High speed video of initial sprite development

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Abstract. High speed video of sprites show that they are typically initiated at an altitude of about 75 km and usually develop simultaneously upwards and downwards from the point of origin with an initial columniform shape. The initial development of sprites appears to be dominated by corona streamers with velocities in excess of 10^7 m/s. Many of the observed characteristics are consistent with a conventional breakdown mechanism for both sprite initiation and initial sprite development.

1. Introduction

Sprites are luminous discharges at altitudes of 40-90 km above large thunderstorm systems [*Sentman et al.*, 1995; *Winckler*, 1995; *Lyons*, 1996]. They are primarily associated with positive cloud-to-ground (+CG) strokes which transfer large quantities of positive charge to ground [*Cummer and Inan*, 1997; *Boccippio et al.*, 1995], though comparatively rare instances of sprites associated with energetic -CGs have recently been observed [*Stanley et al.*, 1998].

Various terms have been used to describe the diversity of forms and features within sprites. A "carrot" sprite is characterized by a relatively bright head region, typically at 66-74 km altitude, wispy structures ("hair") extending above the head and bluish tendrils below [*Sentman et al.*, 1995]. An "angel" sprite also has tendrils, but the head is capped by a diffuse glow. "Columniform" sprites do not show readily identifiable signs of tendrils or hair-like structure under ordinary magnification [*Wescott et al.*, 1998]. Individual sprites which assume one of the above forms (or other forms not mentioned) are observed to almost never occur in isolation, but to be part of a "sprite cluster".

Spectral measurements [*Suszcynsky et al.*, 1998; *Armstrong et al.*, 1998] and VLF observations [*Dowden et al.*, 1996] indicate that significant ionization can occur in the initial phase of sprite development. Observations of sprites at close range [*Stanley et al.*, 1996] or under magnification [*Inan et al.*, 1998] have provided clear evidence that structures with lateral dimensions of $\leq$100 m are present.

Numerical simulations of a runaway electron discharge originating from low altitude are able to reproduce an ionization signature similar to that observed [*Yukhimuk et al.*, 1998, and references therein]. However, the simulations are unable to make predictions of fine structure due to the grid sizes ($\geq$400 m) used in the calculations (*S. Yukhimuk,* private communication, 1999). Numerical simulations of space charge-controlled filamentary discharges in the form of corona streamers predict both the early ionization signature and the existence of fine scale structure in sprites [*Pasko et al.*, 1998]. A corona streamer is characterized by electron impact ionization within a high electric field region at the streamer tip with rapid recombination of electrons behind the tip. Unlike many other forms of streamers, a corona streamer does not significantly heat the neutrals to the point where additional electrons are liberated and thus it would tend to be characterized by short persistence. A corona streamer would be initiated within a region where the electric field exceeds the threshold for conventional breakdown. Such regions might form at high altitude (low atmospheric density) above a CG discharge [*Wilson*, 1925; *Fernsler and Rowland*, 1996; *Pasko et al.*, 1997].

In early October 1997, a high-speed light-intensified camera system was operated from Langmuir Laboratory, NM to observe sprite phenomena. Frame rates of either 1000, 2000, 3000, or 4000 s^{-1} were used to capture the development sequence of 42 separate sprite clusters as well as of several elves at estimated ranges of 200-900 km. This paper presents a couple of illustrative examples of the initial 2-3 ms of sprite development. Much of the initial sprite development appears to be associated with corona streamers and quantitative results are provided for the heights, speeds, and sequence of development of the corona streamers.

2. Instrumentation

A KODAK EktaPro High-Spec Motion Analyzer Model 1012 with a KODAK EktaPro Intensified Imager Model VSG was used to acquire the high speed video imagery of sprites. The pixel array size of the imager sensor was 239x192. The operational wavelength region was 440-700 nm at 50% sensitivity and 350-800 nm at 10% sensitivity. The system was capable of 1000 frames per second (fps) using the full sensor area and higher rates using correspondingly fewer horizontal scan lines. The frame start times were accurate to within 50 μs as determined by GPS timing.

Electric field change data was sampled at 500 kHz in conjunction with the video and was accurate to within 1 μs as determined by GPS timing. The field change system automatically triggered off of electric field pulses of either polarity and stored several milliseconds of data around the triggers. The field change data was used to determine the occurrence, timing, and polarity of CG discharges. The CG

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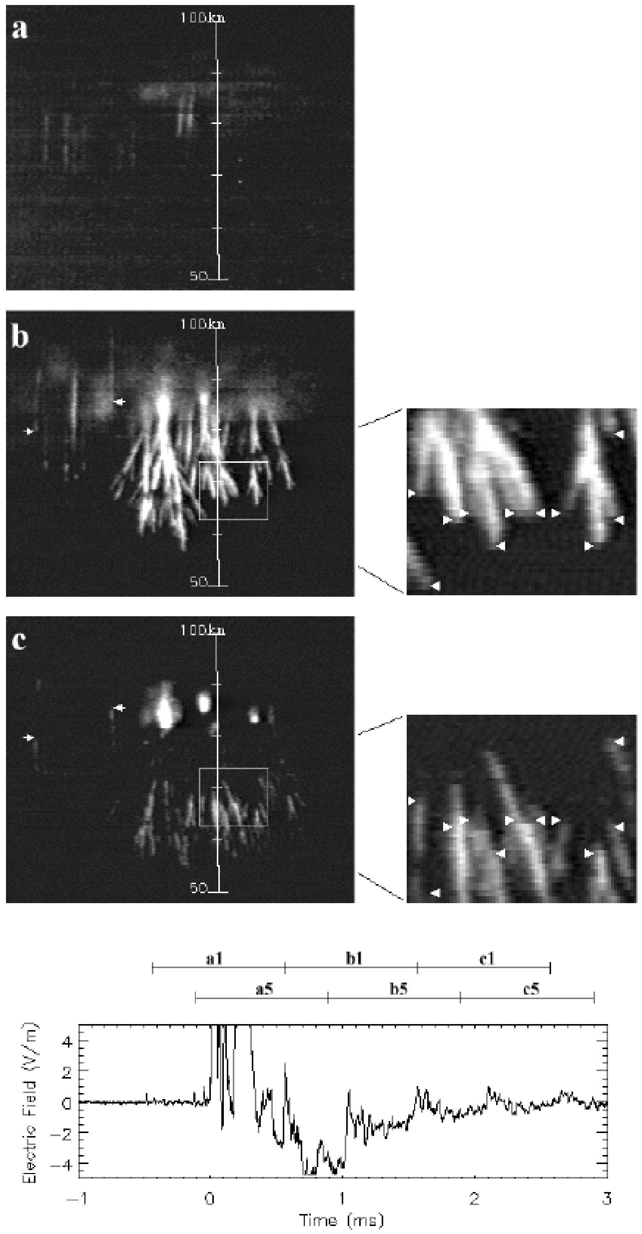

Figure 1. Initial frames of 1000 fps sequence for a cluster of angel and columniform sprites. Corona streamer characteristics are evident for both the columns and tendrils which propagated downwards between frames, as denoted by the arrows in both the overall sequence (left) and expanded images (right). The limiting horizontal and vertical resolution is 400 m. The +CG electric field waveform is shown below the images with the horizontal bars corresponding to the light integration periods for the 1st and 5th video blocks within the frame.

locations and peak currents were obtained from National Lightning Detection Network (NLDN) data.

The high speed camera's pixel sensor was scanned out in blocks of 16 rows each for a total of 192/16 = 12 blocks (at 1000 fps). This scanning proceeded downward from the top of the sensor's active area. Each block had an integration start and end time which was delayed by 1 $ms/12 = 83$ μs from the block immediately above. The lowest block of the frame preceded the top block of the next frame by 83 μs. This timing information was factored into the velocity estimates.

The light integration period was configurable, but was always set to match the duration of the individual blocks within a frame. There was a short period during a block's scan-out interval when light could not be integrated. The duration of the scan-out interval was $\approx$1 μs, which was too small to have any noticeable effect on the images.

3. Results

3.1. Angel and Columniform Sprites

Figure 1 shows high speed video observations obtained at 1000 fps of a cluster of columniform and angel sprites that occurred at 03:40:38 UT over southeastern New Mexico on October 7, 1997. These sprites were associated with a 116 kA peak-current +CG at 298 km range. The vertical bar in Figure 1 is plotted directly above the +CG location and shows the height in km above sea level. The height estimates may be somewhat in error because the radial distance of the sprites from the CG plan location is not known. A radial displacement of 40 km would result in a vertical error of about 10 km.

From the time-correlated field change measurements, the beginning of the frame (top block) in Figure 1a was 0.44±0.05 ms prior to the arrival time of the return stroke pulse at the observation location. Several luminous regions and columns, many of which are paired, are visible in the first frame at inferred heights between 70 and 88 km.

The column pair just left of the height bar in Figure 1a have vertical extents of about 8 km. Taking into account the time it takes the return stroke field change to arrive at the altitude of the top of the columns ($\frac{85\ km}{3\times10^5\ km/s} \simeq 280\ \mu s$), the longer line-of-sight light travel time from the sprites than from the return stroke ($\frac{\sqrt{298^2+85^2}-298\ km}{3\times10^5\ km/s} \simeq 40\ \mu s$), and the video scan information (the top of the columns are within the 5th video block, the start of which is delayed by (5-1)×83 μs $\simeq$ 330 μs from the start of the uppermost video block), the columns were initiated within (–0.44+1)+0.33–0.28–0.04 $\simeq$ 0.57 ms of the arrival of the return stroke pulse at altitude. Since the base of the columns extend down into the next video block, the minimum speed for purely downward development would be about $\frac{8\ km}{(570+83)\mu s}$ = 1.2×10^7 m/s. The minimum speed would be somewhat higher for upward development (due to the video scan nature) and less for the upward and downward components of bidirectional development. The similarity of the minimum velocity estimate to other velocity estimates presented in this paper may indicate that the initiation of the sprites in Figure 1a occurred well within 0.57 ms of the return stroke.

The columns seen in the first video frame (Figure 1a) were in some instances brighter in the second frame (Figure 1b) and showed some downward development. However, the well-developed angel sprites of the second frame were not associated with detectable columns in the first frame. Rather, at least two of the angel sprites developed downwards from enhanced luminous regions visible in the first frame. The surrounding diffuse luminosity expanded outward with time in a manner similar to that seen by the high speed camera in other instances during elves. This suggests that an elve may have directly contributed to the initiation of these sprites, though there was a delay before the angel sprites developed vertically.

In the third video frame (Figure 1c), the heads of the angel sprites are still luminous while the tendrils are only

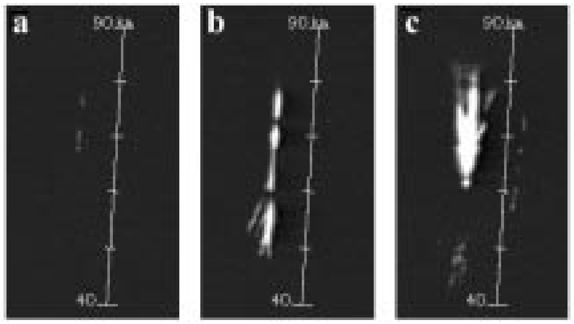

Figure 2. Initial frames of 1000 fps sequence for a carrot and columniform sprite. The carrot sprite began as a columniform sprite in the 1st frame, the downward developing component of which split into tendrils in the 2nd frame. Upward developing structures forked outwards from the carrot sprite's column in the 3rd frame to form the carrot shape. A columniform sprite is visible in the 3rd frame just to the right of the height indicator.

luminous in their downward developing lower extremities. An expanded view of the base of the tendrils in the boxed region is presented to the right of Figure 1b-c. The arrows denote the lower extent of each tendril for the second frame. All but two of the tendrils propagated downward during the third frame with no significant persistence indicated at the 400 m vertical resolution of the camera system, while the two exceptions appear to be accompanied by minor persistence (these may also be a chance superposition of a foreground and background tendril). The lack of persistence clearly indicates that tendrils are propagating events with visual characteristics identical to that of corona streamers. This is consistent with the theoretical predictions of *Pasko et al.* [1998]. The downward direction of development would be in the same direction as the quasi-electrostatic field created by a positive CG (which, in effect, places negative charge into the cloud) and hence the streamers would be of positive polarity.

A general lack of persistence can be seen in the overall picture of Figure 1b-c for the lower portion of a couple of downward developing columns (arrowed) in addition to the tendrils. Thus, these particular columns appear to be at least partially produced by positive corona streamers. This suggests that tendrils are formed by the splitting of a single positive corona streamer tip into additional tips as it propagates downwards and this characteristic was observed directly in other sprite examples.

The most developed of the angel sprites in the second frame had a vertical extent of about 28 km and developed at an apparent minimum velocity of 2.0×10^7 m/s. This velocity is at least a factor of 10 greater than observed in simulations of conventional corona streamers [*Pasko et al.*, 1998]. It is notable that streamer velocities exceeding 10^7 m/s have been observed in both laboratory discharges and lightning discharges when there is pre-existing weak ionization [*Winn*, 1965; *Suzuki*, 1977]. We speculate that the weak ionization normally present within the nighttime mesosphere might have a similar effect.

The brightness of the head of the sprites at an inferred altitude of 80-90 km underwent a gradual decay into later frames (not shown). This decay was observed for about 53 milliseconds.

3.2. Carrot and Columniform Sprites

The 1000 fps image sequence in Figure 2 is of a carrot sprite and a columniform sprite at 8:43:57 UT over northwestern New Mexico on October 3, 1997. The carrot sprite was initiated about 5 ms after the occurrence of a 41 kA peak-current +CG at 295 km range. The carrot sprite began as a dim non-continuous column at an altitude of 67-77 km (Figure 2a) as indicated by the vertical bar plotted above the +CG location. The columniform sprite to the right of the carrot (and just right of the vertical bar) in the 3rd frame (Figure 2c) began as a dimly illuminated sensor pixel at an inferred altitude of 73 km in the second frame (Figure 2b). Two additional columniform sprites formed off to the left of the carrot sprite in later frames (not shown). The rate of sprite initiation for this sprite cluster was considerably slower than that of the angel sprite cluster. This suggests that the quasi-electrostatic field was growing at a much slower rate.

In the second frame (Figure 2b), the carrot sprite column extended primarily downwards and tendrils branched down from the column to an altitude of 47 km. The tendrils appear to terminate at an altitude of 43 km in the third frame (Figure 2c). The average downward propagation speed for the second frame was 1.6×10^7 m/s. Like the tendrils of the angel sprites, these tendrils lack persistence and hence appear to be corona streamers.

Upward developing structures (UDSs) emanate outwards from the column at an altitude of 60-68 km in the third frame (Figure 2c). The exact point of origin along the column is difficult to determine since the image saturated heavily within that region. The UDSs terminated in the same frame at an altitude of up to 84 km with a minimum velocity of 2.1×10^7 m/s for the leftmost branch. Though initiation and termination occurred within a single frame, their development is presumed to be upwards since they branched upwards. The upward motion of these upward branching features was resolved in other carrot sprite examples.

The upper portions of UDSs within the hair of the sprite were not visible in the next frame (not shown). The short persistence of the UDSs within the hair suggests that they have corona streamer characteristics within that region. This was also observed directly for the upper portion of a UDS in another sprite which propagated upwards between frames without any significant persistence.

In contrast, portions of the UDSs within the head of the carrot at 66-74 km persisted into later frames for a total duration of 21 ms. This persistence may also be responsible for its increased brightness within the 1 ms integration time of the high speed video image. The continuous propagation between the head and hair regions along with the similar velocity and tip-splitting characteristics within both regions, as observed in other examples, suggests that the same physical process propagated UDSs up through both regions.

4. Discussion

All sprites observed with the high speed video camera began with a vertical columnar form. There were a few examples where the column appeared to grow from a single point. The point of origin was typically at $\simeq$75 km altitude, which is consistent with theoretical models of conventional breakdown occurring at an altitude high enough for the quasi-electrostatic field to exceed a critical breakdown threshold [*Wilson*, 1925; *Fernsler and Rowland*, 1996; *Pasko et al.*, 1997].

The initial column growth from the point of origin was primarily downwards in a few cases and both upwards and downwards in most other cases. Simulations of electrodeless discharges demonstrate that they can begin as a double headed corona streamer with one head extending towards the anode and the other towards the cathode [*Vitello et al.*, 1994]. Thus, the bidirectional column growth may be a bidirectional corona streamer process.

Computer simulations of negative corona streamers at sprite altitudes [*Pasko et al.*, 1998] show that if they are initiated with a radius less than a critical value (3 m at 70 km altitude, and larger for higher altitudes), they will expand up to the critical radius as they propagate without splitting into additional corona streamers. This suggests that sprites may be initiated with a radius less than a critical radius since the upward growth component of the columns were never observed to split into additional structures. However, the angel sprite example demonstrates that some sprites might in fact be preceded by faint luminosity (with a radius greater than critical) that somehow transitions into a filamentary discharge which propagates to lower altitudes.

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