GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 24, PAGES 3605-3608, DECEMBER 15, 1999

Sprites triggered by negative lightning discharges

C. P. Barrington-Leigh and U. S. Inan

STAR Laboratory, Stanford University, Stanford, CA 94305

M. Stanley

Department of Physics, New Mexico Tech, Socorro, NM 87801

S. A. Cummer

NASA/Goddard Space Flight Center, Greenbelt, MD 20771

Abstract. High altitude air breakdown, manifested as "red sprites," is reported in close association with negative cloud-to-ground lightning (−CG) on at least two occasions above an unusual storm on August 29, 1998. Data from high speed photometry, low-light-level video, and receivers of lightning electromagnetic signatures in the frequency range 10 Hz to 20 kHz are used to establish the association and indicate that the causative −CG discharges effected unusually large vertical charge moment changes (ΔM_{Qv}) of up to 1550 C·km in 5 ms. The existence of sprites caused by −CG's, rather than the regularly associated +CG's, has immediate implications for sprite models and observations.

Introduction

Sprites are often described as an electric discharge or breakdown at mesospheric altitudes occurring above large positive cloud to ground (+CG) lightning. While sprites are known to be associated with +CG discharges [*Sentman et al.*, 1995; *Winckler et al.*, 1996; *Lyons*, 1996], not all sprites closely follow such a discharge, or any recorded discharge at all [*Franz et al.*, 1990; *Boccippio et al.*, 1995; *Winckler*, 1995]. *Winckler* [1998] reports three sprites each occurring within one second of nearby −CG's, but provides no specific evidence of an association closer than one second or 2° (~11 km) of viewing azimuth. In our observations we regularly recorded sprites associated with a sequence of CG's spaced by 10 to 50 ms. More often, sprites are closely associated with a large +CG which moves a large positive charge (ΔM_{Qv} of 250 to 3250 C·km in *Cummer and Inan* [1997]; 200 to 1100 C·km in *Bell et al.* [1998]), and in the case of especially impulsive lightning (>60 kA, in *Barrington-Leigh and Inan* [1999]) the CG is followed by "elves," the flash due to widespread heating of the lower ionosphere by the electromagnetic pulse of lightning. In this paper, we report evidence of at least two sprites that are closely associated with negative cloud-to-ground (−CG) lightning strokes. Among our observations, these events are unique.

Instrumentation

We use three lines of evidence to show that a storm over northwestern Mexico produced two −CG-associated sprites. Intensified broad-spectrum CCD video observations were made from Langmuir Laboratory (33.98°N×107.19°W) on the night of August 29 1998, using a frame-strapped timing system [*Rairden and Mende*, 1995] with 33 ms integration time and GPS time stamping with 1 ms precision. The 15°×20° field of view of the camera was aligned with that of the Fly's Eye photometric array [*Inan et al*, 1997], consisting of nine horizontally aligned photometers, each with a ~2.2°×1.1° field of view, and a central one with a 6°×3° field of view. Each photometer bore a red (> 670 nm) filter and was calibrated using a Hoffman Engineering Corporation Spectral Radiance Standard. Data from the array were recorded digitally in a triggered mode, along with the output of a 350 Hz to 20 kHz Very Low Frequency (VLF) receiver, at a sample rate of 60 kHz per channel. The VLF receiver was fed by an air-core magnetic loop antenna, oriented in a vertical plane 23° east of north. A GPS clock was used for timing with <1 ms absolute uncertainty.

In addition, a calibrated ELF/VLF (10 Hz to 20 kHz) recording with the same timing system was made at Stanford (37.42°N×122.17°W). These data were time aligned with the Langmuir Laboratory data and allowed a determination of the vertical currents flowing on time scales of 1 to 10 ms.

Observations

A thunderstorm system centered at 112.7°W×29.8°N (inset, Figure 1) that was part of a major mesoscale convective system (MCS) over the northern Gulf of California in Mexico produced mainly −CG lightning on August 29. Fig-

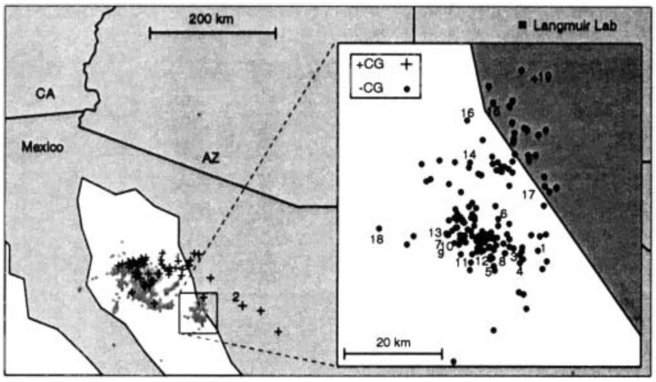

Figure 1. NLDN-recorded flashes from a nighttime MCS on August 29, 1998. The inset shows the storm which produced many large −CG's. Numbered events are detailed in Table 1.

Paper number 1999GL010692.
0094-8276/99/1999GL010692$05.00

Table 1. NLDN-recorded large CG events (>60 kA) clustered around the −CG sprites, between the times 05:49:00 UT and 06:49:00 UT. Charge moment refers to the change in the first 5 ms after the onset of the sferic. Events 2, 15, 17, and possibly 18 were associated with observed sprites.

	Time	NLDN current	Charge moment
1	05:49:13	−73 kA	−230 C·km
2	05:49:23	+69 kA	+480 C·km
3	05:49:31	−64 kA	−110 C·km
4	05:52:39	−62 kA	−120 C·km
5	05:52:51	−71 kA	−140 C·km
6	05:53:07	−79 kA	−370 C·km
7	05:53:30	−69 kA	−280 C·km
8	05:54:23	−78 kA	−80 C·km
9	05:56:47	−64 kA	−140 C·km
10	05:58:28	−69 kA	−120 C·km
11	05:59:22	−71 kA	−130 C·km
12	06:01:00	−91 kA	−270 C·km
13	06:09:36	−73 kA	−310 C·km
14	06:10:02	−79 kA	−200 C·km
15	06:11:14	−93 kA	−1550 C·km
16	06:13:39	−64 kA	−300 C·km
17	06:15:16	−97 kA	−1380 C·km
18	06:18:14	−110 kA	−1340 C·km
19	06:48:04	+120 kA	+1000 C·km

ure 1 shows the +CG (+) and −CG (•) discharges recorded by the National Lightning Detection Network (NLDN, see *Cummins et al.*, [1998]) with peak current >10 kA between 05:49 and 06:49 UT. The largest events (peak currents over 60 kA) in the storm region of interest are numbered and listed in Table 1. According to NLDN, no +CG's (>10 kA) occurred in this region during the 22 minutes prior to each of the two unusual events recorded at 06:11:14.808, and 06:15:16.305. Indeed, over the entire duration of the storm NLDN recorded only five +CG flashes from this active region, constituting ~1.5% of the total flashes. In contrast, the larger MCS surrounding this region exhibited a +CG occurrence of ~ 6%.

Figure 2(a) shows one of these unusual events, each of which consists of a closely associated −CG flash, an elves event, and accompanying sprites. NLDN recorded a −97 kA stroke (event 17 in Figure 1) at 06:15:16.305 UT. The polarity of the sferics recorded at Langmuir and at Stanford (Figure 2) is unambiguous at this range and confirms the polarity of the lightning. The bearing to this stroke and the altitudes overlying its location are shown on the video image. The video's pointing direction was determined with star field alignment. Photometers 1 through 9 show the distinctive signature [*Inan et al.*, 1997; *Barrington-Leigh and Inan*, 1999] of elves. This array shows rapid lateral expansion and, along with P11, the characteristic onset delay after reception of the sferic, in this case ~135 μs. After the luminosity due to elves abates (~1 ms), however, P11 shows a distinct second pulse lasting until at least ~5 ms after the onset of the sferic. In our recordings such a photometric signature from a distant storm is always accompanied by video observations of sprites, and indeed the video frame for this time (Figure 2b and 2c) shows clear evidence of sprites with vertical (columnar) structure, despite intervening cloud cover and the large distance (694 km) of the storm from Langmuir Laboratory. The full vertical extent of the sprites is difficult to ascertain, as their apparent lower limit may be due to a foreground cloud. Figure 2 also shows the vertical current moment and cumulative vertical charge moment change ΔM_{Qv} extracted from the calibrated sferic receiver at Stanford with the method described in *Cummer and Inan* [1997]. By 5 ms after the arrival of the sferic, $\Delta M_{Qv} \approx 1380$ C·km, indicating an abnormally high continuing current for a −CG [*Uman*, 1987, p. 172 and 341]. ΔM_{Qv} before the onset of the second optical peak, or by about 1.38 ms after the onset of the sferic, is 750 C·km, well above the 250 C·km threshold observed for the production of sprites associated with +CG's in *Cummer and Inan* [1997].

Figure 3 shows another similar event, corresponding to a −CG recorded by NLDN at 06:11:14.808 UT with peak current of −93 kA. This discharge (event 17 in Figure 1) produced similar unambiguous video recording of columnar sprite luminosity between 70 and 80 km through an opening in the foreground clouds. The photometric channels and ELF sferic also exhibit evidence of elves and a high current moment, respectively. None of the photometers are pointed directly at this sprite, however, so none of the photometers shows an obvious second pulse in luminosity for the event.

Event 18, recorded at 06:18:14.239 UT, has very similar properties as the two others, but because the region below ~80 km altitude was blocked by clouds, only diffuse light reached the video or P11 (Figure 4). Nevertheless, the photometry and localized brightness in the video image is suggestive of a sprite event similar to those of Figures 2 and 3.

Discussion

The interpretation of these observations is not limited by the detection efficiency of the NLDN. While the NLDN anal-

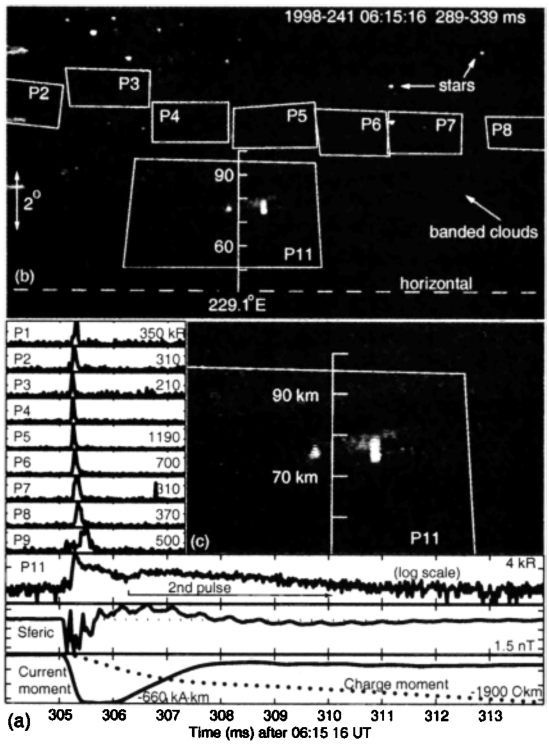

Figure 2. Sprites associated with a large −CG return stroke (event 17) and continuing current. (a) shows photometer responses, recorded lightning sferic, and the inferred current moment. Scales are linear, except for that of P11. The wide field video view in (b) shows the measured fields of view of the photometers, including the observed sprite within the field of view of P11. The image consists of two interlaced fields, exposed from 289 ms to 322 ms and from 306 ms to 339 ms, both of which show the sprite. A closeup of the sprite is shown in (c).

ysis algorithms occasionally (less than once in 1000 flashes) misplace a CG by up to 50 km, they more typically assign a location with an accuracy of ~500 m [*Cummins et al.*, 1998]. Also, the stroke detection efficiency, while low for peak currents <5 kA, improves markedly for peak currents >15 kA within the network [*Cummins et al.*, 1998]. Regardless, the continuous VLF recordings at Langmuir and Stanford are not subject to omission of events, and these data preclude the possibility of a significant +CG having been missed by NLDN and having contributed to the sprites. No sferics caused by +CG's with peaks >0.07 nT as measured at Stanford were recorded within 200 ms of event 17, within 800 ms of event 15, or within 200 ms of event 18.

The two −CG's accompanied by observed sprites, as well as the −CG of event 18, each transferred remarkably large charges as determined from the first 5 ms of the sferic. Within 5 ms of each lightning stroke, downward ΔM_{Q_V} of −1550 C·km, −1380 C·km, and −1340 C·km were evinced by the discharge in the three cases shown in Figures 2, 3, and 4, respectively. Based on the shape of the current-moment waveforms, which have a large initial pulse, these values of ΔM_{Q_V} are likely mostly due to the cloud-to-ground stroke rather than the sprites themselves (compare *Cummer et al.* [1998]).

Current-moment extractions were also performed for the other large (>60 kA) lightning strokes recorded by NLDN in the vicinity of the sprites and during the time period 05:49 UT - 06:49 UT. Event 2, a +69 kA CG shown in Figure 1, was due to a different storm but also produced sprites. Nevertheless, this return stroke sent only +480 C·km to ground in its first 5 ms. Interestingly, event 19, a +120 kA CG which occurred after 20 minutes of inactivity in the storm studied, led to an elves event and produced a 5 ms ΔM_{Q_V} of +1000 C·km but no recorded sprites (if any occurred, they must have been optically weak). Several other moderately large (−70 to −90 kA) −CG strokes listed in Table 1 produced ΔM_{Q_V} of ~300 C·km or more within 5 ms.

In contrast, values of ΔM_{Q_V} for −CG's in the rest of the MCS were considerably smaller. The two largest −CG return strokes recorded during the period 05:49 UT - 06:49 UT in the very active system northwest of the storm studied (*i.e.* in the rest of the MCS) were listed by the NLDN with peak currents of −120 kA and −156 kA, but had ΔM_{Q_V} of only −190 C·km and −180 C·km, respectively, within 5 ms.

Our method of current-moment extraction is sensitive only to vertical currents on timescales less than ~10 ms.

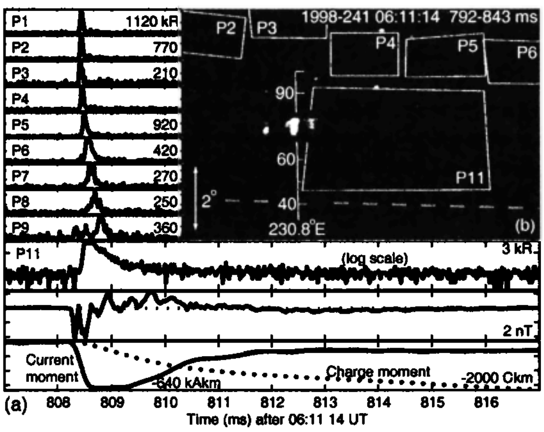

Figure 3. Like Figure 2, but for event 15. P11 may have missed the light due to the sprite.

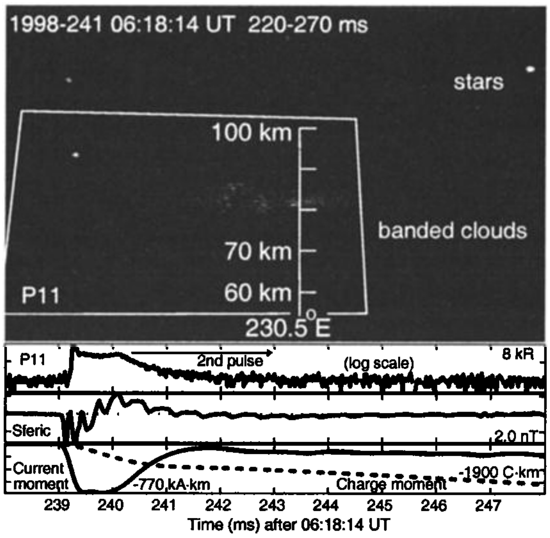

Figure 4. Like Figure 2, but for event 18. Photometers P1-P9, not shown for brevity, recorded a signature of elves, similar to the other events.

Nevertheless, the existence of the −CG-associated sprites documented here leads to several important conclusions:

Sprite polarity asymmetry: Sprites are not uniquely associated with +CG's and therefore are apparently not uniquely associated with downward electric fields in the upper atmosphere. By analogy to the vertical electric field direction associated with +CG's and −CG's, we can classify sprites as "positive sprites" (downward electric field) and "negative sprites" (upward electric field). Our observations of "negative sprites" apparently eliminate the relativistic runaway breakdown mechanism [*e.g. Lehtinen et al.*, 1997] as an explanation for at least a subset of sprites, since this mechanism requires an electric field in the direction of increasing atmospheric density. On the other hand, our observations are in accord with conventional air breakdown models of sprites, and suggest that the most important distinguishing feature of +CG strokes for sprite production is simply their unusually large "continuing current" as compared with the average −CG.

Determining sprite polarity: Sprites which occur without an unambiguous association with a CG return stroke cannot be automatically assumed to be "positive sprites." Instead, a measurement of the sprite current moment from ELF recordings would be necessary to unambiguously determine sprite polarity in these cases. High-resolution imagery may also help to determine sprite polarity, as suggested by the observation of qualitative differences in characteristics of faint, broad positive streamers (observed branching downwards for positive sprites) and brighter, more structured negative streamers (branching upwards) in telescopic video recordings from 1998. It remains to be seen whether higher resolution images of negative sprites similarly exhibit streamers in both directions and whether their vertical extents are comparable to those of positive sprites.

Exception proves the rule: Except in the storm described here, our observed sprites (and even those described in *Winckler* [1998]) have occurred in storms producing large-current +CG's. While we often see sprites which appear to be associated more with a spider lightning (intracloud) propagating series of CG's (usually mostly +CG, but often with some −CG's too) rather than with the precise azimuth and time of any particular (+)CG, the negative sprites observed here were centered in azimuth over the respective

−CG's, which in turn occurred in isolation. Ultimately, an understanding of how charge-transfer processes can lead to sprites from propagating series of modest-current +CG's but rarely from even large multi-stroke −CG clusters may lie almost entirely in cloud physics rather than in any asymmetry in mesospheric breakdown processes. This difficulty is compounded experimentally by the problem of measuring horizontal (intracloud) ELF currents, which do not produce vertical electric fields nor horizontal magnetic fields in the near-field (except above and below the discharge) and do not couple to Earth-ionosphere waveguide modes below ~1.8 kHz [*Wait*, 1957]. Electric field measurements above or below storms producing recorded sprites are a worthy goal in this regard.

Summary

Recordings from intensified video, high-resolution array photometry, and VLF/ELF sferic receivers indicate the existence of high-altitude air breakdown, or sprites, in clear association with cloud-to-ground lightning with the opposite polarity (−CG) to that usually observed with sprites. Because the association is close in time (< 5 ms) and one-to-one (there was no other NLDN-recorded lightning within ~10 s and ~60 km of the causative flashes, nor were there any other candidate sferics preceding the sprites) it is likely that the electrical polarity of the sprites themselves was also reversed (upward electric field). The observation of at least two such "negative sprites" imposes constraints on the applicability of some models of sprite formation. The high values of ΔM_{Q_v} associated with the causative −CG's were comparable to those of +CG's producing sprites. This suggests that the rarity of negative sprites may result from a rarity of large ΔM_{Q_v}'s caused by −CG's.

Acknowledgements

This work was supported by the Office of Naval Research under grant N00014-94-1-0100 and AASERT grant N00014-95-1-1095 and by the National Science Foundation under grant ATM-9731170. We thank Rick Rairden of Lockheed Palo Alto Research Lab for the use of an intensified video camera and light source, and are indebted to Langmuir Laboratory for the use of their facilities.

References

Barrington-Leigh, C. P., and U.S. Inan, Elves triggered by positive and negative lightning discharges, *Geophys. Res. Lett.*, *26*, 683, 1999.

Bell, T. F., S. C. Reising, and U. S. Inan, Intense continuing currents following positive cloud-to-ground lightning associated with red sprites, *Geophys. Res. Lett.*, *25*, 1285, 1998.

Boccippio, D.J., E.R. Williams, S.L. Heckman, W.A. Lyons, I.T. Baker and R. Boldi, Sprites, Q-bursts and Positive Ground Strokes. *Science*, *269*, 1088-1091, 1995.

Cummer, S.A. and U.S. Inan, Measurement of Charge Transfer in Sprite-producing Lightning using ELF Radio Atmospherics. *Geophys. Res. Lett.*, *24*, 1731, 1997.

Cummer, S. A., U. S. Inan, T. F. Bell, and C. P. Barrington-Leigh, ELF radiation produced by electrical currents in sprites, *Geophys. Res. Lett.*, *25*, 1281, 1998.

Cummins, K. L, M. J. Murphy, E. A Bardo, W. L. Hiscox, R. B. Pyle, and A. E. Pifer, A Combined TOA/MDF Technology Upgrade of the U.S. National Lightning Detection Network, *J. Geophys. Res.*, *103*, 9035, 1998.

Franz, R. C., R. J. Nemzek, and J. R. Winckler, Television image of a large upward electric discharge above a thunderstorm system, *Science*, *249*, 48, 1990.

Inan, U. S., C. P. Barrington-Leigh, S. Hansen, V. S. Glukhov, T. F. Bell, and R. Rairden, Rapid Lateral Expansion of Optical Luminosity in Lightning-Induced Ionospheric Flashes Referred to as 'Elves,' *Geophys. Res. Lett.*, *24*,583, 1997.

Lehtinen, N.G., T.F. Bell, V.P. Pasko, and U.S. Inan, A two-dimensional model of runaway electron beams driven by quasi-electrostatic thundercloud fields, *Geophys. Res. Lett.*, *24*, 2639, 1997.

Lyons, W. A., Sprite observations above the U.S. high plains in relation to their parent thunderstorm systems, *J. Geophys. Res.*, *101*, 29641, 1996.

Rairden, R. L., and S. B. Mende, Time resolved sprite imagery, *Geophys. Res. Lett.*, *22*, 3465, 1995.

Reising, S. C., U. S. Inan, T. F. Bell, and W. A. Lyons, Evidence for continuing current in Sprite-producing cloud-to-ground lightning, *Geophys. Res. Lett.*, *23*, 3639, 1996.

Sentman, D. D., E. M. Wescott, D. L. Osborne, D. L. Hampton, and M. J. Heavner, Preliminary results from the Sprites94 campaign: Red Sprites, *Geophys. Res. Lett.*, *22*, 1205, 1995.

Uman, M. A., *The Lightning Discharge*, International Geophysics Series - Vol. 39, Academic Press, Orlando, 1987.

Wait, J. R., and K. P. Spies, Characterstics of the earth-ionosphere waveguide for VLF radio waves, *Tech. Note 300*, Nat. Bureau Standards, 1964.

Winckler, J. R., Further observations of cloud-ionosphere electrical discharges above thunderstorms, *J. Geophys. Res.*, *100*, 14335, 1995.

Winckler, J. R., W. A. Lyons, T. Nelson, and R. J. Nemzek, New high-resolution ground-based studies of cloud-ionosphere discharges over thunderstorms (CI or Sprites), *J. Geophys. Res.*, *101*, 6997, 1996.

Winckler, J. R., Optical and VLF radio observations of sprites over a frontal storm viewed from O'Brien Observatory at the University of Minnesota, *J.A.S.T.P.*, *60*, 679, 1998.

C. P. Barrington-Leigh and U. S. Inan, STAR Laboratory, Stanford University, Stanford, CA 94305. (e-mail: cpbl@nova.stanford.edu)

(Received June 1, 1999; revised August 11, 1999; accepted August 30, 1999.)