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Statistical Characteristics of Sprite Halo Events Using Coincident Photometric and Imaging Data

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[1] Sprite halos are brief, diffuse flashes, which occur at the top of a sprite and precede the development of streamer structures at lower altitudes. We have investigated the characteristics of sprite halos in detail using coincident photometric and imaging data obtained during the Sprites'96 and '99 campaign in Colorado and Wyoming, USA. It is found that the average altitude of the centroid of the halo emission and the mean horizontal diameter of the halo events are ~80 and ~86 km, respectively, while the average speed of the descending motion of the sprite halos was $\sim 4.3 \times 10^7$ m/s. It was also found that the peak current intensity of the causative CG decreases with time delay from the onset of the sferics. *INDEX TERMS:* 1854 Hydrology: Precipitation (3354); 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology. **Citation:** Miyasato, R., M. J. Taylor, H. Fukunishi, and H. C. Stenbaek-Nielsen, Statistical Characteristics of Sprite Halo Events Using Coincident Photometric and Imaging Data, *Geophys. Res. Lett.*, *29*(21), 2033, doi:10.1029/2001GL014480, 2002.

1. Introduction

[2] Sprites are luminous discharges extending in height from mesospheric to stratospheric altitudes (range ~40–90 km) and occurring above large thunderstorm systems [e.g., *Sentman et al.*, 1995; *Lyons*, 1996]. On the other hand, elves were first observed from the ground during the Sprites'95 campaign using a multi-channel, high-speed photometer and an image-intensified CCD camera from Yucca Ridge Field Station, Colorado [*Fukunishi et al.*, 1996].

[3] Observation techniques for sprites and elves have made remarkable progress recently, providing information both on the rapid spatial and temporal development of luminous glows and the ionization and heating processes. *Stanley et al.* [1999] reported the use of a high-speed (1000 frames per second), image-intensified video system for sprite observations. Using this system, *Barrington-Leigh et al.* [2001] demonstrated that a brief diffuse flash, which is referred to as a "sprite halo", occurs at altitudes from 70 to 85 km, preceding the development of sprites with streamer structures at lower altitudes. The sprite halo is a descending glow with lateral extent of ~40–80 km. An upward concave shape is sometimes evident in the sprite halo. *Barrington-Leigh et al.* [2001] explained that this curved-shape indicates that significant ionization occurs in the lower boundary of the sprite halos. *Stenbaek-Nielsen et al.* [2000] also recorded images of sprites at 1 ms resolution by a high-speed image intensified CCD camera. Using the same high-speed video system, *Wescott et al.* [2001] made three-dimensional triangulation of elves, sprite halos and sprite streamers.

[4] *Veronis et al.* [1999] developed a new two-dimensional cylindrically symmetric electromagnetic model which encompasses the effects of both the quasi-electrostatic (QE) field and the electro-magnetic pulse (EMP) process. This model can simulate the lightning-ionosphere interactions on time scales ranging from several microseconds to tens of milliseconds. They determined that the characteristics of elves observed by a high-speed photometer, such as lateral expansion, apparent downward motion, and duration are consistent with the result of the model simulation [*Veronis et al.*, 1999]. *Barrington-Leigh et al.* [2001] used this model to study the relationships between elves, sprite halos and sprite streamers. They suggested that elves are produced by EMP, while both the sprite halos and the streamers are produced by the QE fields under the condition that large charge moment changes occurring over relatively short timescales (~1 ms). They also suggested that charge moment changes exhibiting longer timescales (>1 ms) would produce only sprite streamers without a preceding sprite halo. Differences in the photometric signatures of elves and sprite halos observed by a vertical array photometer were theoretically predicted by *Barrington-Leigh et al.* [2001], but have yet to be verified.

[5] Since studies of sprite halos are still in their early stage, it is essential to investigate their characteristics in detail. In this paper we have analyzed coincident photometric and imaging data recorded during the Sprites'96 and '99 campaigns conducted in Colorado and Wyoming, USA, to determine the characteristics of sprite halos including their relationships to elves and sprite streamers.

2. Observations

[6] Observation using a high-speed vertical array photometer, with a time resolution of 50 μs and an image-intensified CCD camera, with a time resolution of 16.7 ms, were made from Yucca Ridge Field Station (YRFS, 40.7°N, 104.9°W), Colorado during several sprite campaigns carried out from 1996 to 1999. The array photometer has a square field-of-view of 10.7° by 10.7°, and consists of 16 individual horizontal array stacked in the vertical direction. Thus each channel of the array photometer has a rectangular field-of-view of 0.67°(vertical) by 10.7°(hori-(horizontal). We also operated intensified Isocon TV camera

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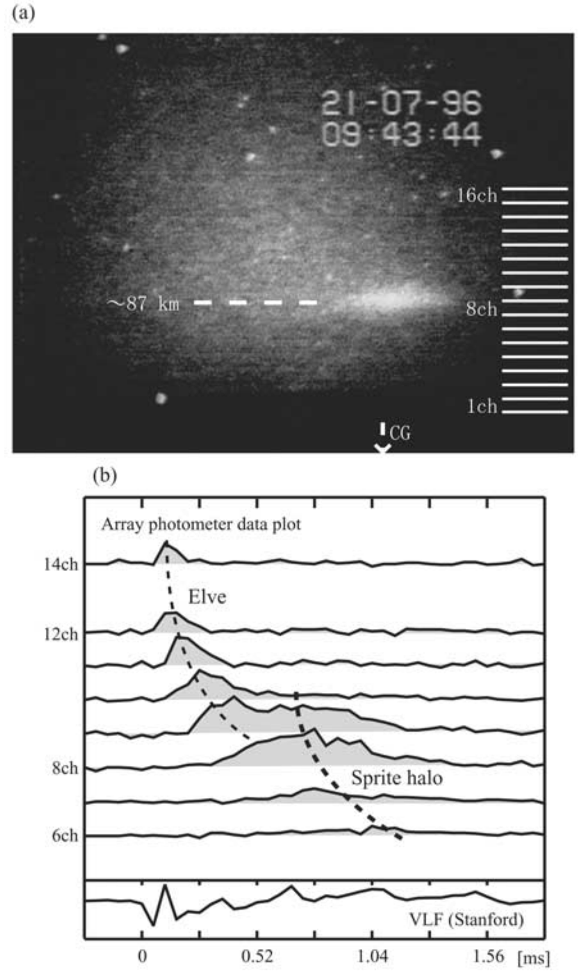

Figure 1. Example of a sprite halo without following sprite streamers, observed from YRFS at 09:43:37 UT on July 21, 1996. (a) Isocon camera image, and (b) array photometer data and VLF sferics waveform. The time after the VLF onset is displayed in milliseconds.

with a time resolution of 20 ms at YRFS in 1996 and a high-speed (1000 frames per second) image-intensified video system at the University of Wyoming Infrared Observatory (WIRO) in Wyoming in 1999.

[7] Figure 1a shows an example of a sprite halo event without following sprite streamers observed from YRFS at 09:43:37 UT on July 21, 1996. The coincident vertical array photometer data are presented in Figure 1b which shows that the initiation of the luminous glows started in the higher elevation channels and exhibited an apparent downward motion (channels 9–14). This glow is identified as an elve from its extremely short time delay of ~0.2 ms after the causative CG. There is no evidence of the elve in the video data due to its extremely short lifetime. The development of the sprite halo image in Figure 1a is indicated by the second set of downward moving perturbations in channels 7–9 of Figure 1b, during which the luminosity reaches a peak at ~0.7 ms after the onset of the causative sferics. To help illustrate this, we have displayed the 16 fields-of-view of the array photometer only in the vertical direction on the right side of Figure 1a The altitude range of the sprite halo emission and the azimuth of the CG are also indicated in the image. Almost all the sprite halo events occurred in association with positive CGs and we found only one event caused by a negative CG of −160 kA at 08:24:10 UT on July 21, 1996. The image and array photometer data of this event are shown in Figures 2a and 2b, respectively. It was found that the space-time structure of this event is very similar to that of the positive CG halo event presented in Figure 1, although an upward concave shape is evident in the video in this case.

[8] Figure 3a shows five consecutive 1 ms high-speed imager frames recorded from the Wyoming Infrared Observatory (WIRO), of a sprite at 07:00:12 UT on August 18, 1999. Array photometer data from YRFS corresponding to these image data are shown in Figure 3b. Note, in this case, the 16 fields-of-view of the array photometer have been superposed on the images in Figure 3a by comparing the high-speed imager data with image-intensified CCD data at YRFS. In the first frame the occurrence of a sprite halo is seen in channels 7–8, while in the second frame the sprite halo moves downward (channels 6–7) and sprite streamers begin to develop. In the third frame the sprite streamers develop further and the top of the sprite (hair) is enhanced (channel 8). In the fourth frame the sprite stream-

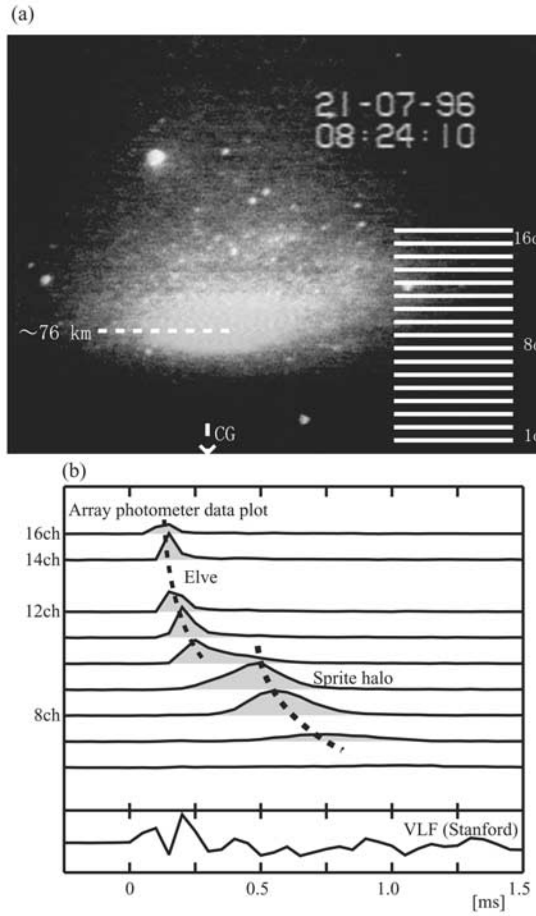

Figure 2. Example of a sprite halo induced by a negative CG, observed from YRFS, CO at 08:24:10 UT on July 21, 1996. (a) Isocon camera image, and (b) array photometer data and VLF sferics waveform.

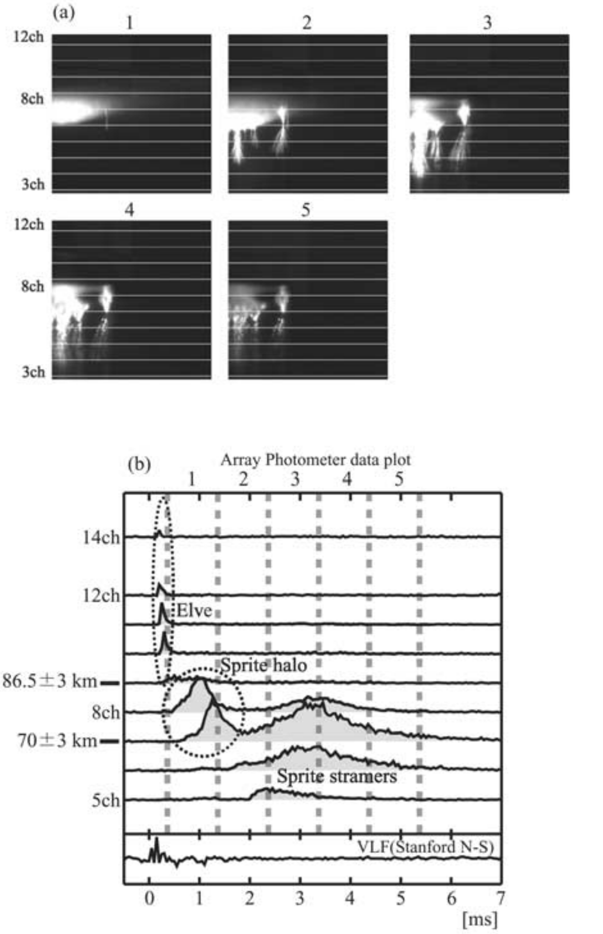

Figure 3. (a) High-speed imager data from WIRO, at 1 ms resolution showing a sprite event at 07:00:12 UT on August 18, 1999, and (b) associated array photometer data plot and VLF sferics waveform.

ers decay, but the hair of the sprite increases in luminosity. Finally the overall luminosity decays in the fifth frame. Note that brief luminosity enhancement evident in the higher elevation channels (channels 10–14) in Figure 3b is due to an elve which occurs ~0.2 ms after the onset of the causative sferics. This enhancement is not identified in the first image of Figure 3a probably due to its low luminosity. This event clearly demonstrates the importance of the array photometer and imager for distinguishing the temporal, spatial, and altitudinal structures of elves, sprite halos and sprite streamers.

3. Characteristics of Sprite Halos

[9] Using the array photometer and image-intensified CCD camera data obtained at YRFS in August 1999, we selected 89 sprite events for analysis. Out of these, we selected sprite halo events which have clear features of diffuse, disk-like glows with horizontal scales less than 120 km and apparent downward motions (indicated in photometer data). A total of 35 sprite halo events were found, which is ~39% of the observed sprite events. These 35 events were then classified into four cases: (1) sprite halo alone, (2) sprite halo with preceding elves, (3) sprite halo with preceding elves and following sprite, and (4) sprite halo with following sprite. The result of the analysis is summarized in Table 1. In comparison, Table 2 summarizes the occurrence rate of sprite halos on individual days during the Sprites'99 campaign. It was found that the occurrence rate of sprite halos is in the range 33–55% during this period.

Table 1. Occurrence Probability of Sprite Halos Classified Into Four Cases

Sprite halos alone	26%
Sprite halos with preceding elves	3%
Sprite halos with preceding elves and following sprites	34%
Sprite halos with following sprites	37%

Table 2. Occurrence Rate of Sprite Halos During the Sprites'99 Campaign

	Number of sprite halo events	Number of sprite events	Occurrence rate of sprite halos [%]
August 11, 1999	4	12	33
August 12, 1999	6	11	55
August 14, 1999	6	11	55
August 18, 1999	18	55	33

[10] Using these data, we have also estimated the altitude range and the horizontal scale of the halos, the time delay from the onset of causative sferics to the peak of the halo emission, the duration of the halos, and the speed of their downward motion. In these estimations, we have assumed that sprite halos are centered above the causative CGs and that the 'edge' of sprite halos is defined as the location at which the intensity drops to less than 30% from the peak intensity. The elevation of the center of each channel of the array photometer was then converted to altitude. The altitude range is defined by the starting and finishing altitudes of the downward motion observed by the array photometer. The peak current intensities of the causative CGs were obtained from the US National Lightning Detection Network (NLDN) data. These results are summarized in Table 3. The relationship between the time delays (T_{delay}) from the onset of the causative sferics to the peak current intensities (I_{peak}) of causative CGs is shown in Figure 4. It was found that I_{peak} decreases with increasing T_{delay}. Assuming a continuing current flow in the CG with a value of I_{peak} for the time interval T_{delay}, the charge, Q, removed from the thundercloud, is estimated as $Q = I_{peak} \times T_{delay}$. The

Table 3. Characteristics of Sprite Halos

Altitude : Starting	87.2 ± 3 km	(Mean of the centroid: 80.4 km)
: Finishing	73.0 ± 3 km	
Horizontal scale	50–110 km	(Mean: 85.5 km)
Time delay from the CGs	0.45–1.5 ms	(Mean: 0.85 ms)
Duration	0.6–2.2 ms	(Mean: 1.0 ms)
Speed of downward motion	$3.0–6.0 \times 10^7$ m/s	(Mean: 4.3×10^7 m/s)
Peak current intensity of CG	50–180 kA	(Mean: 98.6 kA)

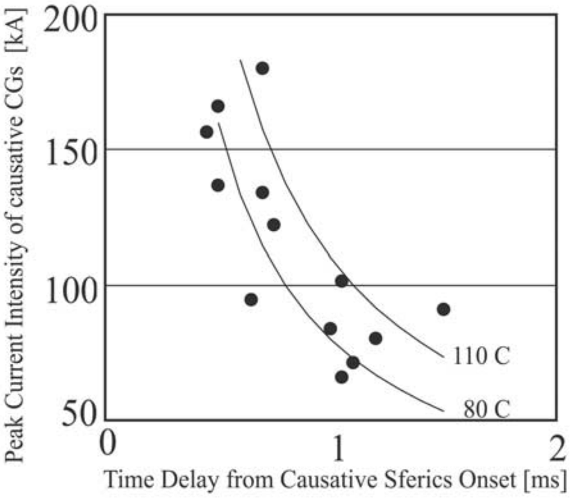

Figure 4. Relationship between the peak current intensities of the causative CGs and the time delay from the onset of causative sferics to the peak of sprite halo emission.

two curves denoted in Figure 4 represent this relation for Q = 80 and 100 C, respectively.

4. Discussion and Summary

[11] The average altitude of the centroid of the halo emission and the mean horizontal scale of the halo emission were found to be ~80 and ~86 km, respectively. These results are consistent with the triangulation study of *Wescott et al.* [2001], which indicated that sprite halos have a mean altitude of ~78 km with a 1/e thickness of ~4 km and a Gaussian 1/e diameter of ~66 km. Our results are also consistent with those obtained numerically by *Barrington-Leigh et al.* [2001], who estimated that the altitude and lateral extent of sprite halos is ~70–85 km and ~40–70 km, respectively. Thus the spatial structures of halos support the QE model. In this model, the sprite halo is produced by quasi-electrostatic (QE) field, in contrast with an elve which is produced by an electromagnetic pulse (EMP). Another important result obtained in this study is a fact that sprite halo events with no associated sprite streamers have a significant occurrence probability of ~26%. *Barrington-Leigh et al.* [2001] pointed out that lightning discharges with a fast (<1 ms) charge moment change are sufficient to cause sprite halos at higher altitudes where the threshold for ionization and optical excitation is lower, but if lightning currents do not continue to flow, there may be insufficient electric field to initiate sprite streamers. Thus our result suggests that the fast (<1 ms) and large charge moment changes, resulting from a sudden removal of charge due to CG discharges, occur in ~1 in 4 intense CG discharges. This said that further statistical studies should be performed to determine whether scattering in the occurrence rate of sprite halos on individual days (shown in Table 2) results from the differences in their parent thunderstorm systems or not.

[12] The array photometer data have provided accurate information on the speed of descending motion and the time delays from the onset of the causative sferics to the peak of sprite halo emissions. The average speed of descending motion of sprite halos is estimated as $\sim 4.3 \times 10^7$ m/s. This is consistent with the result obtained from the numerical simulation by *Barrington-Leigh et al.* [2001] and the observational evidence given by *Wescott et al.* [2001]. They both pointed out that sprite halos descend in altitude in rough accordance with the local electrical relaxation time $\tau = \varepsilon_0/\sigma$ (where ε_0 is the permittivity of free space and σ is the local conductivity). The relaxation time is estimated to be $\sim 10^{-2}$ and $\sim 10^{-4}$ s at altitudes of 75 and 85 km, respectively, when the QE field E is equal to the breakdown field E_k.

[13] The peak current intensities of the CGs inducing the sprite halos was found to be ~50–180 kA with a clear tendency for the peak current intensity to decrease with time delay from the onset of sferics to the peak of sprite halo emissions. Assuming that there is an inverse relation between the peak current intensity and time delay, we suggest that there is a threshold for the charge removed from thundercloud to induce sprite halos and following streamers. The upper limit of this threshold is estimated as ~80–110 C. Further investigation of the relationship between sprite halos and the associated charge moment changes would be most beneficial.

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