# Submillisecond imaging of sprite development and structure

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[1] We report intensified high speed video observations of two mesospheric transient luminous events acquired at 5000 and 7200 frames per second. Downward streamers appear to initiate either spontaneously or from brightening inhomogeneities at the bottom of a halo, and branch as they propagate downward. Simultaneously, a brighter column expands upward and downward from the initiation point. This expansion is usually followed by the development of bright upward propagating streamers that originate from the bottom of the expanding bright column and that terminate in diffuse emissions. The lower portions of these upward streamers are typically brighter and more persistent and form the bright core of the sprite. A new phenomenon is observed in which the tips of downward-moving sprite streamers are attracted to and, in some cases, collide with adjacent streamer channels. The points of streamer collision appear to become long-persisting sprite beads, which have been suggested previously to affect mesospheric chemistry. Other persistent beads appear to form spontaneously on the downward streamer channels near the lower edge of the bright upper portion of the sprite.

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## 1. Introduction

[2] The effort to improve the spatial, temporal, and spectral resolution of measurements of the many classes of mesospheric transient luminous events (TLEs) driven by lightning has been continuous since their discovery. Each improvement has revealed important new information about the processes involved and their possible larger scale impact on the upper atmosphere. The first high speed TLE images were reported by *Stanley et al.* [1999] and revealed the dynamics of sprite development, specifically the downward propagating and branching positive streamers sometimes followed by brighter upward propagating structures. *Stenbaek-Nielsen et al.* [2000] and *Moudry et al.* [2003] reported sprite and halo images recorded at 1000 frames per second using a camera that resolved fine spatial structure. These images revealed complex, long lasting optical emission elements that reflect possible mesospheric modification by the TLEs. It was noted, however, that many sprites develop too quickly to be fully resolved at 1 ms time resolution. Adapting the telescope-based technique first employed with regular speed video by *Gerken et al.* [2000], *Marshall and Inan* [2005] reported telescopic imaging at 1000 fps and also acknowledged the need for sprite imaging with greater time resolution. Array photometers have also been used to probe the detailed space-time structure of sprites, particularly for measuring the velocities of upward and downward development [*McHarg et al.*, 2002].

[3] The acknowledged need for higher time resolution TLE imaging motivated an experimental campaign in July and August 2005 at the Yucca Ridge Field Station in Fort Collins, Colorado that employed an intensified high speed imager capable of imaging at many thousands of frames per second. Over the entire campaign, 76 individual TLE sequences were captured on the high speed imager on 7 different nights; 66 of these sequences contained distinguishable sprite elements (the others were halos and elves) and our generalizations are based on these. At least 565 TLE sequences were captured on regular speed imagers throughout the same period, and continuous wideband (<1 Hz to 30 kHz) recordings were also made of the lightning-produced magnetic and electric fields.

[4] Here we report and analyze in detail high speed images of two sprites on 13 August 2005. Through these images we first illustrate the basic structure and dynamics of the majority of the sprites imaged at high speed during this campaign. The reported space-time morphology is typical of sprites that initiate quickly after the lightning return stroke (10 ms) and that do not interact with previous sprites in the same location. We then show how these images clearly reveal the specific sprite features that result in persistent optical emissions from sprite beads and the sprite core that have been linked to possible effects on mesospheric chemistry [*Stenbaek-Nielsen et al.*, 2000]. These features include a previously unobserved process in which streamer tips collide with older streamer channels and form bright, persistent beads at the point of collision.

## 2. Instrumentation

[5] The suite of instruments fielded at Yucca Ridge Field Station during the campaign included multiple low light video cameras, one intensified high speed camera, two magnetic field sensors to record the full horizontal magnetic field produced by lightning discharges, and one electric field sensor to record the corresponding vertical electric field. The electromagnetic sensors were designed and built by QUASAR, Inc. and their wide bandwidth (<1 Hz to 30 kHz) enabled relatively short range measurements of fields from both return strokes and continuing currents with accurate GPS absolute timing.

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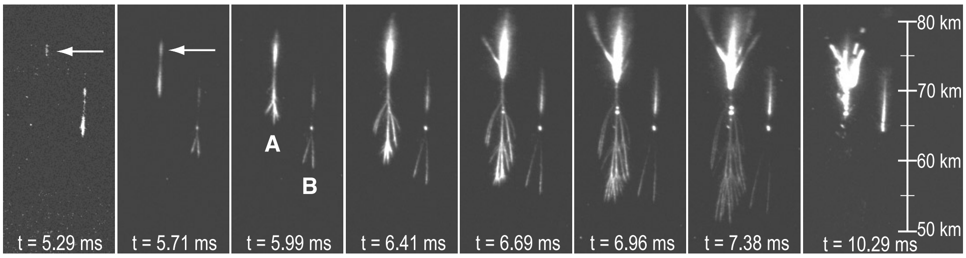


**Figure 1.** High speed sprite images from 13 August 2005 at 03:43:09.4 UT, each labeled with its time from the lightning return stroke onset. The initiation point of the left sprite (A) is marked with an arrow. The first image is contrast enhanced.

[6] The high speed camera was a Vision Research Phantom 7.1 monochrome high speed imager coupled to an ITT Gen III image intensifier with spectral response from 450 to 900 nm. The phosphor persistence of this intensifier was measured with controlled sources to have a half-life between 0.35 ms (dim features) and 0.70 ms (bright features). The images reported here were recorded at 640 by 480 pixels and 5000 and 7200 frames per second. The camera time stamps every image with the end of the integration time as computed from an external GPS-synched IRIG time code. The absolute image timing accuracy was confirmed to be better than 10 microseconds by imaging an LED driven by the one pulse per second output from a TrueTime XL-AK GPS receiver.

[7] We estimate TLE feature altitude through star field analysis that includes corrections for atmospheric refraction. The height scales presented apply for optical emissions directly above the National Lightning Detection Network (NLDN) return stroke location. Line-of-sight range shifts of 10 km correspond to altitude errors of 2–3 km, depending on range. For perspective, *Wescott et al.* [1998] reported sprite centroid/return stroke offsets of several tens of km.

## 3. Prototypical Sprite

[8] We first report the time sequence of a prototypical sprite, which is well-resolved in both time and space in these images. Many of the sprites we recorded with this imager are composed of clusters of individual sprite elements that each follow this development sequence. This event is not particularly large or complex, making it easy to follow its overall development. Although the sequence of events broadly follows that reported by *Stanley et al.* [1999], the higher time resolution and good spatial resolution illustrates all of these processes in a level of detail not previously reported and also reveals some new features, such as the spontaneous formation of bright spots on some downward propagating streamer channels.

[9] Figure 1 shows a subset of the 143 images recorded at 7200 fps acquired for a sprite event from 13 August 2005 at 03:43:09.4 UT. This sprite is composed of two distinct sprite elements whose development follow the same general sequence. The causative lightning stroke was a +72.4 kA cloud to ground (CG) lightning stroke with an impulse charge moment change ($i\Delta M_q$) in the first 2 ms of 260 C km. The distance between the camera and the stroke was 270 km. The first sprite (right, labeled B) initiated 4.7 ms after the return stroke and the second (left, labeled A) followed quickly. Each began as a small and dim streak between 70 and 75 km altitude and developed initially as downward streamers [*Stanley et al.*, 1999; *Stenbaek-Nielsen et al.*, 2000]. The downward propagation and branching into multiple channels is clear, and these channels fade with a half-life of ~0.8 ms. This decay is close to the measured intensifier persistence and the images are thus consistent with a small, luminous streamer tip followed by a much dimmer streamer channel [*Stanley et al.*, 1999].

[10] The development of the upper portion of both sprites follow a different sequence. The following description applies to both elements. The initiation streaks brighten and spread both upward and downward. The downward expansion follows the initial downward streamer path, while in contrast the upward expansion occurs in a region with no previous visible optical emissions. This expanding bright column is significantly brighter and appears wider than the initial downward streamers.

[11] As this bright central column expands, distinct bright dots appear ahead of the downward limit of expansion, some of which are eventually absorbed into the still-expanding bright column. These isolated dots have been observed in low speed telescopic images of columniform sprites [*Gerken and Inan*, 2002]. These and other high speed images indicate that these isolated dots are a common feature in this early stage of sprite development. While they are most easily seen in simple sprites, they occur frequently in more complex events in which later optical emissions mask this dot-gap structure. They thus may only be clearly visible for 1–2 ms and may not always be visible at all in regular speed video. From a single image, it is tempting to view the dot as the sprite initiation point, with purely upward development above and purely downward development below, but the image sequence shows that this is not the case. Although in these cases these dots are near branch points of the downward streamers, they also appear in locations where no branching of the downward streamers is visible.

[12] In the fourth image there is no branching evident in the upper part of either sprite and their overall shape is the well-known "columniform" sprite [*Wescott et al.*, 1998]. But in the fifth image, upward propagating filamentary structures appear to develop spontaneously from the bottom portion of the expanding bright column in the left sprite. Their narrow size and upward propagation in the downward electric field suggests that they are negative streamers. The upward streamers in this sprite do not visibly branch but in some other cases are seen to split, although never as prolifically as the downward streamers. They begin as narrow channels but terminate in diffuse glows once they

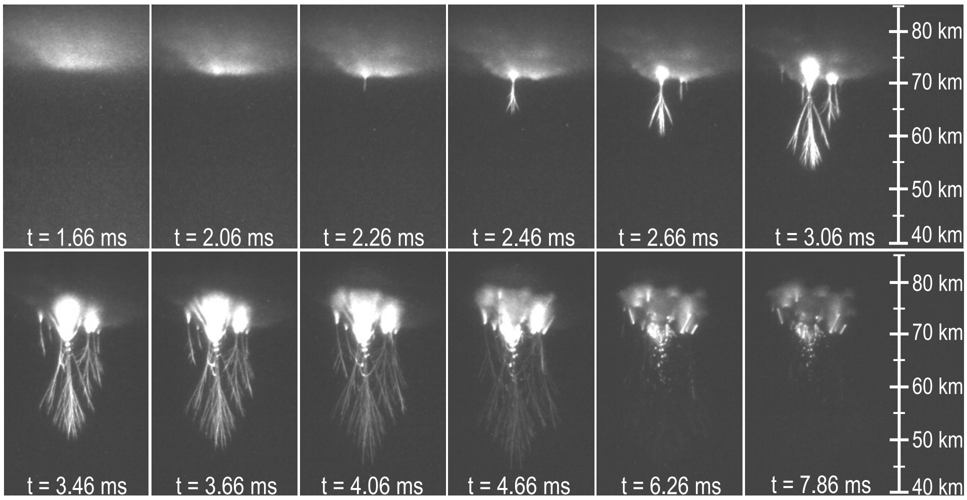


**Figure 2.** High speed sprite images from 13 August 2005 at 03:12:32.0 UT, each labeled with its time from the lightning return stroke initiation.

reach the altitude where the electrical conductivity is too high to support streamer propagation [*Pasko and Stenbaek-Nielsen*, 2002].

[13] The lower (below 65 km) and upper (above 75 km) portions of the sprites fade rapidly, leaving a bright, long-persisting core that is composed of the lower altitude parts of all of the upward streamers. The origin of this core is discussed further in the context of the next event.

## 4. Initiation and Streamer Dynamics

[14] Figure 2 shows the sequence of images captured at 5000 frames per second of a halo and sprite on 13 August 2005 at 03:12:32.0 UT. This event followed a +166.3 kA, 500 C km $i\Delta M_q$ lightning return stroke at a range of 284 km from the camera. The sprite elements initiate 2.2 ms after the return stroke at 73 km altitude from the bottom of a relatively bright halo that began 1.4 ms earlier. The sprite initiation sequence of this event qualitatively follows an idea discussed first by *Pasko et al.* [1996] and later by *Barrington-Leigh et al.* [2001], in which sprites form from an instability at the bottom edge of the halo. The combined time and space resolution in these images clearly shows that bright spots develop at the lower edge of the originally homogeneous halo and sharpen until a downward streamer initiates from that point.

[15] The expanding bright columns in these sprites are wider and appear more diffuse than the same feature in the sprites in Figure 1. That this wide, bright column is diffuse is supported by how it contains almost no structure as it decays, unlike adjacent regions where channels are visible as they decay. This may reflect that in this case, the upward expansion is into a region that has already been substantially modified by the halo. But as in the other case, this wide column expands upward and downward. Streamers then develop from the bottom of the bright column, propagate upward at velocities from $0.5-2 \times 10^7$ m/s (consistent with reports by *Stanley et al.* [1999]), and terminate in diffuse emissions in the same way as the previous example.

[16] Individual upward and downward streamers typically appear 2–3 pixels wide (corresponding to 300–400 m) and are almost certainly not fully resolved in these images. But the spatial resolution of these images is sufficient to resolve the structure and dynamics of individual streamers. Interestingly, the presence of adjacent streamers influences their propagation paths. A small fraction of streamer tips are attracted to the channels left behind by other streamer tips that passed through the same region a fraction of a millisecond previously, and in many cases, the streamer tips collide with these "old" (about 1 ms) streamer channels and stop. This attraction and collision is seen most clearly in the Figure 2 images between $t$ = 3.46 and $t$ = 4.06 ms. We are confident that these are collisions because, when this occurs, the streamer tips are clearly attracted to the streamer channels and the streamer tip stops at the collision point. For most overlapping streamers, there is no evident attraction and the streamers continue to propagate, indicating that most streamer tips simply pass in front of or behind an adjacent streamer channel. A similar phenomenon has been reported in laboratory experiments [*van Veldhuizen et al.*, 2002]. This indicates that streamer channels are sufficiently conducting (and thus ionized) that a nearby charged streamer tip can induce negative charge on the conducting channel and be pulled toward the channel, in the same way that an electrically conducting object attracts any charged object sufficiently close to it. Note that this attraction does not require net negative charge on the old streamer channels, but only a sufficiently high conductivity. These colliding downward streamers result in structures that can be misinterpreted in single images as upward moving streamers that originate, rather than terminate, at the collision point.

[17] And, perhaps most interestingly, essentially every point where the streamer tips and channels collide and stop becomes a spot significantly brighter than the adjacent streamer channel. These spots remain essentially static on the time scale of milliseconds and persist significantly longer than any other feature on the downward streamers. The top panels in Figure 3 shows an expanded view of this process from the 03:12:32 sprite. Although some collision points are brighter than others, even in the same sprite, these points are essentially always significantly brighter and more persistent than any adjacent emissions from the streamer channels. It seems likely that these bright points of streamer collision are at least some of the long-persisting sprite beads

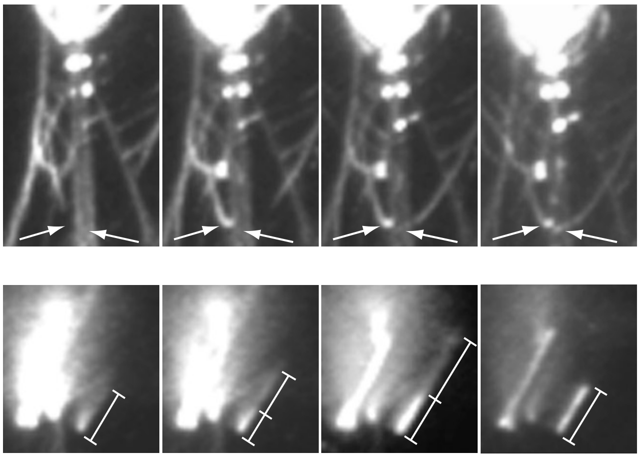

**Figure 3.** (top) Expanded images showing streamer collision and simultaneous sprite bead appearance. Streamer collision points are marked with arrows. Images were recorded at $t$ + 3.46, 3.66, 3.86, and 4.26 ms. (bottom) Expanded images of upward streamer and the later, brighter, and persistent emission that follows the same channel. The two separate regions are marked with line segments. Images were recorded at $t$ + 4.26, 4.46, 4.86, and 6.26 ms.

reported by *Stenbaek-Nielsen et al.* [2000]. We have also recorded at least one instance of the collision of upward-propagating streamers with older upward streamer channels that result in the same persistent bright beads. Thus the formation of bright spots through streamer collision does not appear to depend on the streamer polarity. Note that while streamer collisions create beads, not all beads appear to originate from collisions. The upper beads in the top panels of Figure 3 appear to form spontaneously as the expanding bright column moves downward, before streamers from adjacent sprites have had a chance to be attracted to older streamer channels. This apparently spontaneous bead formation is seen routinely, particularly in simpler sprites such as that in Figure 1.

[18] The other feature with persistent optical emissions are the bright bars that, when clustered, form the core of the sprite. This observation was first reported by *Stanley et al.* [1999] but additional details are resolved in the images reported here. These bars originate in the later, upward streamers, as shown in the bottom panels of Figure 3. These streamers are composed of two distinct discontinuities: the leading edge, behind which is a modestly bright channel, and a transition to a much brighter part of the channel, which expands along the pre-existing streamer channel. Both discontinuities appear to propagate upward, and the brighter part ultimately extends about half of the length of the entire channel. It is these bright, lower portions of the upward streamers whose optical emissions persist in the bars that form the sprite core. This morphology is seen in most of our images that contain sufficient spatial resolution to resolve the individual bars.

## 5. Summary

[19] Submillisecond sprite images with good spatial resolution recorded during a summer 2005 campaign are reported and analyzed. First, the development sequence of a prototypical sprite are presented through images that resolve in time and space many details of these processes. Well-resolved spatial and temporal structure reveals how some sprites initiate from brightening inhomogeneities at the bottom of a developing halo. Second, we analyze the processes and features responsible for the long-lasting optical emissions in sprites. A new phenomenon is observed in which some downward streamer tips collide with adjacent streamer channels, presumably via electrostatic attraction between the charged streamer tip and the conducting but uncharged streamer channel. At most and maybe all points of streamer collision, bright spots occur that appear to be some of the long persistent sprite beads reported in previous observations. Other persistent beads appear spontaneously just beyond the expanding lower edge of the upper, brighter portion of the sprite. Bright persistent bars that form the core of the sprite originate in the lower portion of upward propagating streamers. Defining the processes in which these persistent optical emissions originate is a step toward understanding of the microphysical processes inside them and the potential mesospheric effects they produce.

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