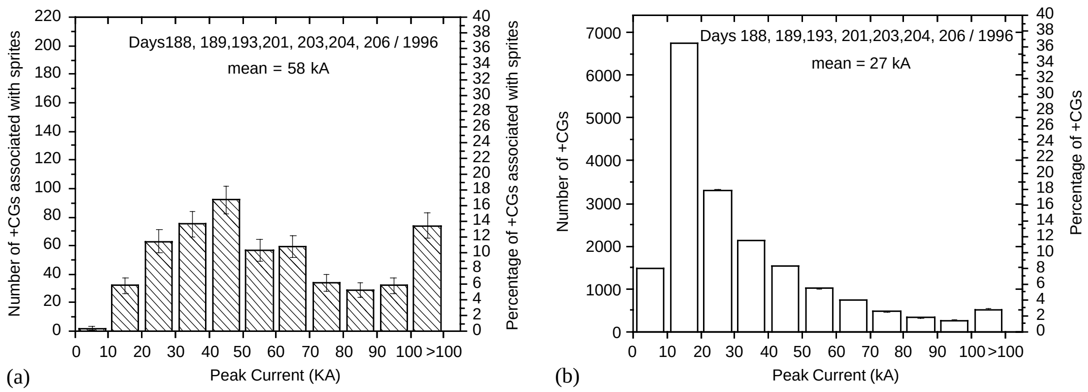

Fig. 11. Percentage distribution of the peak current of +CG associated with sprites (a), and (b) of the totality of +CGs of the storm (São Sabbas 1999). The last column, in both figures, is the percentage of all +CGs with peak current greater than 100 kA.

2. No correlation between the apparent visual size and brightness of sprites, and time delays from the associated +CGs was found. No correlation was found between with the size or brightness of sprites and the time interval or distance from their parent lightning, i.e. smaller/dimmer sprites or sprites further away from the associated +CG did not have longer time delays from the parent +CG then the bulk of the sprite population.
3. The distribution of time intervals between sprites and parent +CGs showed a peak between 10 and 20 ms with a mean of 30 ms (20 ms excluding the outliers). We suggest that this distribution characterizes the time scale for the development of an individual electron avalanche into a streamer between ~70 and 85 km altitude, as given in the Pasko et al. (1998) model. Most sprites occurred within 40 ms from the parent +CGs, suggesting this time interval as upper limit for the characteristic time delay between the +CG flash and the sprites observed during this night.
4. The distribution of the distance between sprites and parent +CGs showed that sprites have the tendency to occur within 50 km lateral displacement from the CG, consistent with results previously reported by Wescott et al. (1998) and Lyons (1996).
5. The peak current distribution of +CGs associated with sprites exhibited a larger mean and standard deviation than the distribution of all positives in the storm. It had a maximum between 40 and 50 kA and a mean of 58 kA, compared to a 10–20 kA maximum and 27 kA mean of the distribution for all positives.

The present work is the first statistical study to use both GPS timing for images and triangulated positions of sprites, where both temporal and spatial criteria are used to select the parent +CG. Additional statistical studies utilizing large data sets (> 100 sprites) over numerous storms distributed globally are necessary to arrive at a tightly parameterized definition of "sprite independent event".

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