Comparison of photometric measurements and charge moment estimations in two sprite-producing storms

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Received 1 October 2003; revised 19 November 2003; accepted 24 December 2003; published 7 February 2004.

[1] In one relatively small storm on July 2, 2000, 276 sprites were observed between 04:00–07:00 UT. These sprites were largely confined to 70–85 km altitude, were relatively faint and diffuse, and were typically associated with very high peak currents and short time duration. A second storm, on July 4, 2000, had a much larger spatial extent and 27 sprites were observed between 04:00–07:00 UT in a wide range of shapes and time scales spanning 40–90 km altitude. These sprites were produced by 20–120 kA CG's, had complex optical signatures, and were frequently associated with observed ELF radiation. We hypothesize that relatively small storms mainly produce sprites in the form of diffuse glow whereas larger storms with higher cloud tops can initiate streamer discharges leading to more spectacular sprites. *INDEX TERMS:* 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3324 Meteorology and Atmospheric Dynamics: Lightning; 3332 Meteorology and Atmospheric Dynamics: Mesospheric dynamics; 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques; 6994 Radio Science: Instruments and techniques. **Citation:** Gerken, E. A., and U. S. Inan (2004), Comparison of photometric measurements and charge moment estimations in two sprite-producing storms, *Geophys. Res. Lett.*, *31*, L03107, doi:10.1029/2003GL018751.

1. Introduction

[2] Sprites are large luminous lightning-related discharges that appear in the altitude range of ~40 km to 90 km above thunderstorms [e.g., *Sentman et al.*, 1995]. It is generally accepted that the dominant mechanism involved in sprite production is the quasi-static electric field imposed between the clouds and the ionosphere by the occurrence of a cloud-to-ground lightning stroke [*Pasko et al.*, 1997]. Hundreds of sprites have been observed by the Stanford University telescopic imager [*Gerken et al.*, 2002]. This imaging system includes a telescopic (~1°) photometer, a wide field of view (~3.3° by 6.6°) photometer, and two intensified CCD cameras. Electromagnetic signatures of causative lightning discharges, known as radio atmospherics (or sferics), are recorded simultaneously using crossed-loop magnetic antennas and ELF/VLF receivers located at Stanford and in Colorado. The photometer tubes are Hamamatsu HC-124-01 photometers and have photocathodes that are sensitive to photons between 185 nm and 800 nm wavelength. The wide field of view (FOV) photometer is long-pass filtered with a cutoff of ~650 nm in order to provide a better signal-to-noise ratio for the observation of excitation in sprites, namely the N2 first positive band around 700 nm. The electrical signal output from a single photometer is low-pass filtered to frequencies below 25 kHz. An encoded IRIG-B GPS signal is used for timing information.

0094-8276/04/2003GL018751$05.00

2. Two-Storm Comparison Study

[3] Typically, large mesoscale convective system (MCS) storms are associated with sprite production [*Lyons*, 1994]. MCS's are frequently observed drifting east over the Great Plains of the central United States. Sprites are generally produced in the decaying part of the storm over the trailing stratiform region [*Lyons*, 1994], which develops as the thunderstorm anvil descends. Although it is less electrically active, this region of the storm is where the bulk of positive CG's are located [*Lyons*, 1994]. Occasionally a small storm may produce an extremely high rate of unusually small and dim sprites. Only a few cases of this sort of sprite-producing storm have been recorded during several sprite campaigns conducted in the summers of 1998 to 2000. In this section, we compare and contrast the characteristics of sprites produced by a typical MCS and a small but high-sprite-rate storm. Photometric and VLF data presented in this paper were recorded at the Yucca Ridge Field Station in Fort Collins, Colorado [40.5 N, 105.0 W].

[4] A large MCS occurred on July 4, 2000 and 28 sprite events were observed during the two hour period of 04:00–07:00 UT. By contrast, during a much smaller storm on July 2, 2000, as many as 276 sprites were observed in the same amount of time (04:00–07:00 UT). The sprites produced in the July 2 storm were consistently very small in both altitude and lateral extent, and produced a sharp peak of optical brightness in photometric data. The luminous structure of the sprites of the July 4 storm varied widely with many large and intense events as well as smaller less intense events. The photometric signatures of these events were generally complex, with several peaks of brightness exhibited. The majority of the July 4 sprites contained fine filamentary structure (i.e. the so-called "carrot" and "angel" sprites) while the July 2 sprites were more diffuse and typically consisted of several small patches of luminosity within a 10 × 10 km area on the video image. A substantial amount of ELF radiation was observed in the waveforms of sferics associated with sprites produced by the July 4 storm

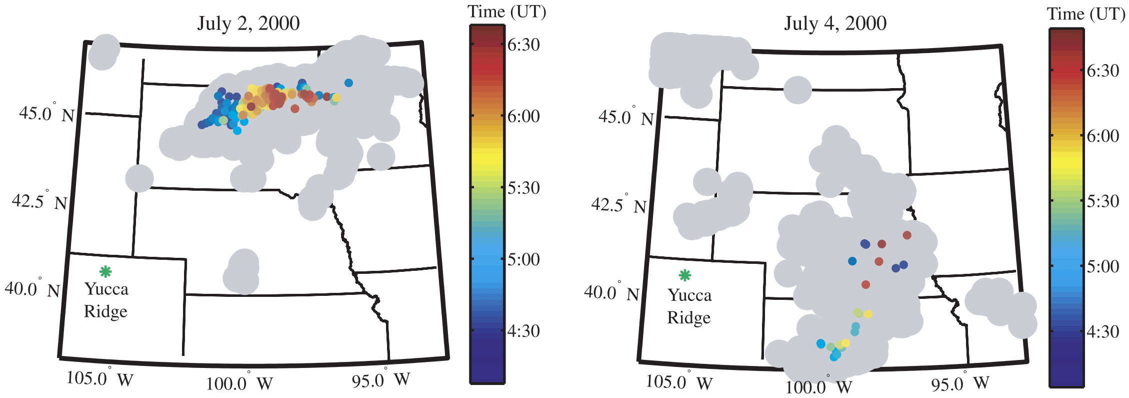

Figure 1. NLDN lightning stroke data for the (left panel) July 2 and (right panel) July 4, 2000 storms. All the NLDN-recorded strokes during 04:00–07:00 UT are plotted in gray on the maps. Those strokes associated with sprite events are plotted in color. The color scale is a function of time with the blue dots occurring earlier than the red dots. As can be seen the sprite-associated strokes in the July 2 storm progress to the northeast in time while sprite events in the July 4 storm are scattered in time throughout the storm.

(i.e., pulses coincident with the sferic onset and pulses correlated in time with peaks in sprite brightness).

[5] According to GOES (Geostationary Operational Environmental Satellite) infrared imagery of the storm on July 4, 2000 at 06:15 UT, the storm clouds covered an area of ~527,000 square kilometers. The cloud tops of this storm were very cold with ~55,000 square kilometers exceeding −75°C. The corresponding GOES infrared imagery for July 2, 2000 shows that this storm covered only ~121,000 square kilometers, and had warmer cloud tops, with only a small portion of the storm reaching −70°C. Typically, the colder a cloud top is, the taller it is [*Arking and Childs*, 1985], indicating that the July 4 storm extended to significantly higher altitudes than the July 2 storm.

[6] The maps in Figure 1 show the NLDN-recorded lightning activity during both storms. The gray dots show the locations of all the lightning strokes occurring between 04:00–07:00 UT while the colored dots indicate those strokes associated with sprite events observed by the Stanford telescopic imager. The color scale is a function of time and progresses from blue (04:00 UT) to red (07:00 UT). It is evident that in the July 2 storm (lefthand panel) the majority of the sprite-associated CG strokes were tightly clustered in time and moved toward the northeast along with the storm. On the other hand, the July 4 storm (righthand panel) remained relatively stationary and the sprite-associated lightning strokes were scattered throughout the storm. Note that while the lightning strokes in the two panels (gray dots) appear to cover a similar area, the July 2 storm was moving in time toward the northeast and had a much smaller extent than the other storm at any given instant.

[7] As shown in the upper panels of Figure 2 the sprites on July 2 typically occurred at a rate of one every ten seconds with the smallest difference being only 1 s. By contrast, the storm on July 4 had much greater intervals between sprites - typically on the order of 5 min and ranging up to ~30 min. The sprites on July 2 were similar to each other and were primarily confined to altitudes of ~75–85 km (inferred on the basis described in *Gerken et al.*, 2000). In contrast, there was wide variability in the luminous structure of sprites in the case of July 4, which occurred over altitudes of ~40–95 km.

[8] Histograms of the NLDN-reported currents for the two storms are shown in the lower panels of Figure 2. The number of negative CGs recorded during the July 4 storm (lower panel) is about an order of magnitude greater than that on July 2. By contrast, comparable numbers of positive CGs were recorded in both storms. The distribution of

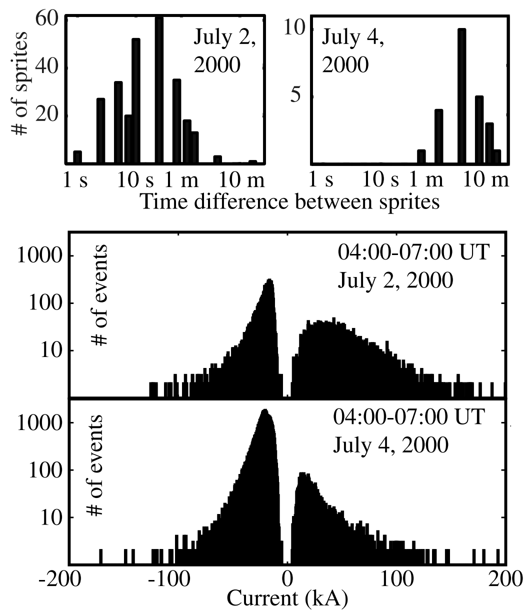

Figure 2. *top panels*: The histograms show that the distribution of the time interval between sprites on July 2 peaks in the tens of seconds while on July 4 the peak is on the order of minutes. The majority of sprites on July 2 occurred less than a couple minutes apart while on July 4 there were delays of tens of minutes between sprites. *bottom panels*: Histogram of NLDN lightning currents recorded during the July 2 and July 4 storms. Note the events are plotted using a log scale. While the July 4 storm has about an order of magnitude more negative CGs than the July 2 storm, the number of positive CGs is comparable in the two storms. The distribution of positive currents in the July 2 storm is shifted to higher values than the July 4 storm.

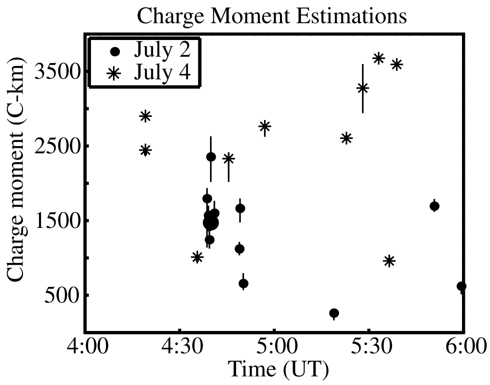

Figure 3. The sprites observed on July 2 mainly had charge moments ranging from 1000–2000 C-km. On July 4, however, the measured charge moments ranged from 1000–3700 C-km.

positive currents during the July 2 storm appears to be shifted to somewhat higher current values than those for the July 4 storm. Since sprites are commonly associated with strong positive CGs [e.g., *Boccippio et al.*, 1995], it is not surprising that the July 2 storm produced more sprites than the July 4 storm despite the much lower overall flash rate of the storm.

2.1. Charge Moment Estimations

[9] Estimation of charge moment (i.e., the product of the amount of charge removed and the altitude from which it is removed) using ground-based recordings of ELF/VLF sferic waveforms of causative lightning discharges is now a well-established method [*Cummer and Inan*, 2000, and references therein]. Although the uncertainties involved in charge moment estimation should ideally be limited to an imperfect knowledge of the ionospheric profile, in practice other uncertainties are also present. In the case of the particular measurement setup used for the July 2000 observations, the charge moment estimation is limited by the fact that IRIG-B GPS timing was used for the photometric recordings which allowed a time resolution of only 1 ms.

[10] Figure 3 shows charge moment estimates using the *Cummer and Inan* [2000] model for selected sprite events in the July 2 and 4 storms. Reported charge estimates are those calculated at the end of the sprite event as observed in the photometers within a 1 ms error. The majority of sprites observed on July 2 had a sferic-to-sprite delay of 1 ms or less while those on July 4 were highly variable with delays ranging from less than 1 ms to greater than 30 ms. As shown in Figure 3, the sprites observed on July 2 mainly had charge moments ranging from 1000–2000 C-km. On July 4, however, the measured charge moments were higher, ranging from 1000–3700 C-km.

2.2. Optical Decay Time Constants

[11] Although sprites frequently emit complex optical signals, exponential decay is often observed as the sprite brightness fades away [*Barrington-Leigh et al.*, 2002]. Exponential curves fitted to the photometric data are used to determine time constants of decay with the fitted curves having the form $y = A + Ce^{-t/\tau}$ where τ is the decay time constant and A and C are constants to be determined by the fit. Selected sprites from the storms of July 2 and July 4, 2000 were examined to assess the presence and rate of exponential decay. While all the sprites reported in this paper were observed in video data, only a subset were also in the FOV of the photometer and this determined the selection criteria. Since the sprites on July 2 were much smaller than those of July 4, a much lower percentage occurred in the FOV of the photometer.

[12] The righthand panel of Figure 4 shows a plot of decay time constants versus NLDN peak current for sprite events recorded by the wide FOV photometer, revealing several interesting relationships between time constants and peak current in these two storms. Firstly, the July 2 sprites are associated with NLDN peak currents greater than 80 kA. The sprites on July 4 are associated with peak currents ranging from 20–120 kA, the majority of which being less than 80 kA. Secondly, all of the time constants measured on

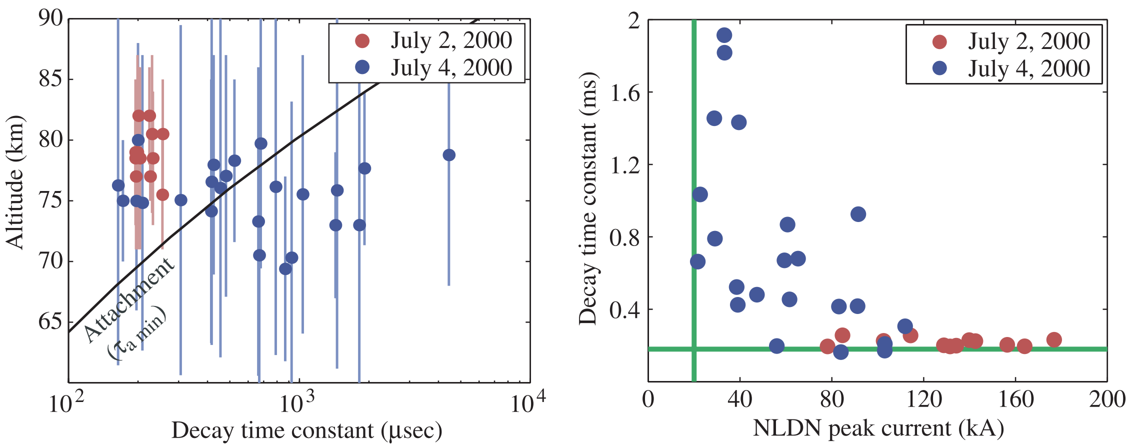

Figure 4. *right panel*: Decay time constants versus NLDN peak current for selected sprite events during the July 2 and July 4 storms. When looking at the data set as a whole, it appears that the data points are following a curve with two asympotes: a 200 μs time constant and a 20 kA peak current. *left panel*: Time constants versus altitude measured for the same selected sprite events as in the righthand panel in the July 2 and July 4 storms. The minimum attachment time constant is superimposed for reference.

July 2 were less than 400 μs while those on July 4 ranged from 200 μs to almost 2 ms with the majority of events being greater than 400 μs. Viewing the results in Figure 4 as a whole, it appears that the data points follow a curve with two asymptotes; ∼200 μs time constant and 20 kA peak current. These asymptotic values also are in good agreement with those found in other data sets [e.g., *Barrington-Leigh et al.*, 2002].

[13] The lefthand panel of Figure 4 shows a plot of time constants versus altitude measured for the same selected sprite events shown in the righthand panel of Figure 4. The error bars correspond to the FOV of the photometer and the dots represent the midpoint on that FOV. The impact of this wide FOV is that for sprites which extend over a large altitude range, the decay time constants from a number of altitudes are superimposed and the signal is blurred. While the sprite events of July 4 are widely distributed both in altitude and decay time constant, the events of July 2 are tightly clumped in an altitude range of ∼75–85 km and time constant range of ∼200–400 μs. *Barrington-Leigh et al.* [2002] showed that in streamer discharges, the exponential decay of optical brightness may be explained by the presence of quasi-constant electric fields inside of the streamers. In such cases, the optical brightness of streamers observed at sprite altitudes should decay with a time scale exceeding the minimum attachment time constant. For comparison, the minimum attachment time constant versus altitude is superimposed on the data set. When the error bars are taken into consideration, it is possible that all but two of the events of the July 4 storm decay with a time constant greater than the minimum attachment time constant at that altitude as predicted. Even with error bars, however, all of the July 2 events decay with a time scale less than the minimum attachment time constant and are more closely associated with the dielectric relaxation time constant. This result is consistent with the fact that the quasi-static electric fields driving these diffuse glow discharges observed at these high altitudes likely dissipate rapidly (due to relatively high conductivity) at the dielectric relaxation rate.

3. Discussion

[14] Our comparative study demonstrates that storm geometry may play a significant role in determining the type of sprite discharge produced. A key difference between the two storms is evident in the GOES satellite infrared imagery. The cloud tops in the July 4 storm were significantly cooler than those of the July 2 storm, and thus it is likely the thunderclouds in this storm extended to a higher altitude. The charges moved by +CGs from higher altitudes would produce higher electric fields at mesospheric heights. The altitude variation between the two storms likely explains why the July 4 storm had sprites with a full altitude extent while the July 2 storm mainly produced diffuse glow discharges. Additionally, the MCS-type storm on July 4 may have had a much larger charge pool to draw from. While peak currents in this storm were relatively low, ELF components coincident with the sferic onset were frequently present in electromagnetic recordings indicating the existence of continuing currents [*Reising et al.*, 1996], possibly drawing charge from distant parts of the storm through horizontal intracloud processes. On the other hand, the associated sferics of the July 2 storm produced less ELF energy, but had high peak currents indicating fast charge removal processes. Since this storm covered a much smaller area, it would not have been able to draw charge from distant charge pools and would thus be less likely to produce the long continuing currents observed in the case of the July 4 storm.

[15] The most important parameter in sprite initiation is believed to be the charge moment which is equal to the charge removed from the thundercloud times the altitude from which the charge was removed [e.g., *Pasko et al.*, 1997; *Hu et al.*, 2002, and references cited therein]. Accordingly, there do exist two means of sprite initiation - short duration and high peak currents, or long continuing and lower peak currents [*Bell et al.*, 1998]. Fast charge removal leads to diffuse glow breakdown at higher altitudes and longer continuing currents with large charge removal allow sufficient electric field to initiate streamers at lower altitudes [*Barrington-Leigh and Inan*, 2001]. It appears that those sprites observed in the July 2 storm were mostly diffuse glow discharges while those of the July 4 storm involved both diffuse glow and streamer processes.

[16] Due to the wide FOV of the photometer, the photometric recordings during the July 4 storm are likely dominated by bright streamer processes at lower altitudes. Hence, the fact that the observed optical decay time constants are slower than minimum attachment time constants is in accordance with that expected for streamer processes [*Barrington-Leigh et al.*, 2002]. On the other hand, the optical decay time constants observed in the July 2 storm appear to be solely due to diffuse glow discharge. At the high altitudes of diffuse glow processes, the dielectric relaxation rate is much faster than that of attachment and is the dominant time constant. It may thus be possible to use photometric recordings of sprites to distinguish between streamer and diffuse glow processes by examining the optical brightness decay time constants. Precise measurements of these time constants may potentially be used for remote sensing of atmospheric parameters such as conductivity and minimum attachment time constants.

[17] **Acknowledgments.** This work was supported by the Office of Naval Research under grant N00014-94-1-010 and by the National Science Foundation under grant ATM-9908766. We are grateful to Dr. Ken Cummins for providing NLDN data, Dr. Walt Lyons and Tom Nelson for hosting our experiment at Yucca Ridge Field Station, and Dr. Victor Pasko, Dr. Steve Cummer and Wenyi Hu for advice on data analysis.

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