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Telescopic imaging of sprites

E.A. Gerken, U.S. Inan, C.P. Barrington-Leigh,

STAR Laboratory, Stanford University, California

Abstract. Telescopic images of sprites show a wide variety of generally vertical but also slanted fine structure, including branching tree-like shapes and well defined but isolated columns, with transverse spatial scales ranging from tens of meters to a few hundred meters at ∼60–85 km altitude. Simultaneous analysis of radio atmospheric and lightning data indicates that specific columnar regions are selectively excited by successive discharges.

Introduction

Sprites are large luminous discharges which appear in the altitude range of ∼40km to 90km above large thunderstorms [e.g., *Sentman et al.*, 1995]. Previous video observations have revealed an interesting menagerie of fine structures in sprites, including the so-called 'fireworks' [*Sentman et al.*, 1996], downward branching [*Taylor and Clark*, 1996], and upward branching shapes [*Stanley et al.*, 1996]; [*Fukunishi et al.*, 1996].

A theoretical explanation of observed spatial fine structures in sprites was put forth in the context of a new streamer-based model of electrical breakdown above thunderstorms [*Pasko et al.*, 1998], predicting characteristic structure widths for each altitude, ranging from ∼10 m at 70km to ∼100 m at 85 km. Recognition of the fact that such small fine structure is beyond the resolution of conventional wide-field-of-view video imaging motivated the use of high-resolution telescopic imaging for sprite observations with a long focal-length, wide aperture instrument as described in this paper.

Description of the Experiment

During the months of July and August 1998, the Telescopic Imaging of Sprites Experiment, consisting of a ∼41 cm diameter, f/4.5 Dobsonian-mounted Newtonian reflecting telescope with an intensified CCD camera attached to its eyepiece and a bore-sighted wide field of view (FOV) camera mounted on top, was deployed at the Langmuir Laboratory (LL), located in the Magdalena mountains of central New Mexico and operated by the New Mexico Institute of Mining and Technology. The FOV of the telescope (0.5 in CCD) was 0.7° by 0.92° while that of the bore-sighted camera (.33 in CCD, 50 mm lens, f/1.4) was 9° by 12°. The output from these cameras was fed to VHS video recorders with GPS timing stamped on each frame. The narrow FOV camera was field-selected, creating images exposed for ∼17ms while the wide FOV camera was in interlaced frame mode creating images exposed for ∼33ms. Over 30 storms were observed during two months. Real-time data from the National Lightning Detection Network (NLDN) and infrared maps from the GOES satellites were used to locate large area thunderstorms with high positive cloud-to-ground (+CG) activity since nearly all previously observed sprites have been associated with +CGs [*Boccippio et al.*, 1995]. We used the known fact that sprites occur in close proximity to each other for several tens of minutes during a typical storm [*Lyons et al.*, 1996] to zoom in on observed activity.

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Camera Calibration

For quantitative measurements the camera on the telescope was calibrated for brightness, edge-sharpness, and phosphor persistence. The brightness levels of the images were calibrated using a light source of a known radiance at 600 nm which was covered by a narrow band (7 nm) Melles-Griot filter. The spectral response of the telescopic images is limited to ∼450-850nm by the GenII image intensifier tube. The camera system was determined to saturate at ∼3 MegaRayleigh (MR) or 10^{12} photons-cm^{-2}-s^{-1}-str^{-1}. Reported brightness values represent an average over one exposure. The edge-sharpness calibration was performed by imaging scenes with adjacent black and white blocks. Transitions from the minimum black value to half of the maximum white value occurred over four camera pixels. Accordingly, filamentary widths reported in this paper assume a sharp boundary and are 4 pixels less than that seen in the image (2 per boundary). Uncertainties quoted are based on the width of one pixel. The persistence of the phosphor in the intensifier tube of the camera was examined by imaging a bright light streaked in front of the camera. Dim images (less than 3 MR) were found to decay before the onset of the next frame as desired [*Burke*, 1996].

Results

On July 13 and August 6, 1998, ∼50 sprites were observed over northwestern Mexico, ∼450 to 580 km away from LL. The moon was nearly full on the night of August 6, increasing the background light level. Lightning location and peak current data from NLDN [*Cummins et al.*, 1998] were used to determine the range of the sprites from LL on the basis of the largest +CG stroke recorded in temporal proximity to each sprite. The altitudes of the sprites (and associated uncertainties) were determined by assuming them to be roughly (within ±40 km) centered above the causative +CG stroke [*Winckler et al.*, 1996]; [*Lyons et al.*, 1996] and using the recorded starfields to determine the elevation angle of the telescope.

Figure 1 shows a large sprite observed on July 13 at 06:00:00 UT, which lasted a maximum of ∼50 ms (one video frame). The upper panel displays the wide FOV while the lower panel shows the narrow (telescopic) FOV. The white

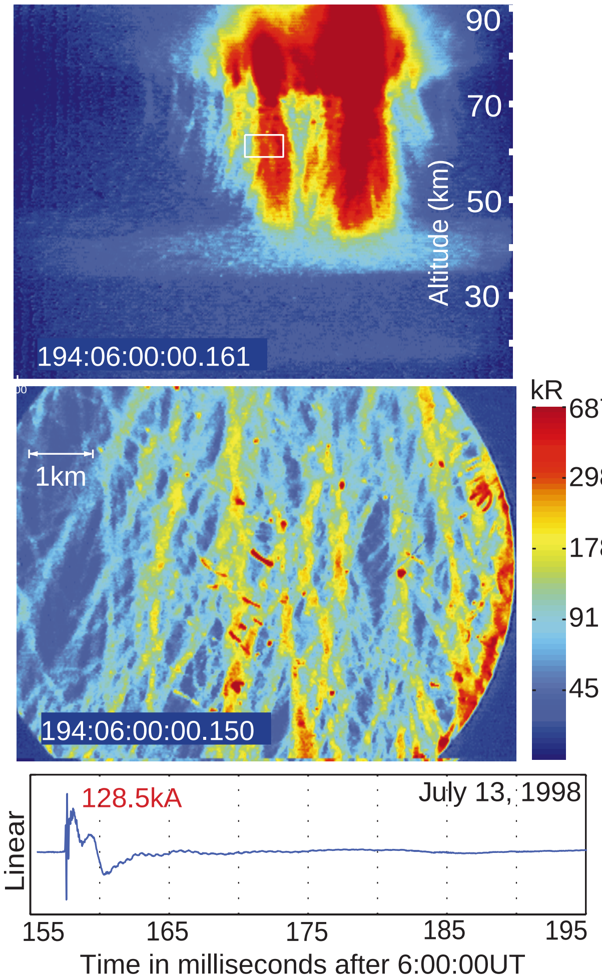

Figure 1. Wide (top panel) and narrow (lower panel) FOV images of a bright sprite event. Format and colorcoding in subsequent figures are the same as shown here unless otherwise noted.

rectangle on the upper panel outlines the narrow FOV with respect to the wide FOV .The images have been false-colored and saturate at 685 kR in order to better represent intensity and bring out dimmer features (see colorbar). Time stamps correspond to the beginning exposure time for each image. The broadband VLF sferic recorded at Yucca Ridge Sprite Observatory in Colorado (40°40′06″ N, 104°56′24″ W) is shown below the two images with an arbitrary linear intensity scale. NLDN current amplitudes are shown next to sprite-associated sferics. There are propagation delays of ∼4 ms and ∼2 ms from the sprite regions shown to Yucca Ridge and Langmuir respectively. This type of very large sprite has been previously observed [*Winckler et al.*, 1996] and is believed to occur in response to very rapid removal of a large quantity of charge, consistent with the relatively large peak current (+128 kA) of the associated CG discharge [*Bell et al.*, 1998]. It is evident from the narrow FOV image that such sprite structures consist of densely-packed branching streamers in the tendril region of the sprite. The transverse scale of filamentary structures in this image ranges from 60 to 145 m (±12 m) in the altitude range of 60–64 km (±4.5 km).

In the sprite event shown in Figure 2 the telescope reveals a bright central column with branches that appear to emanate from it at ∼45°. The central column is 650 kR at its brightest point while the branches are ∼90 kR. A 'columniform' sprite [*Wescott et al.*, 1998] is evident in the background. Sprites with unusual tree-like morphology similar to that shown in Figure 2 have not been reported before but were observed in several other cases during the July–August 1998 campaign. The branching may be due to the horizontal electric field of the intensely ionized bright column, creating a local distortion in the largely vertical primary quasi-static field. Figure 3 shows a 'carrot' sprite [*Winckler et al.*, 1995]. The telescopic view indicates that the upper part of the sprite appears to branch upward while

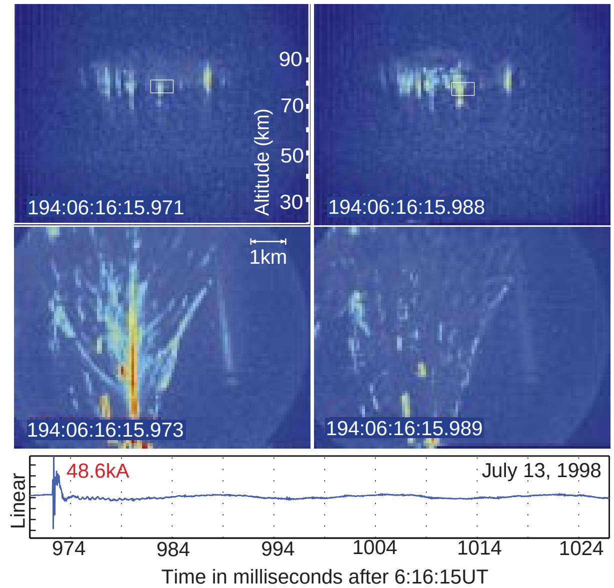

Figure 2. Images of a sprite exhibiting a branching tree-like structure.

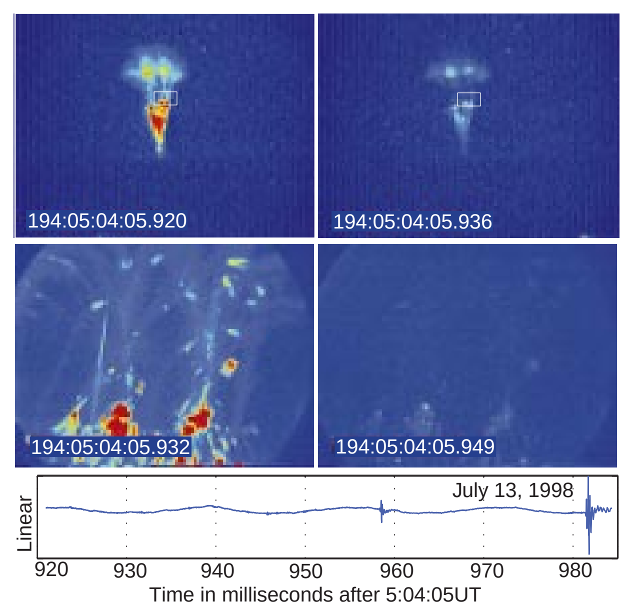

Figure 3. Images of a carrot sprite.

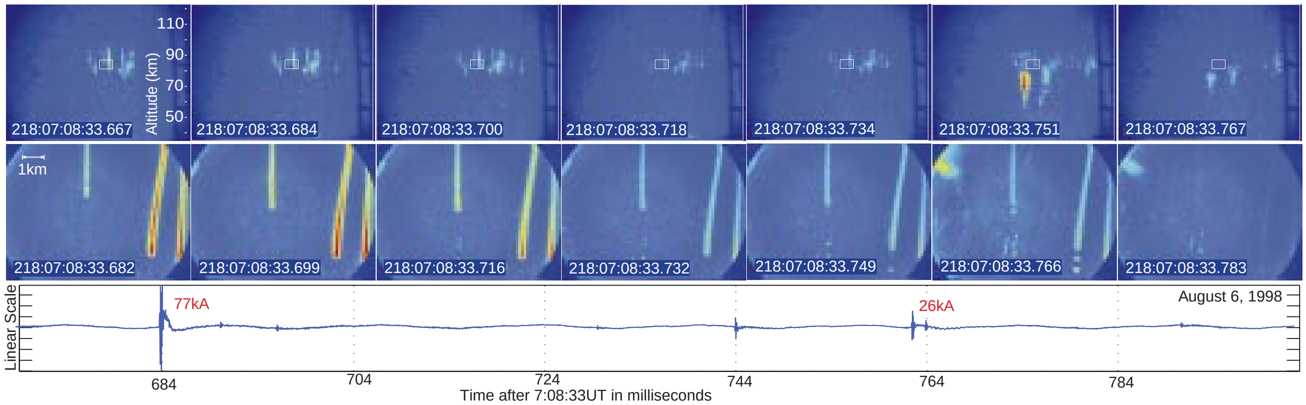

Figure 4. Successive images showing time evolution of isolated columnar structures.

the lower part branches downward. The brightest portion of the telescopic image is 1.6 MR and lasted 5 video fields. No NLDN stroke or large sferic was associated with this event.

Figure 4 shows a columniform sprite event observed on August 6. The columns first appear in the field shown apparently initiated by a 77 kA CG stroke and appear subsequently to extend downward and to fade by the fourth and fifth field. In the sixth field another sprite event occurs just below the FOV of the telescope, apparently in response to the 26 kA CG flash, which also leads to the slight re-brightening of the columnar forms and in particular the beads at the bottom. Remarkably, these columnar forms have relatively sharp edges (5 pixels) and lack fine structure. The widest of the columns is 196 m (±13 m) across in the altitude range of 81–85 km (±6 km).

In Figure 5 the sprite apparent in the first wide FOV image is produced in response to a 145 kA +CG discharge, which occurs during the last few milliseconds of the telescopic field shown, thus clearly indicating rapid sprite formation, consistent with the high peak current of the discharge [*Bell et al.*, 1998]. The sferic waveform of the +CG discharge exhibits a 'slow-tail' typical of many sprite-producing lightning discharges [*Reising et al.*, 1996]. Apparent in the narrow FOV shown below is a near-vertical column of illumination consisting of bands of high and low intensity. The lateral extent of this luminous column is 150±13 m over the altitude range of 76–80 km (±5 km). Note that both the overall sprite and the narrow column fade away in the next two video fields but are re-excited in the fourth frame, apparently in response to a CG discharge with peak current ∼78 kA. The re-excited column indicates that this preconditioned region of the atmosphere was primed for excitation with respect to its immediate surroundings. This result is most likely is due to the persistence of ionization from the first sprite which is expected to chemically dissipate in several tens of seconds in the altitude range of ∼76–80 km [*Pasko and Inan*, 1994]. The re-excited column appears to fade away in the next field, followed by a dramatic explosion of luminosity, in spite of the apparent lack of any large associated sferic occuring between the 5th and 6th fields. This case may well be an example of delayed sprites of the type reported by *Bell et al.* [1998], probably due to continuing currents which flow for up to 100 ms or more following the initial discharge. It is interesting to note from the 6th narrow FOV image that the singular column is again re-excited, but is now accompanied with a host of other narrow near-vertical forms, ranging in lateral size from 27 to 54 m (±13 m) in this altitude range of 76–80 km (±5 km).

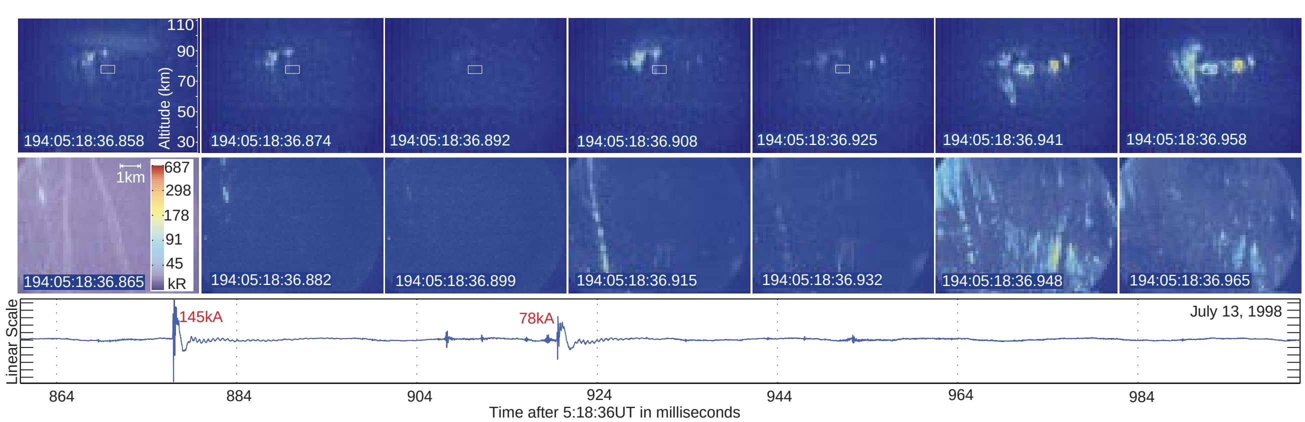

Figure 5. Successive rexcitation of columnar forms. Format and color coding of brightness levels are modified in the lower left-most panel as indicated.

Summary and Discussion

Analysis of telescopic imaging data shows that sprites have complex fine structure with lateral extents ranging from tens of meters to a few hundred meters in the altitude range of ∼60–85 km. Sprite brightnesses integrated over a video field (∼17 ms) are often found to be in several MegaRayleigh range. Tree-like structures with streamers apparently emanating from a central column are observed, as well as homogeneous columns with no fine structure. The central region of a carrot sprite appears to be the transition between upward and downward branches. Specific columnar regions are selectively excited by successive discharges and re-brighten, indicating the presence of persistent ionization.

The fine streamer structure with transverse extents of 20–50 m (±13 m) observed in the altitude range 76–80 km (±5 km)(Figure 5) agrees well with theoretical predictions of elementary streamer processes for these two altitude ranges [*Pasko et al.*, 1998]. However, structures with extents of 196 m (±13 m) observed at 81–85 km (±6 km)(Figure 4), 150±13 m at 76–80 km (±5 km)(Figure 5) and 60–145 m (±12 m) at 60–64 km (±4.5 km)(Figure 1) appear to be substantially wider than those derived from similarity laws for elementary streamers [*Pasko et al.*, 1998].

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E. A. Gerken, U. S. Inan, and C. P. Barrington-Leigh, STAR Laboratory, Stanford University, Stanford, CA 94305. (e-mail: egerken@stanford.edu; inan@nova.stanford.edu; cpbl@nova.stanford.edu)

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