PERGAMON

Journal of Atmospheric and Solar-Terrestrial Physics 60 (1998) 733–740

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

Observations of 'Columniform' sprites

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Received 11 September 1997; accepted 17 February 1998

Abstract

This paper reports observations of a distinctive form of sprites associated with positive CG flashes carrying currents of 23 or less to about 100 kA in mesoscale thunderstorms. The sprites are characterized by long vertical columns about 10 km long, less than 1 km in diameter, and show virtually no variation in brightness along their length. Three dimensional triangulation of what we define as a 'columniform' sprite (c-sprite) event on the evening of 19 June 1995 showed that the individual elements had an average terminal altitude of 86.7 km and an average bottom of 76.2 km. Some show faint diffuse 'hair' or tendrils extending above and below the column. The sprite columns are nearly vertical, in video imagery. On some evenings, c-sprites are the dominant form of sprite activity above thunderstorms but, on other nights with many sprites, they may not be observed at all. Comparison of c-sprite forms vs National Lightning Detection Network (NLDN) positive cloud-to-ground current, shows a progression from simple thin vertical forms to brighter and more complicated forms. Theoretical explanations which predict the form and vertical structure of the classical sprites do not at present account for these different forms.

1. Introduction

The observations of Franz et al. (1990), Sentman and Wescott (1993), Sentman et al. (1995), Lyons (1994), Sentman and Wescott (1994), Boeck et al. (1995) and Winckler et al. (1996), among others, described upper atmosphere flashes called sprites. Sprites generally have a vertical brightness structure and a diameter of 5 km or greater. The brightest feature is usually at about 70 km altitude. Figure 1 shows a TV frame of what might be described as a classic sprite, showing typical vertical structure. The TV image was taken at 08 : 14 : 37.120 UT, 24 July 1996 from the University of Wyoming Infra-Red Observatory (WIRO) on Jelm Mountain.

During June and July 1995, the University of Alaska operated a high resolution, narrow field of view monochromatic TV camera on Mt Evans, Colorado, during the same time that similar observations were made by FMA Research, Inc. at Yucca Ridge near Ft Collins, Colorado. On the night of 19 June 1995, both cameras obtained excellent views of sprites above thunderstorms located near the North East corner of New Mexico. The background star fields in the TV images were sharp enough at both locations to perform three-dimensional triangulations of seven different groups of sprites. Most were of the classic sprite type as shown in Fig. 1, described by Sentman et al. (1995). However, three of the sprite displays were quite different, and characterized by numerous long vertical columns of optical emission. The columns exhibit a large length to diameter ratio, (about 10 : 1), are apparently nearly vertical, and show little or no brightness variation along their length. For this reason the name 'columniform' sprites, hereafter called c-sprites, was proposed by Wescott (1996), and discussed by Sentman et al. (1996) and Moudry et al. (1996). There is some indication of very faint 'hair' discharges above the top and tendrils below the bottom similar to those in classic sprites, but these were too faint to be triangulated.

Figure 2 shows a TV frame from Mt Evans of a large group of c-sprites at 06 : 35 : 48.583 UT, 19 on June 1995. We also observed similar c-sprites on other evenings from Mt Evans and Yucca Ridge, but not concurrently, so they cannot be triangulated. During July 1996, more high

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S1364-6826/98/$—See front matter
PII: S1364-6826(98)00029-7

Fig. 1. A TV frame at 08:14:47.120 UT, 24 July 1996, from the Wyoming WIRO site of a classic sprite showing the typical vertical structure. Note that there is both 'hair' above and dendrils below the carrot shaped sprite body. The triangulated vertical scale shows the altitude of the various features.

resolution TV sprite observations were made by several groups at the FMA Research, Inc. site at Yucca Ridge, including the University of Alaska. From 10–26 July, the University of Alaska operated from the University of Wyoming Infrared Observatory (WIRO) where we obtained data for triangulation with Yucca Ridge images. C-sprites were seen on many evenings during the 1996 campaign. On the night of 21 July 1996, we observed 30 c-sprite groups (60% of the events) during an interval of 2 h. The storm was in South Dakota, at a slant range of about 600 km.

2. Analysis

The feature locations of 7 groups of sprites near the North East corner of New Mexico on 19 June 1995 were triangulated using computer programs STAR and STEREO (H. Nielsen, private communication). STAR is used to fit stars from the Smithsonian Observatory catalogue onto the observed stars on the video frame. The catalogue star field can be stretched and rotated until a good fit is obtained. This provides the transformation from any pixel location on the video frame to azimuth and elevation. Program STEREO is then used to triangulate on any feature seen from two or more optical sites. If there are sufficient stars in the field of view near the object of interest, then one pixel is about the uncertainty of the triangulation.

To star fit to the example shown in Fig. 2 was excellent, including ninth magnitude stars in the Constellation Corona Australis, implying a high degree of confidence in the 28 triangulated points. The triangulated altitudes of the tops of the c-sprites shown in Fig. 2 ranged from 84.3–88.9 km, with a mean value of 86.4 km and a standard deviation of 1.9 km. The mean value of the bottoms was 76.1 km with a standard deviation of 1.4 km. Figure 3 shows a map of the triangulated locations of the c-sprites shown in Fig. 2. The sprites were associated with a 75.9 kA positive CG lightning flash reported by the National Lightning Detection Network (NLDN) at 06:35:48.484 UT. The CG flash was not located at the center of the ring of c-sprites, but rather near the northern edge shown by a + in Fig. 3.

The centroid of the group of c-sprites was at a slant range of about 425 km from Mt Evans, and about 525 km from Yucca Ridge. Thus, one pixel on a Mt Evans TV frame represents about 400 m vertical × 490 m horizontal at the source, and 510 × 640 m on a Yucca Ridge frame. The apparent width of a single c-sprite column is one pixel, implying that its diameter is ⩽490 m.

C-sprites do not always appear as a pure group, but may also occur in the company of 'classic' sprites. At 06:23:53.867 UT on 19 June 1995, a group of three c-

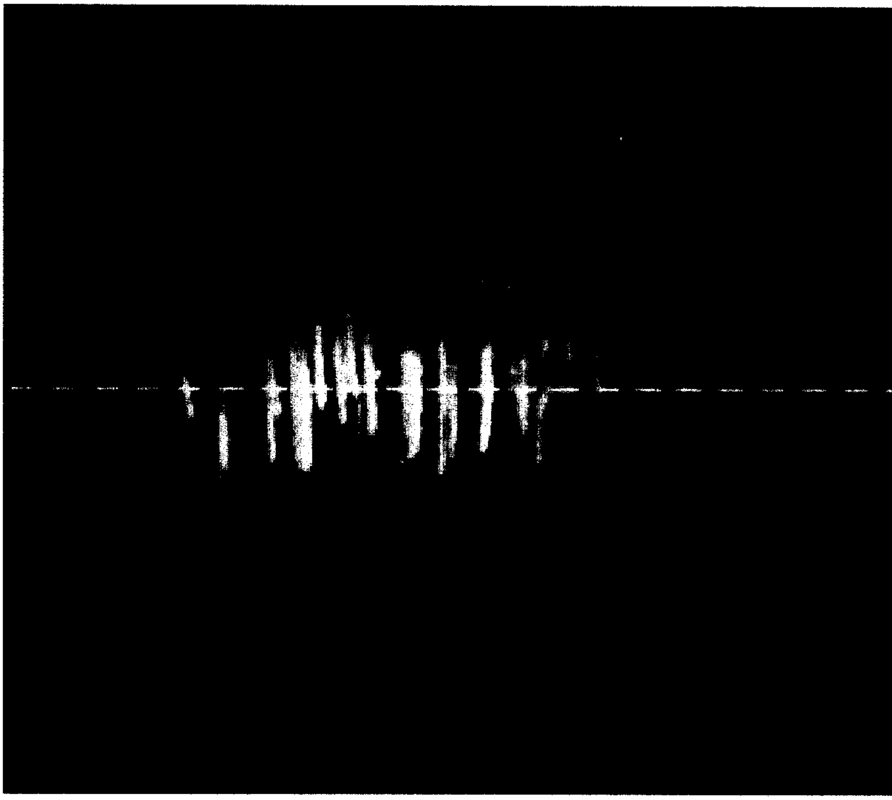

Fig. 2. A 18.0° H × 13.7° TV monochrome intensified CCD TV frame at 06:35:48.583 UT, on 19 June 1995, showing a large group of columniform sprites observed from Mt Evans, Colorado. The dashed line shows the location of a spectrograph slit.

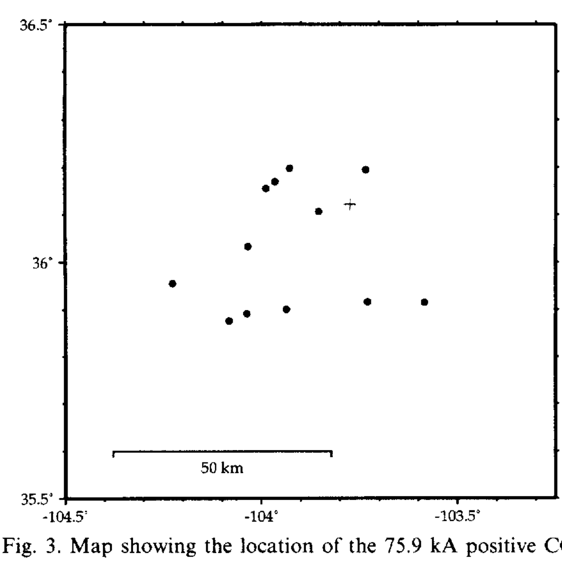

Fig. 3. Map showing the location of the 75.9 kA positive CG flash (cross) derived from the NLDN and the triangulated positions of the c-sprites shown in Fig. 2.

sprites occurred near a short oval sprite with a center altitude of 70.7 km. The three c-sprites had a mean top altitude of 81.5 ± 0.2 km, and a mean bottom altitude of 75.2 ± 1 km. All the sprites followed at +CG multiple stroke flash of 28.7 kA, located at a distance of 20 km from the group. At the extreme, c-sprites can appear as a single form, as shown at 05:39:24.164 UT, on 19 June 1995 in Fig. 4. This c-sprite followed a NLDN derived 26.1 kA positive flash at 05:39:24.131 UT.

On 7 July 1996 at 04:54:52.759 UT, we observed a spectacular group of sprites located in North East Colorado at a slant range between about 150–190 km from Yucca Ridge, Colorado. Figure 5 shows the TV frame of this display. The most obvious feature of this group of sprites which we call the 'fireworks event' is the curvature of some of the elements, which otherwise look like the more common variety of c-sprites possessing nearly vertical straight columns. Any curvature in the columns would be more obvious in this example compared to the example shown in Fig. 2 because it was much closer to the camera, the view elevation was greater, and thus the view component parallel to the column is foreshortened.

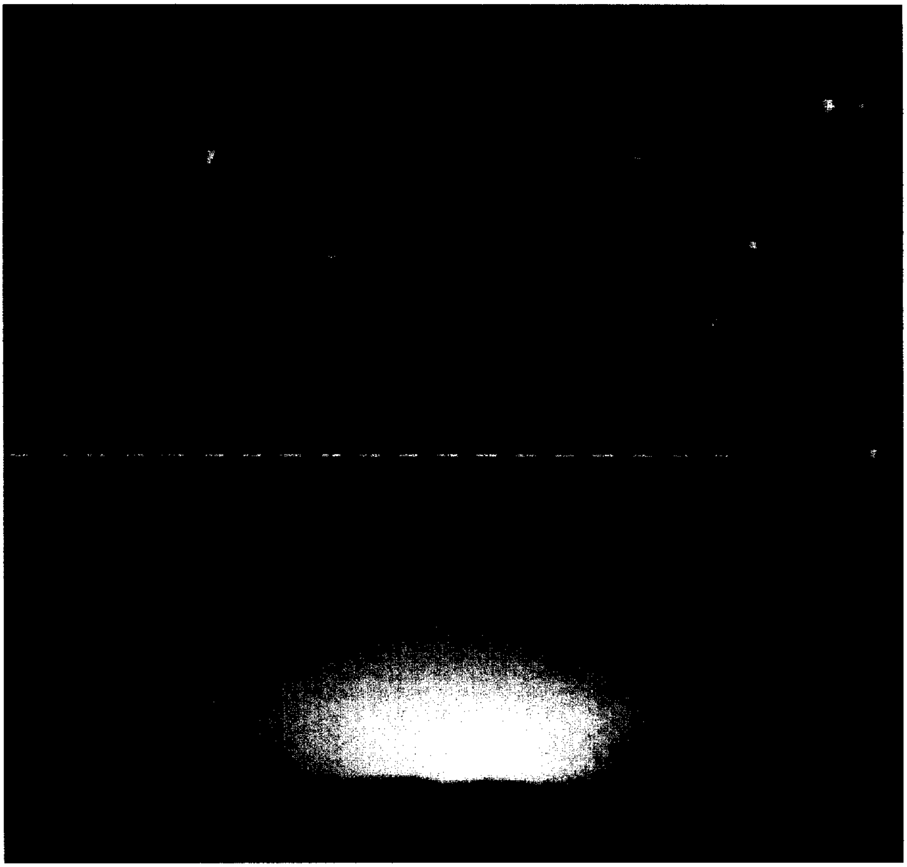

Fig. 4. TV frame of a single c-sprite, 05:39:24.164 UT, 19 June 1995, in the same general vicinity as the c-sprites in Fig. 2. The associated positive flash carried 26.1 kA.

It was not possible to triangulate on this group of sprites, as they were only recorded from the Yucca Ridge site. However, it is possible to use the star background to establish the azimuth and elevation angles of any feature of the sprites. Then by assuming that the altitude of the bottom end of the features was the same average value as the c-sprites in Fig. 2, we calculated the latitude and longitude. Figure 6 shows a map plot of the estimated locations. One error bar is plotted showing the uncertainty in the slant range due to the estimated error in the altitude of the bottoms of the sprite elements. The azimuth and elevation are accurately determined from the star fit. With the field of view on this occasion, a pixel is about 140 m vertical $\times$ 185 m horizontal at the sprites, and the resolution is much better than in Fig. 2. There were two NLDN flashes close in time and location to the sprites, shown as +s on the map. Note that the 49.9 kA strike is located near the southern edge of the group of c-sprites, while the larger flash is nearly 50 km from the center.

We have analyzed many of the sprites which were recorded with a narrow field (7.8° $\times$ 12.2° fov) TV camera on 21 July 1996. Figure 7 shows 6 examples from that night, and the NLDN current of the causative flash. They were only recorded from the one site at WIRO, so they cannot be triangulated. However, we were able to estimate the positions and altitude of the individual c-sprites using the azimuth and elevation derived from fitting the star positions, and assuming that the NLDN flash position is located within or near the edge of the perimeter formed by the sprites. Using these assumptions, we found that the lower and upper altitudes of the elements agreed well with the values, 76.2 km and 86.7 km respectively, derived from triangulated positions of the group in Fig. 2. There is vertical structure in many of the c-sprites, particularly evident in the upper two frames. Many of the forms are broken by two distinct dark bands near the bottom, making a dash about 2 km long above a small spot. On some, only the spot is evident.

For the c-sprites shown in Fig. 7 it is suggested that the positive CG current associated with c-sprites relates to their form. Faint c-sprites were observed with a reported NLDN current of as little as 23 kA. At about 40 kA, as in the top two frames, the sprite elements are

Fig. 5. TV frame from the University of Alaska narrow field camera at Yucca Ridge, 7 July 1996 at 04:54:52.759 UT showing a portion of a sprite group called 'the fireworks event'. The slant range from the sprites to the camera was about 150 km. These seem to be c-sprites, but many of the features show curvature not evident in Fig. 2. The high view elevation angle accentuates the curvature and the short slant range provides spectacular details of fine structures in sprites.

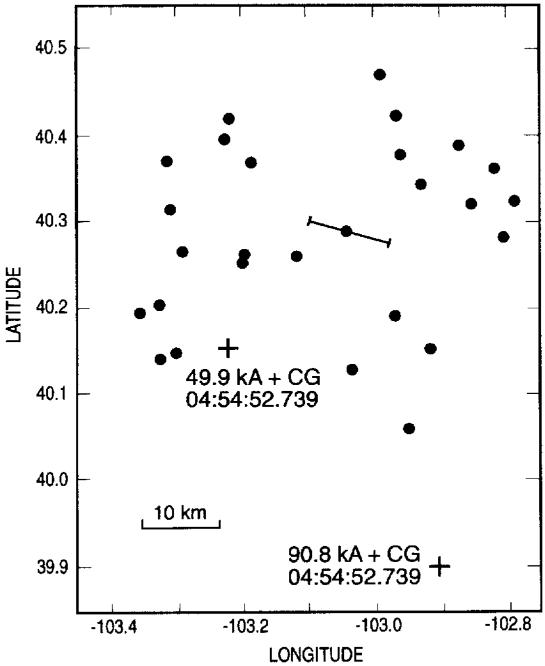

Fig. 6. Map of the estimated locations of the major features in the 'fireworks' group, shown in Fig. 5, using the star background for azimuth and elevation, and calculating the location of the lower end of the features, assuming a height of 75 km.

bright and sharp, with the obvious dark bands. There is some evidence of faint fuzzy discharges at the top of some elements. With a higher current more completed features are seen, such as the upward branches at the base of elements at 07 : 49 : 05 : 01 with current of 59.8 kA. In the lower left frame the forms, while still recognizable as basically c-sprites, have much more complicated features, with fuzzy 'discharges' surrounding the tops. The dark band features are still evident, however. The lower right frame shows a group of sprites which are so bright that blooming is evident, with much 'fuzzy' discharge, but they still look like c-sprites.

3. Spectrum of c-sprites

Hampton et al. (1996) measured the spectra of many sprites from Mt Evans. Among the spectra were some of c-sprites. Figure 8 shows a spectrum of a c-sprite with a spectrum of a standard sprite. The amplitude scale is the same, but the classic sprite spectrum has been shifted up to avoid overlap. The c-sprite spectrum is much noisier because it was much less intense. Inspection reveals that all the identifiable bands of the first positive N_2 are present in both, but the relative amplitudes show some differences. In particular the 4-1 band at 678 nm is much

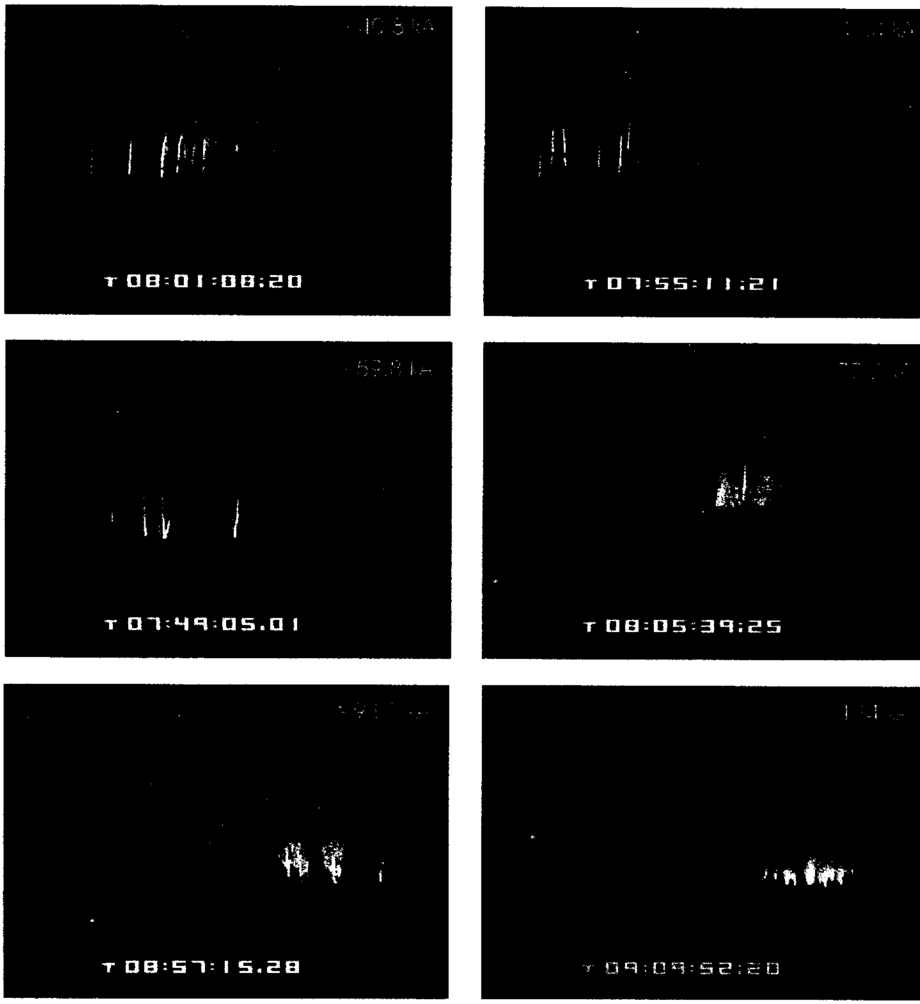

Fig. 7. Six TV frames from a narrow field camera at the WIRO Observatory on Mt Jelm Wyoming, on the evening of 21 July 1996. The frames show c-sprites with increasing NLDN+CG flash current. The sprites associated with larger currents have more complex forms, and more fuzzy 'discharges' around and above the tops. Note the obvious dark bands near the bottoms of the individual forms, particularly in the top 2 frames.

higher in relative intensity in the c-sprites spectrum than in the classic sprite spectrum.

4. Discussion

C-sprites seem to occur frequently above thunderstorms on some nights, but not at all on other nights. Currently, we have no explanation for the occurrence of c-sprites. On one night, 60% of the sprites were c-sprites. From the limited analysis it seems that c-sprites are not associated with the very large positive NLDN flashes. They were observed to occur with NLDN derived currents of as low as 23 kA, as very faint columns. Obvious c-sprites were seen with currents near 100 kA, but the thin vertical forms were mixed with more off-vertical elements. The large group of columniform sprites shown in Fig. 2 was associated with a 75.9 kA flash, and the 'fireworks' group shown in Fig. 6 was associated with 49.9 kA (NLDN) flash. The single c-sprite shown in Fig. 4 followed a 26.1 kA flash. The obvious dark bands near the base of many c-sprites is perhaps the most interesting feature. The physics of this feature should be the subject of further theoretical investigation.

Cummer and Inan (1997) have presented an analysis of the rate of charge transfer and the ELF waveform associated with a variety of sprites. They present four examples of sprites ranging from very large and bright (300 kA) to the barely detectable (40 kA). One of their examples, that at 05 : 05 : 32.218 on 24 July 1996 was also

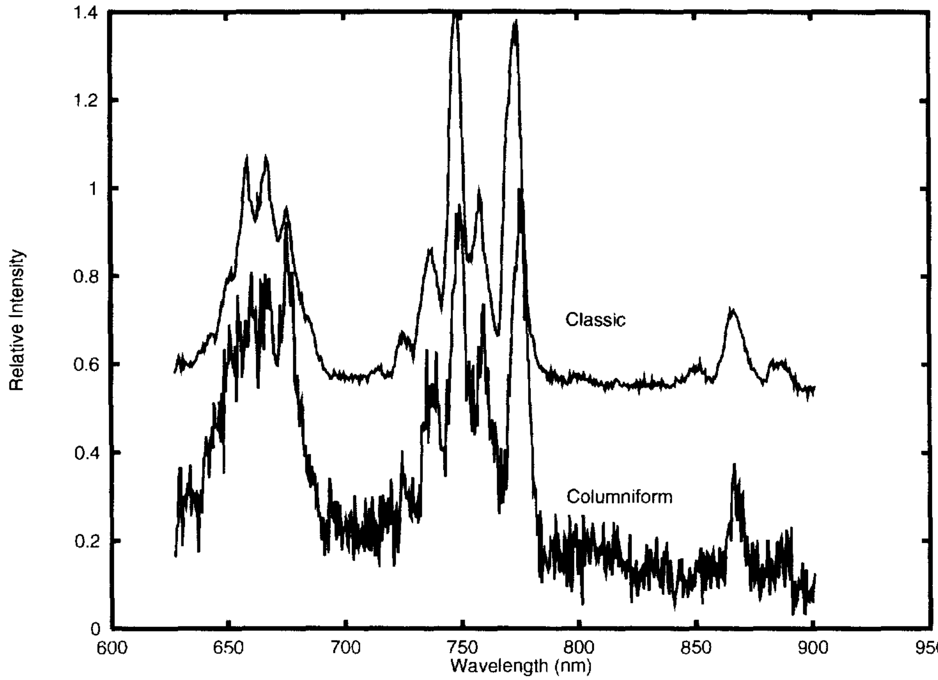

Fig. 8. Optical spectra of a normal sprite and a c-sprite (for discussion, see text).

observed by the University of Alaska at WIRO, seems to be a group of c-sprites. The calculated current was 50 kA, without a secondary maximum in the tail. The ELF wave train had a maximum amplitude of about 0.75 nT. These values of charge, current and ELF amplitude are much less than some other examples of large sprites, but are above the levels where no sprite was seen. However, the c-sprites which we observed, associated with flashes of about 23 kA, would be less than the 40 kA, barely detectable sprite level, of Cummer and Inan (1997).

From the limited analysis presented in this paper, we conclude that c-sprites follow positive flashes with currents ranging from about 23–100 kA. The preliminary analysis needs to be followed by more detailed analysis of the thunderstorm environment which leads to c-sprites. The spectra suggest that there may be significant differences between c-sprites and other types of sprites, but more observations are needed to quantify these differences.

Acknowledgements

The University of Alaska portion of this research was sponsored in part by NASA Grant NAG5-5019, in part by the Department of the Air Force Phillips Laboratory contract F19628-97-C-0021, and in part by Contract OH-000 9605304 from Mission Research Corporation. The work could not have been done without the encouragement and support of Mary Mellott and Rick Howard at NASA Headquarters. We acknowledge the support of Laila Jeong at Phillips Laboratory, whose interest made the 1996 campaign possible. We appreciate the use of the University of Denver facilities on Mt Evans and very helpful interaction with R. Stencel, M. Jones, and M. Jalakas of the University of Denver. We thank R. Howell and the staff of the University of Wyoming Infrared Observatory on Jelm Mountain for the use of the facilities and their help. We thank Mike Taylor of Utah State University who cooperated with the University of Alaska in triangulating sprite positions in 1996, including the sprites shown in Fig. 1. We thank T. Hallinan of the Geophysical Institute, University of Alaska, for the use of TV cameras and H. C. Stenbaek-Nielsen for the use of computer programs STAR and STEREO. J. Desrochers engineered the systems used in the observations and helped to take the data.

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