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ELF Radiation Produced by Electrical Currents in Sprites

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Abstract. Measurements of ELF-radiating currents associated with sprite-producing lightning discharges exhibit a second current peak simultaneous in time with sprite luminosity, suggesting that the observed ELF radiation is produced by intense electrical currents flowing in the body of the sprite.

Introduction

Luminous high altitude glows referred to as sprites provide dramatic evidence of electrodynamic coupling between tropospheric lightning and the overlying mesosphere and lower ionosphere. Proposed generation mechanisms for sprites include heating of ambient electrons by quasi-electrostatic (QE) thundercloud fields [e.g. *Pasko et al.*, 1997b], runaway electron processes driven by the same QE fields [*Bell et al.*, 1995; *Roussel-Dupré and Gurevich*, 1996], and heating by lightning electromagnetic pulses [e.g. *Milikh et al.*, 1995]. Sprites are observed in association only with intense cloud-to-ground (CG) lightning discharges which strongly radiate electromagnetic energy in the ELF ($\lesssim$1.5 kHz) frequency range [*Boccippio et al.*, 1995], indicative of continuing currents lasting over time scales of at least a few ms [*Reising et al.*, 1996]. ELF radio atmospheric waveforms originating in sprite-producing lightning discharges have been used to infer the magnitude of the charge removed [*Cummer and Inan*, 1997; *Bell et al.*, 1996]. Unusual features of some of these waveforms have raised the question of possible ELF electromagnetic radiation from the sprite itself [*P. Krehbiel*, personal communication; *Sukhorukov and Stubbe*, 1997]; however, up to now, no experimental evidence of electromagnetic radiation from sprites has been published.

In this paper, we present the first experimental evidence that electrical currents may be flowing in the body of sprites, producing ELF electromagnetic energy at levels comparable to that produced by the parent CG lightning discharge. The evidence is in the form of simultaneous observations of ELF radio atmospheric waveforms and photometric measurements of sprite luminosity which exhibit a remarkable temporal association. The estimated conduction current densities that are required to produce the observed ELF radiation are consistent with the QE field levels expected to occur at 70-80 km altitudes for relatively bright sprites [*Pasko et al.*, 1997b].

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Experimental Data

Sprite brightness was measured with ~30 μs time resolution by a ~3.5° by ~7° field-of-view (FOV) photometer as part of the Fly's Eye instrument operated during the summer of 1996 at Yucca Ridge, Colorado [*Inan et al.*, 1997]. To calibrate the observed brightness variations, the received light is necessarily averaged over the entire FOV of the photometer, implying that the actual peak sprite brightness is larger than the presented magnitudes. Continuous broadband ELF/VLF (5 Hz-22 kHz) observations were made at Stanford University using a system described in *Cummer and Inan* [1997]. Continuous broadband VLF (300 Hz-22 kHz) intensity was also measured at Yucca Ridge and recorded simultaneously with the Fly's Eye optical data. This on site recording of the causative atmospherics was used to unambiguously time align the Stanford and Yucca Ridge data sets. All of the data reported in this paper were recorded on July 22, 1996. A map of the observation sites and of the locations of the three sprites to be examined (as well as the millisecond-accurate lightning discharge times as recorded by the National Lightning Detection Network, which is the time by which the events will be referred in this paper) is shown in Figure 1.

Data Analysis

Sprite-producing sferics observed at Stanford were aligned with the same sferic observed at Yucca Ridge on the basis of the well-defined onset of the sferics. This onset is determined by the highest frequency components measured (~20 kHz), which propagate nearly at the speed of light with negligible dispersion over the distances of interest here.

The current-moment waveform which radiated the ELF/VLF sferics observed at Stanford was extracted by decon-

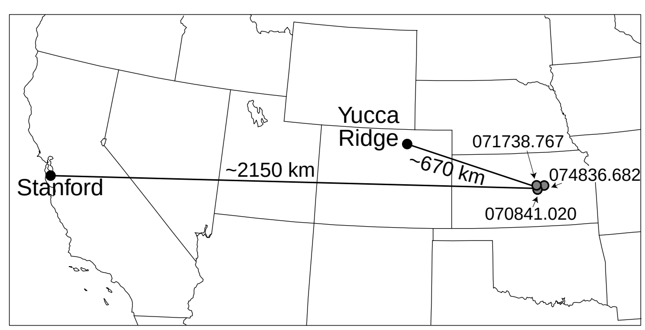

Figure 1. Map showing optical and VLF receiving site (Yucca Ridge), ELF receiving site (Stanford), and the locations and NLDN times (in UT) of the three sprite events to be examined.

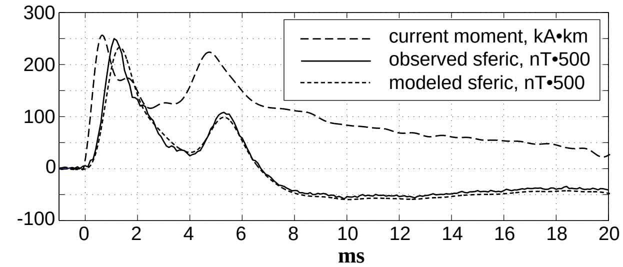

Figure 2. The extracted current-moment waveform, the observed ELF sferic in nanotesla (nT), and the modeled ELF sferic for the 07:48:36.682 sprite.

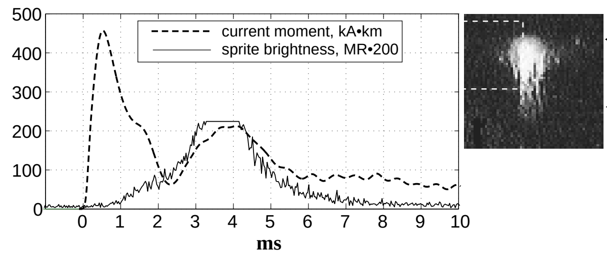

Figure 4. The extracted current-moment and sprite brightness waveforms, time-aligned as at the source, for the 07:08:41.020 sprite. The inset shows a video image of the sprite and the outline of the field-of-view of the photometer.

volving the observed ELF sferic waveform with a modeled ELF impulse response. This method is similar in principle to that used by *Cummer and Inan* [1997], who extracted parameters of a model source waveform to obtain good agreement between theory and observation. In this work we execute the necessary deconvolution using the CLEAN method [*Teuber*, 1993, p. 216] to obtain a more general current-moment waveform.

Figure 2 shows, for a sprite-producing discharge observed at 07:48:36.682, the filtered Stanford ELF sferic, the extracted current-moment waveform, and the modeled sferic obtained from the convolution of the modeled ELF impulse response and the extracted current. The modeled and observed ELF sferics agree well, verifying the accuracy of the extracted current-moment waveform. The curves are aligned so that the speed-of-light delay (since the sferic was observed ~2000 km from the source current) is removed. The apparent remaining delay is due to the fact that the group velocity in the Earth-ionosphere is slightly less than the speed of light for these frequencies.

Figure 3 shows plots of the source current-moment and sprite brightness for the same event, time-aligned as they would be at the source location. Also shown is the sprite image taken by the video camera at Yucca Ridge, with the dotted line outlining the field of view of the Fly's Eye photometer element with which the sprite brightness was measured. The altitude of the sprite was estimated by assuming that the sprite occurred directly over the NLDN-recorded location of the associated CG lightning discharge. The simultaneity of the onset, maximum, and end of the second peak of the source current and sprite brightness at ~5 ms after the start of the discharge is striking. This simultaneity (at the source) indicates that the observed ELF sferic radiation appears to be produced by a source current proportional to the spatially-integrated sprite brightness, most likely flowing in the body of the sprite itself.

A second example of a such a temporal association is shown in Figure 4 for a sprite-producing discharge observed at 07:08:41.020 UT. The observing photometer for this sprite (which is the same as for the next case) was in a different location and had a different sensitivity than that for the previous example. A distinct second peak in the extracted source current-moment waveform is once again temporally aligned with the sprite brightness, though at a different delay from the start of the discharge than for that in Figure 3. The clipping of the brightness is caused by saturation of the photometer.

A third association between ELF and sprite brightness is shown in Figure 5 for the sprite-producing discharge observed at 07:17:38.767. In this case, the broad second current-moment peak reached its maximum ~5 ms before the observed onset of sprite brightness. We attribute this to the fact that there are several distinct sprite elements in the video image, not all of which were in the photometer FOV. If the elements on the right appeared first and radiated ELF while not in the FOV, then the current would appear to flow before the sprite appeared in the photometer. The brightness endures for more than 30 ms, and the source current lasts equally long and decays at a similar rate. As in the other two cases above, the radiating current appears to be proportional to the brightness.

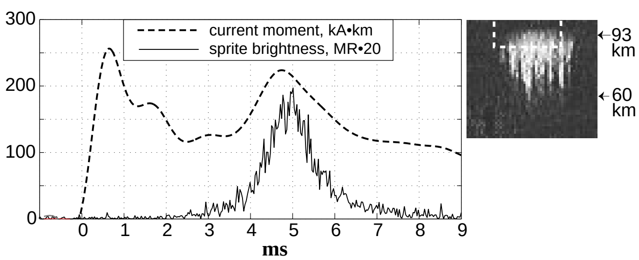

Figure 3. The waveforms for the extracted current-moment and sprite brightness in MegaRayleighs (MR), time-aligned as at the source, for the 07:48:36.682 sprite. The inset shows a video image of the sprite and the outline of the field-of-view of the photometer.

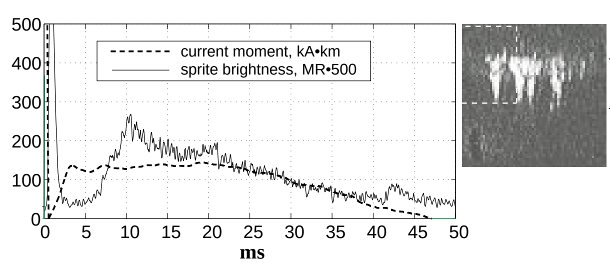

Figure 5. The extracted current-moment and sprite brightness waveforms, time-aligned as at the source, for the 07:17:38.767 sprite. The inset shows a video image of the sprite and the outline of the field-of-view of the photometer.

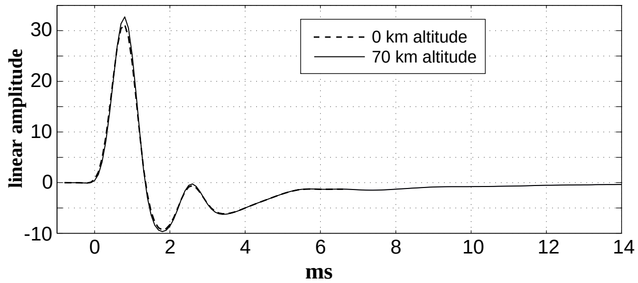

Figure 6. Theoretical ELF sferics for impulsive discharges at altitudes of 0 and 70 km.

Discussion

The data presented above are strongly suggestive of a physical relationship between the ELF-radiating current (specifically the second major peak) and the brightness of the optical emissions constituting the sprite. Examination of the ELF/VLF sferics received at Stanford shows that there is no significant VLF radiation associated with this second peak, indicating that the source current for this ELF radiation peak must turn on and turn off slowly ($\gtrsim$0.5 ms) and that this peak is not due to a second, distinct lightning discharge occurring within a few ms after the initial CG discharge.

The fact that conduction current in the sprite appears to be roughly proportional to sprite brightness is not entirely unexpected in the context of theory. The luminosity of the sprite is believed to be due to the first positive band of N_2 excited by heated electrons, which are created either by QE heating [*Pasko et al.*, 1997b] or as secondaries of a runaway electron beam [*Bell et al.*, 1995; *Taranenko and Roussel-Dupré*, 1996]. Since the heating and cooling times for ambient electrons at the altitudes of interest occurs over time scales much less than a millisecond, at any given point the luminosity is proportional (though not linearly) to the local electric field E [*Pasko et al.*, 1997b] and thus also to the conduction current density $J_c = \sigma E$, with σ being the local conductivity.

As observed at a distant site, ELF source currents from cloud to ground and currents high in the atmosphere radiate nearly identically. Figure 6 shows the similarity of the theoretical ELF magnetic field waveforms as received at Stanford from vertical impulsive current-moments at the ground and at 70 km altitude (representative of sprite altitudes) under the ionospheric electron density profile used in *Cummer and Inan* [1997]. This fact makes it difficult to distinguish between source currents at cloud or sprite altitudes solely on the basis of observed ELF signatures. We cannot entirely rule out the possibility that the sprite-correlated vertical current flowed between the cloud and ground and not in the sprite. However, since sprite models indicate that charge (not current) is the quantity which most directly controls sprite brightness [*Pasko et al.*, 1997b], the observed correlation between brightness and current strongly suggests that the current is indeed flowing in the sprite.

The straightforward relationship between ELF peak intensity and source current intensity enables a robust estimate of the total vertical current flowing throughout the body of the sprite based on the observed ELF radiation. Since the ELF wavelengths (300 km at 1 kHz) are much larger than either the vertical or horizontal spatial extent of the sprite, the spatially- integrated current throughout the entire sprite acts as a short, narrow, and vertical ELF dipole antenna. ELF radiation from currents above ~70 km (for the assumed ionospheric conductivity) is not as simply described because these currents are within a significantly conducting region. This would reduce the ELF radiation observed on the ground from such currents, but for a first-order solution, we neglect this effect.

We estimate the vertical sprite currents by assuming that they flow downward uniformly in a channel of 30 km height (approximately the vertical extent of the observed sprites) for the duration of the second current peak, and that ~50% of the measured peak current moment is due to currents in the sprite (the remainder would be smoothly decaying continuing currents in the lightning stroke common in positive discharges [*Uman*, 1987, p. 200]). This implies that the peak vertical current integrated over the entire horizontal cross section of the sprite would be 3.3 kA, 3.3 kA, and 1.6 kA, respectively, for the three cases presented in Figures 3–5. Based on the duration of these currents, the total ionospheric charge transfer for these three events would be 5 C, 6 C, and 42 C. These estimates may be low because of the effect described above where currents above ~70 km are less effective radiators than those below.

Since the average width of the three sprites is ~35 km, we assume that the inferred total source-current of 3.3 kA is uniformly distributed over a circular cross-section of 17 km radius, in which case the current density within the sprite body that is required to produce the observed ELF second peak is of order 3 μA/m^2. For an ambient conductivity of σ=10^{-7} S/m at 80 km altitude [*Pasko et al.*, 1997b], this current density of 3 μA/m^2 corresponds to an electric field of 33 V/m, consistent with QE fields predicted by runaway electron and QE heating models [*Bell et al.*, 1995; *Pasko et al.*, 1997b] during the sprite event for typical sprite luminosities. The precise means by which this conduction current reaches lower altitudes appears to be an open question. For example, at 60 km altitude, with an ambient conductivity of 10^{-9} S/m, a current density of 3 μA/m^2 corresponds to an electric field of 3.3 kV/m, substantially larger than the maximum QE fields at this altitude even under conditions of the most intense uniform heating [*Pasko et al.*, 1997b], suggesting that larger conductivities are required. The existence of filamentary streamer- like columns of ionization with high conductivity at lower sprite altitudes has been theoretically proposed [*Pasko et al.*, 1997a] and is consistent with the documented spatial structure of sprites [*Taylor et al.*, 1996].

In their measurements of sprite-producing lightning currents, *Cummer and Inan* [1997] assumed that all of the ELF-radiating current was part of the lightning current. The fact as suggested by this work that some of this current may have been in the sprite itself would reduce their measured values of total lightning charge transfer responsible for sprites. However, this does not change their conclusion that some of the sprites observed were associated with CG charge transfers less than predicted by existing theories [*Pasko et al.*, 1997b; *Roussel-Dupré and Gurevich*, 1996].

Conclusions

Simultaneous measurements of bulk sprite brightness and ELF-radiating current moment waveforms for three sprite events observed on July 22, 1996 strongly suggest that the pronounced second peak in the ELF radiation is produced by a source current moment peak that appears to be proportional in amplitude to the brightness of the sprite. The lack of any associated VLF radiation indicates that these secondary peaks are not likely to be due to subsequent, distinct lightning discharges. The simplest explanation for the observed temporal association is that the source currents for this second peak flow in the body of the sprite itself. The spatially-integrated peak vertical current flowing in the three sprites studied is estimated to range between 1.6–3.3 kA. These currents represent a potential new source of ELF electromagnetic waves launched into the magnetosphere as a result of lightning discharges. Such injected ELF waves may then interact with energetic radiation belt particles and cause them to precipitate out of their trapped orbits, as so whistler waves originating in conventional lightning discharges [*Burgess and Inan*, 1993]. Further measurements of the sprite-produced ELF radiation and thus the electrical currents in sprites may also provide additional insight into the internal dynamics and production mechanisms of sprites.

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