Submillisecond Resolution Lightning Currents and Sprite Development: Observations and Implications

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Abstract. We analyze synchronized high speed video images and ELF-VLF radio emissions from 11 sprite clusters observed on 6 October 1997. Quantitative analysis shows that vertical lightning charge moment changes of 150–1100 C·km occurred before the optical emissions reached their peak with delays of 2–11 ms from the lightning discharge. This threshold unexpectedly decreases with increasing delay from parent lightning to peak emissions. We also find that sprite charge moment change and minimum sprite altitude are not well correlated with the vertical charge moment change in the parent discharge. These observations do not agree well with present sprite generation models, and we suggest that streamer development and horizontal lightning charge motion can play a significant role in sprite generation.

Introduction

The leading theories of sprite generation are based on the production of large, quasi-static electric fields above thunderstorms following large movements of charge to the ground or distant cloud regions. These electric fields may accelerate thermal electrons to energies of a few eV which are required to generate light and ionization (conventional breakdown) [*Fernsler and Rowland*, 1996; *Pasko et al.*, 1997], and they may also accelerate MeV electrons produced by cosmic rays into an upward propagating, avalanching beam of runaway electrons (runaway breakdown) [*Lehtinen et al.*, 1997; *Yukhimuk et al.*, 1998]. A critical parameter in each of these theories is the electric charge moment change created by the parent lightning discharge, which is directly related to the quasi-static mesospheric electric field thought to be the driving force in sprite generation. Measurements of the lightning charge moment change associated with sprite clusters provide quantitative constraints on these theories. Techniques for remotely measuring vertical charge moment change have been developed [*Cummer and Inan*, 1999] and implemented [*Cummer et al.*, 1998; *Bell et al.*, 1998], but the difficulty in identifying precise sprite onset times from the standard 33 ms resolution video observations has made it difficult to measure accurately the charge moment thresholds required for sprite initiation. High speed photometer observations have been used to identify precisely sprite cluster onset times and relate them to lightning current moment waveforms [*Cummer et al.*, 1998], but some theories predict that the minimum altitude of sprite emissions depends strongly on the magnitude of the charge moment change [*Pasko et al.*, 1997]. It is thus important to measure simultaneously the lightning charge moment change and the vertical extent of the optical emissions, which cannot be done with a single photometer channel.

The combination of extracted current moment waveforms and photometer observations have also confirmed the existence of large electrical currents flowing in sprites themselves [*Cummer et al.*, 1998], an idea which had been proposed some time before [*P. Krehbiel*, personal communication, 1996]. However, the relationship of this sprite current to sprite development has not been investigated because of a lack of optical observations with sufficient spatial and temporal resolution.

In this work, we use synchronized high speed optical and radio observations to measure the vertical lightning charge moment change associated with sprite clusters, to examine the relationship of charge moment and altitude distribution of optical emissions, and to investigate the relationship of sprite current and sprite morphology. As will be shown below, the observations do not agree well with present theories, indicating that unconsidered processes are involved in sprite generation.

Instrument Description

Simultaneous lightning-related optical and ELF-VLF radio measurements were made at the Langmuir Laboratory, New Mexico Tech, on October 6, 1997. A high speed video camera (operated for the events presented here at 2000–4000 frames per second and described in detail by *Stanley et al.* [1999]) on loan from Bill Abrahams of Speed Vision Technologies recorded the optical development of sprites with high temporal resolution. A single wide horizontal slit photometer, which was aligned with the video camera, measured sprite cluster brightness variations with higher time resolution. Broadband magnetic field ELF-VLF sferic waveforms were recorded with a receiver and loop antennas on loan from Stanford University. Time synchronization was provided by a GPS receiver.

The photometer and ELF-VLF sferics were sampled for 10 ms at 500 kHz and for 300 ms at 10 kHz. The periodic powerline noise was removed from the field measurements by simple subtraction of a noise-only waveform. The receiver had a -3 dB low frequency cutoff at 350 Hz and provides usable signal down to ~50 Hz for the events examined. We estimate the absolute magnetic field intensity calibration error to be approximately 20%, and the measured charge moment changes presented here are thus equally uncertain. To produce the altitude labels on the images, we assume that

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the sprite clusters are centered directly over the parent discharge, whose location is determined by the National Lightning Detection Network (NLDN), and we account for atmospheric refraction. Range errors of 40 km correspond to altitude errors of 6 km at observation distances of ~900 km.

Data Analysis

The observed sprite-associated ELF sferics were quantitatively analyzed to extract the lightning current moment (current times vertical channel length) waveform which radiated them. This technique is described in detail by *Cummer and Inan* [1999] and was used previously by *Cummer et al.* [1998]. The receiver frequency response and noise level limit the current extraction to currents lasting up to approximately 10 ms after the discharge onset. The extracted current moment represents the actual current flowing between the cloud and ground and does not include any image charge effects. The GPS time-alignment of the extracted current moment waveforms and the high speed video images allow us to determine, within the time resolution of the high speed video, the temporal development of the sprite cluster and therefore determine the details of the relationship between lightning charge moment, sprite initiation, and sprite development. The time scale is not shifted for any time of flight effects and thus the current and optical emissions represent those that would be observed simultaneously by hypothetical in situ detectors.

Figure 1 shows the time-aligned current moment waveform, the cumulative charge moment variation (defined as the time integral of the current moment), the uncalibrated photometer-observed brightness, and the high speed video images for a sprite cluster which occurred in response to a positive cloud to ground (+CG) discharge 880.2 km from the receiver. This event is representative of those observed on this day. The development of these sprites, which is slow enough that it is well-resolved by the high speed video, follows the general pattern described by *Stanley et al.* [1999]. A single sprite initiates at 78 km altitude in the first image and additional sprites initiate 1 ms later between 74 and 82 km altitude in the second image (the intervening image was omitted). The additional sprites extend vertically in the next image, with the short persistence typical of tendrils evident in the downward development into later frames. The sprite cluster reaches peak brightness 4.3 ms after the discharge, with emissions extending from 48–84 km, and then decays in brightness. This complicated sequence of events highlights the difficulty of precisely defining "sprite onset".

As has been observed before [*Cummer et al.*, 1998; *Reising et al.*, 1999], the second peak in the current moment waveform varies almost linearly with the overall sprite cluster brightness recorded by the photometer, indicating that the source of this second current peak is current in the sprites themselves (i.e., the sprite current). We separate probable lightning and sprite current by assuming that the lightning current moment varies linearly after the first millisecond of the discharge. Thus the dotted line in Figure 1 separates the sprite current moment from the lightning current moment.

With this division, the vertical lightning charge moment change before this sprite cluster achieved peak brightness was 820 C·km. We find a peak sprite current moment of 300 kA·km and a total sprite charge moment change of 390 C·km. Assuming that the current flows uniformly throughout the observed ~35 km vertical extent of the sprite cluster, these magnitudes are equivalent to 8.6 kA and 11.1 C and are comparable to those in an ordinary CG discharge. From the images, it is clear that the sprite current intensity varies as the brightness of the upper portion (above ~50 km altitude) of the sprites, while sprite tendrils (seen in the fourth image between 40 and 50 km altitude) dim significantly before the sprite current reaches its peak. This sequence is typical of the other sprite clusters observed on this day, and indicates that the sprite current flows in this upper part of sprites and is not associated with the downward moving tendrils which fade before the upper portion brightens.

Lightning-Sprite Relationship

Employing the above procedure for separating sprite and lightning currents, Figure 2 shows the vertical lightning

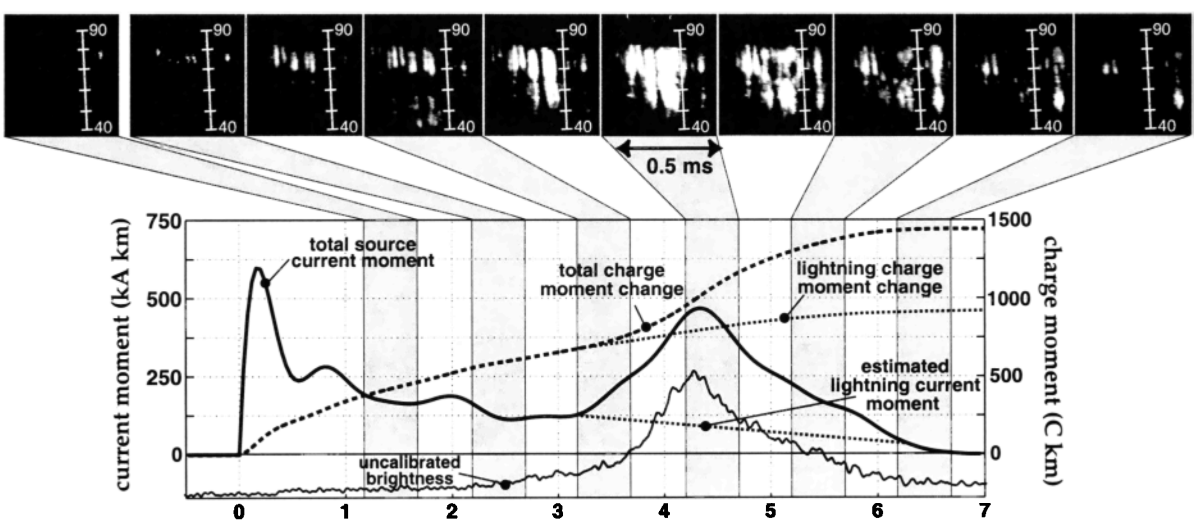

Figure 1. Time-aligned high speed video images, photometer-observed brightness, lightning and sprite current moment waveform, and cumulative charge moment change from a sprite cluster on 6 Oct 1997, 04:45:59.10691 UT. The contrast of the first two images is enhanced to highlight the optical emissions.

charge moment change at peak sprite cluster brightness as a function of the delay from +CG onset to peak sprite cluster brightness for 11 sprite clusters. We excluded 4 observed sprite clusters that were significantly delayed (>40 ms) from their parent CG discharge because of the difficulty in accurately measuring vertical currents from ELF measurements on time scales this long [*Cummer and Inan*, 1999]. We use the time of peak brightness as a reference as it is well-defined, easily determined from the video images, and easily compared with simulations. In the events analyzed here, the optical emissions were first visible ~1.0–2.5 ms before the peak brightness was achieved and began after lightning vertical charge moment changes 75–95% of those at peak sprite cluster brightness. The initial breakdown altitudes and charge moment changes are in rough agreement with those expected from calculations [*Fernsler and Rowland*, 1996; *Pasko et al.*, 1997].

Each point in Figure 2 is labeled with the lowest emission altitude at the time of peak brightness. As indicated by the images in Figure 1, this is also the lowest altitude of sustained (>1 ms) emissions. It should be emphasized that this altitude is not the lowest altitude reached by the downward moving tendrils, which is often more than 10 km lower than the lowest altitude of sustained emissions. The highest emission altitude for each sprite cluster was between 81 and 89 km. The data show that vertical charge moment changes of 800–1100 C·km in 2–4 ms are associated with sustained emissions at altitudes as low as 50 km. This is a factor of 2 and 10 times smaller than the vertical lightning charge moment changes required to produce runaway and conventional breakdown at 50 km, respectively. Additionally, neither the conventional nor the runaway breakdown model reproduces the observed spatial and temporal sprite dynamics in which downward-moving tendrils extend to ~40 km altitude and subsequent bright emissions persist at all altitudes (~50–85 km) for more than 1 ms.

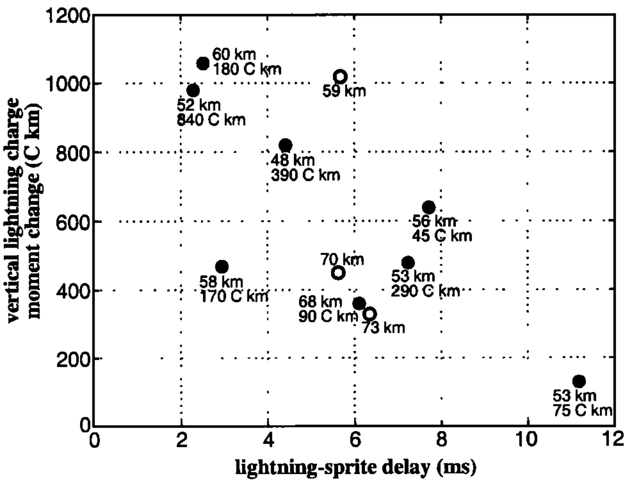

Figure 2. Vertical lightning charge moment change as a function of lightning-sprite delay. Filled circles denote sprite clusters with detectable sprite currents, while open circles denote those without. Each point is labeled with the lowest altitude of bright emissions at the time of peak sprite cluster brightness and with the total sprite charge moment change associated with the cluster.

A possible source of this disagreement is that important physical processes are not accounted for by current models. This is true to at least some extent, as recent observations show that sprites are composed of fine streamer structure rather than diffuse glows [*Inan et al.*, 1998; *Stanley et al.*, 1999]. While the upward-moving nature of the sustained emissions [*Stanley et al.*, 1999] implies that breakdown occurs near the bottom of the sprite (~50 km), the small-scale streamer nature of these emissions [*Inan et al.*, 1998] also implies that breakdown need only occur in a small region to produce visible emissions throughout a large volume of space. This breakdown occurs not in unperturbed air but in regions through which the downward propagating tendrils passed only ~ 1 ms previously. The downward tendrils may create significant conductivity and charge inhomogeneities in this region that enhance the local electric field and aid in the initiation of these upward streamers.

Another possibility is that processes other than vertical charge motion contribute to the mesospheric electric field and thus breakdown. This idea is supported by the data in Figure 2 that show that the vertical lightning charge moment change associated with sprite clusters decreases with increasing lightning-sprite delay. The t-test [*Press et al.*, 1992, p. 631] shows that this downward trend is significant at the 2% level, and the temporal uncertainty for each point due to the image integration time is between 0.25 and 0.5 ms and thus does not affect this conclusion. It should be mentioned that the sprite cluster that reached peak brightness after only 150 C·km appeared 80 ms after another sprite cluster in the same general location, and residual fields or charge may be partly responsible for the unusually low charge moment threshold. If only vertical charge motion contributes to the sprite-producing mesospheric electric field, then the lightning charge moment change required to create above-threshold mesospheric electric fields should be relatively constant with respect to the lightning-sprite delay. Also, we observe in Figure 2 that discharges which apparently move vertically the same charge in the same time produce sprite clusters with drastically different lower altitudes and overall brightness, again indicating that some factor other than total vertical charge moment change contributes significantly to sprite generation. These facts indicate that horizontal charge motion, which radiates weakly at ELF and is thus difficult to observe remotely but produces mesospheric electric field enhancements in much the same manner as vertical charge motion, can contribute to sprite generation, as was suggested by *Bell et al.* [1998]

Sprite Currents

Each point in Figure 2 is also labeled with the total sprite charge moment change associated with each. The sprite current, when present, typically lasts from 2–4 ms and is roughly linear in its growth and decay (see Figure 1), which means that the peak sprite current moment in kA·km is approximately one-half to one times the total sprite charge moment change in C·km. The sprite charge moment change magnitudes, spanning a few tens to a few hundred C·km, are in general agreement with observations reported earlier by *Cummer et al.* [1998] and *Reising et al.* [1999].

Figure 2 shows that large sprite charge moment changes are preferentially produced by sprite clusters which extend to low (~50 km) altitudes; the 3 largest sprite moment changes were produced by clusters which extended below 53 km, while only one of the 4 clusters not reaching 60 km produced a detectable sprite current. When coupled to the observation of *Reising et al.* [1999] that sprite charge moment is strongly correlated with spatially-summed sprite brightness, this indicates that the quality most strongly related to sprite current and charge moment magnitude is sprite "spectacularity", i.e., a bigger, brighter, and more vertically-extended sprite cluster will generally contain larger sprite currents. However, Figure 2 also shows that the sprite charge moment magnitudes are not simply related to vertical lightning charge moment changes. If only vertical moment lightning changes drive the sprite current, then they should be roughly linearly related [*Pasko et al.*, 1998]. This also indicates that some other factor often contributes significantly to sprite generation. As before, one possibility is that horizontal currents are driving a significant fraction of the mesospheric electric field (and thus sprite current) in some sprites, while another is that processes important in controlling breakdown are not included in present models. Slowly varying linear horizontal currents over a conducting surface (i.e., the ground) are very difficult to detect remotely as their quadrupole charge distribution (due to the image charges in the ground) does not efficiently radiate electromagnetic waves. Measurements of the electrostatic field change in the immediate vicinity of a sprite-associated discharge combined with remote measurements of vertical charge motion would help determine whether horizontal charge motion contributes to the electric field change responsible for the sprite.

Conclusions

We analyzed the high speed video images and ELF radio emissions associated with 11 sprite clusters. The temporal variation of the sprite current and the optical emissions show clearly that the sprite current flows in the upper portion of sprites (from ~85 to 50–60 km altitude) when they brighten after the tendrils have propagated downward and faded. Peak sprite cluster brightness was achieved after 150 to 1100 C·km of vertical lightning charge moment change with lightning-sprite delays of 2–11 milliseconds. These charge moment changes are substantially smaller than those required by runaway and conventional breakdown to produce the observed sustained optical emissions at altitudes as low as 50 km. This discrepancy may exist because models do not yet include the complicated streamer development now known to be a major component of sprites.

We find that the apparent vertical charge moment threshold for sprite generation unexpectedly decreases with increasing lightning-sprite delay. The magnitudes of the observed sprite charge moment changes of 50–840 C·km are not well correlated with the vertical lightning charge moment change, but they are generally larger in sprite clusters which extend to altitudes below ~55 km. Also, we observe that discharges with similar total vertical lightning moment changes can produce sprites with very different vertical extents and brightnesses. These observations are consistent with the generation of significant mesospheric electric fields by horizontal currents in some sprites, but we cannot rule out other processes as the explanation for the observations. The sprite image sequences and measured vertical current moment waveforms presented here represent the output and (at least) partial input, respectively, of sprite generation models and thus can be used to test directly present and future sprite models.

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