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Observations of streamer formation in sprites

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[1] Sprites have been recorded at 10,000 fps with 50 μs image exposure time. At this time resolution it is possible to resolve the temporal development of streamer tips. The recordings show that sprites start with a streamer head forming at an altitude near 80 km. The streamer head moves rapidly downwards while brightening, and $\sim$300 μs after streamer passage longer lasting emissions ensues. This is essentially the C-sprite. In some events upward moving streamer heads are also observed, in which case we have a carrot-sprite. The streamer speeds vary between 10^6 and 10^7 m/s. Both positive and negative accelerations, of magnitude 10^5 – 10^{10} m/s^2, were observed. Upward streamers, when present, always start later and from a lower altitude than downward streamers, and they start from existing structure in the sprite. **Citation:** McHarg, M. G., H. C. Stenbaek-Nielsen, and T. Kammae (2007), Observations of streamer formation in sprites, *Geophys. Res. Lett.*, *34*, L06804, doi:10.1029/2006GL027854.

1. Introduction

[2] The idea that sprites initiate with streamer, or filamentary, activity has significant theoretical background [*Pasko et al.*, 1996; *Raizer et al.*, 1998; *Pasko et al.*, 1997; *Pasko et al.*, 1998; *Pasko et al.*, 2000; *Pasko and Stenbaek-Nielsen*, 2002; *Barrington-Leigh et al.*, 2002; *Liu and Pasko*, 2004; *Liu and Pasko*, 2006]. Efforts have been made to observe at higher spatial resolution and at higher temporal resolution and it is becoming clear that sprite development involves processes with spatial scales of order 10 m and temporal scales in the sub-ms range.

[3] High speed video at 1,000 – 4,000 frames per second (fps) of sprites reported by *Stanley et al.* [1999] are consistent with streamer theory, showing both upward and downward propagation of luminosity with speeds in excess of 10^7 m/s. Additionally, *Stenbaek-Nielsen et al.* [2000] used 1,000 fps imaging to demonstrate that sprites can modify and result in a highly structured mesosphere. Measurements of sprites with high speed imagery and array photometry by *Barrington-Leigh et al.* [2001] show filamentary sprite breakdown very closely following the sprite halo. *McHarg et al.* [2002] used array photometry and measured upward and downward propagation of luminosity in the 10^7 – 10^8 m/s range consistent with streamers.

[4] *Gerken et al.* [2000] and *Gerken and Inan* [2002] used video rate low light level imagery with a telescope to reveal fine spatial scale structure consistent with streamer development in sprites. *Moudry et al.* [2003] demonstrated in 1,000 fps imagery that a bead of luminosity was followed by development of the tendril in an isolated sprite. *Marshall and Inan* [2005] combined telescopic observations with a 1,000 fps low light imager to reveal beads of luminosity consistent with a few hundred meter wide streamer propagating through the field of view of the instrument. *Cummer et al.* [2006] used 5,000–7,200 fps video to show that '...downward streamers initiate either spontaneously or from brightening inhomogeneities at the bottom of a halo...' Additionally, *Cummer et al.* [2006] showed streamer tips colliding with older streamer channels to form bright persistent beads.

[5] We present here sprite observations made at 10,000 fps and exposure times of 50 μs, which reveal new, previously unobserved, details of sprites. The observations can resolve the temporal development of tendrils which are actually rapidly moving streamer head structures. Further, the observations show sprite development to be in essentially two phases: first, an active initial phase characterized by fast moving bright streamer tips; and second, a relaxation period in which the sprite decays with little or no apparent spatial motion.

2. Instrumentation

[6] The observations were made with a Phantom 7 high speed camera, with a Video Scope International VS4-1845 HS image intensifier. The Phantom images are 800 × 600 pixels with 4096 gray levels (12 bits), but the operational software allows selection of smaller sections to be stored in the buffer. The camera is equipped with 1 Gigabyte digital memory serving as a circular buffer. The total time covered by the images in the buffer will depend on a combination of frame rate and selected image size. Sprite events were identified using a bore sighted intensified CCD (ICCD) video camera. When a sprite was observed the operator would stop the Phantom camera and save the images in the buffer to a laptop computer hard disk.

[7] We typically observed at frame rates between 4,000 and 10,000 fps with 512 × 256 pixels or 256 × 256 pixels of the 800 × 600 pixels array recorded. This provided a little less than 1 second of data in the buffer, just enough to provide the observer time to react to an event. With a 50 mm Nikon Lens the two image sizes had a field of view of 12 × 6 or a 6 × 6 degree respectively. In addition to control of the frame rate the camera intensifier allows gating of the exposure synchronized to the CCD read out. This allows the user to 'gate' the exposure time independently of the time between images which is set with the camera frame rate. Using gating avoids streaking in individual images resulting from read-out of the CCD while exposed to a bright scene. For most of our observations we used 50 μs integration time for each image with 100 μs between images. The Video Scope image intensifier has a 1 μs persistence phosphor

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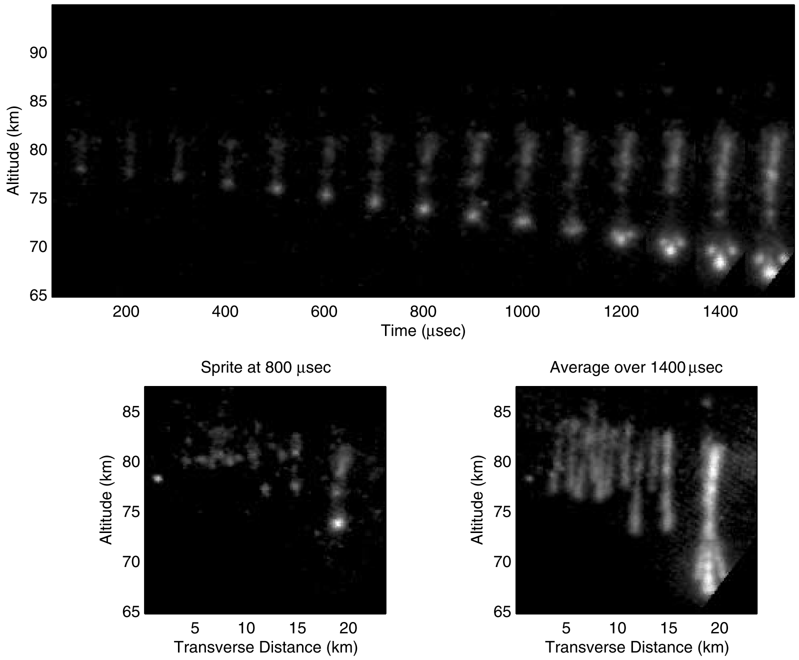

Figure 1. (top) 15 successive strip images of a single sprite event recorded on 9 July 2005 at 04:15:17 UT. The images were recorded at 10,000 fps (100 μs between images), and 50 μs integration time. (bottom, left) The entire field of view of the 8th image. (bottom, right) The average over 1400 μs. Figure 1 (top) shows a clearly defined streamer tip propagating downward. Beginning in the 12th strip image, the streamer tip divides into three parts, and propagates out of the field of view. The event had multiple streamers as indicated in Figure 1 (bottom).

(P-24), and hence there is no smearing from one image to the next. Each image in both the Phantom and the ICCD video camera was time stamped using GPS time.

3. Data and Analysis

[8] All observations were made from the Langmuir Laboratory, located west of Socorro, New Mexico (33°58′31″ N 107°10′50.6″ W, altitude 3,255 m). Since no second station observations are available to allow triangulation all altitudes were determined using elevation angles derived from stars present in the images together with an assumed range provided by the location of the associated lightning strike as provided by the National Lighting Detection Network (NLDN). *Lyons* [1996] and *Wescott et al.* [2001] found the locations of sprites to be within, on average, 42 km and 25 km, respectively, of the causative lightning. At the elevation angles of our observations a 25 km range uncertainty translates to an uncertainty in altitude of approximately 5 km.

[9] A total of 52 sprite events were recorded on the nights of 2, 7, and 9 July 2005. For the observations presented here we selected an event at 04:15:17 UT on July 9, 2005. This event has well identified down and upward moving streamer heads. The images were recorded with the camera in a mode with automatic background subtraction and hence, the background brightness level is 0.

[10] Figure 1 (top) shows sections from 15 successive sprite images recorded at 04:15:17 UT on 9 July 2005. They were recorded at 10,000 fps and 50 μs image gating. The entire eighth image is shown in Figure 1 (bottom left), while an average over 1400 μs is shown in Figure 1 (bottom right). The range to the 75 km altitude point for this sprite is 332 km, the resolution is 0.024° per pixel, and the resulting spatial resolution for this event is ~140 meters. The square root of the image intensity is plotted in Figure 1 for contrast enhancement.

[11] A faint streamer can be observed at approximately 78 km altitude in the first image. In subsequent strips this streamer head moves downward, with a remnant emission in the region where the streamer passed through. The remnant optical emission from the initial streamer intensifies into a typical column, or ‘C’, sprite. As can be seen in Figures 1 (bottom left and bottom right), other streamer heads are visible within the field of view of the camera. These streamer heads also propagate downward, and result in a series of C sprites when observed at standard TV frame rates. *Gerken et al.* [2000] used telescopic imaging and reported the time averaged size of sprite streamers is 10s to hundreds of meters. Thus the moving streamer heads we report here are presumably not spatially resolved.

[12] As the streamer head moves downwards it brightens and eventually saturates the imager. Analysis of star fields indicates that at 10,000 fps the camera saturates at a brightness of about 60 MR. In most events streamer heads saturate the camera solidly and thus must be substantially brighter than 60 MR. Analysis is underway to determine the total maximum volume emission rate.

[13] In the 12th and 13th strips in Figure 1, the streamer head clearly divides into three, while continuing to move downward. This splitting is observed in many events and we consider it a common occurrence. The location of the streamer head is generally well resolved in space and time. In this event we find an approximately uniform downward

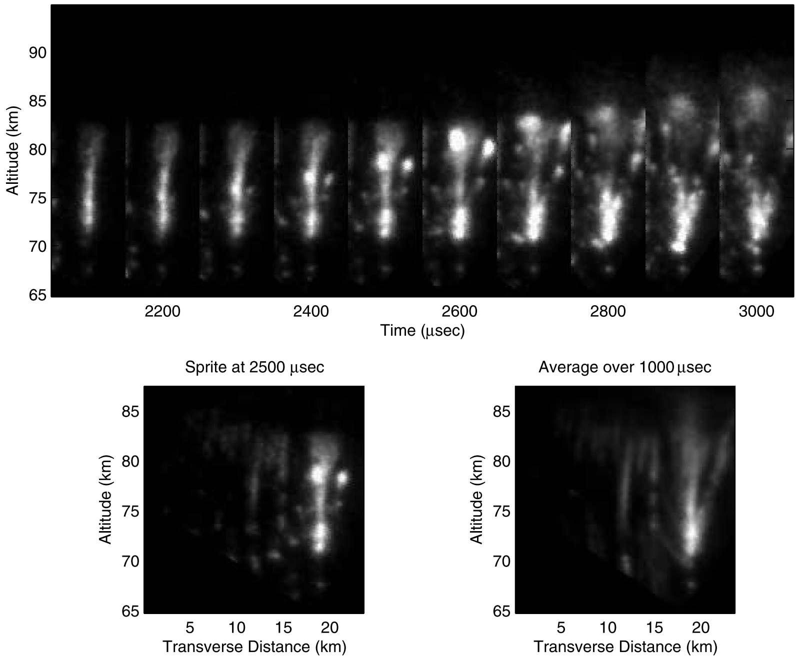

Figure 2. (top) 10 strip images from later in the same event with the time axis below the strips referenced to the first strip image of Figure 1. Figure 2 (top) shows a streamer tip propagating upwards within the central luminous column. At 2700 μs it crosses the top of the column and becomes diffuse. On either side of the central luminous column there are smaller upward propagating streamer tips which propagate upwards at a marked angle to the vertical. (bottom, left) The entire field of view of the 5th strip image and (bottom, right) the average over 1000 μs.

acceleration of $4.6 * 10^9$ m/s^2. We note that the direction of the streamer heads propagating downward are usually close to the vertical.

[14] Figure 2 (top) shows 10 strips taken from the same event, 9 July 2005 at 04:15:17 UT. Animation S1 in the auxiliary material[1] shows the entire sequence of events for Figures 1 and 2. Figure 2 has no contrast enhancement. The timing in the strips in Figure 2 are referenced to Figure 1, with the first strip in Figure 2 occurring 21 frames after the first strip in Figure 1. Figure 2 (top) shows a series of upward propagating streamer heads originating from the remnant emission of the sprite body. The upward propagating streamer heads start at a lower altitude than the original downward propagating streamer heads. This feature was also noted by *Stanley et al.* [1999] and *Cummer et al.* [2006]. In all events recorded we find the upward propagating streamers, when present, to start after and from a lower altitude than the downward propagating streamers. Further, while the downward streamers may appear out of a dark background, the upward streamers always start from an existing reasonably bright sprite structure. We also note that in the upward propagating streamers we see evidence of the transition region between the upper diffuse and lower streamer regions reported by *Pasko and Stenbaek-Nielsen* [2002].

[15] Unlike the downward streamers, the upward streamers have a significant horizontal velocity component which accounts for many sprites to be horizontally broader at the top. Based on TV images such sprites have been labelled ‘carrot sprites,’ as indeed would be the case for the average image of the sprite shown in Figures 1 (bottom, right) and 2 (bottom, right).

[16] Altitude time series were extracted from successive images for 20 streamers, 10 propagating downward and 10 propagating upward. The selected streamers all had a streamer tip well defined within the image sequence so that the streamer tip position within each image was unambiguous. The altitude was derived assuming the sprite to be located at the location of the associated NLDN recorded lightning strike. The 20 streamers came from 9 different sprite events. Velocity and acceleration of the streamer tip in the 20 streamers were derived by taking the first and second differences of the data points within each time series.

[17] The distribution of altitude and velocity values in the 20 time series is shown in Figures 3 and 4 respectively. The upward propagating streamers cover a smaller altitude range, 75–95 km, than the downward, 82–45 km (Figure 3), but the velocities are generally similar, 10^7 m/s (Figure 4). In individual events the downward streamers typically propagate farther than the upward streamers, and since the speeds are similar, the time series for the downward streamers will have more entries, as is evident in Figures 3 and 4. The overlap in altitude between the two distributions, 75–80 km (Figure 3), reflects that the downward streamers start at a higher altitude than the upward streamers.

[18] Changes in velocity within individual streamers were observed. Of the 10 upward propagating streamers 7 slowed down, but only 4 of the 10 downward streamers did so. The average rate of change was $1.8 * 10^{10}$ m/s^2 for the upward propagating streamers and $0.5 * 10^{10}$ m/s^2 for the down-

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2006GL027854.

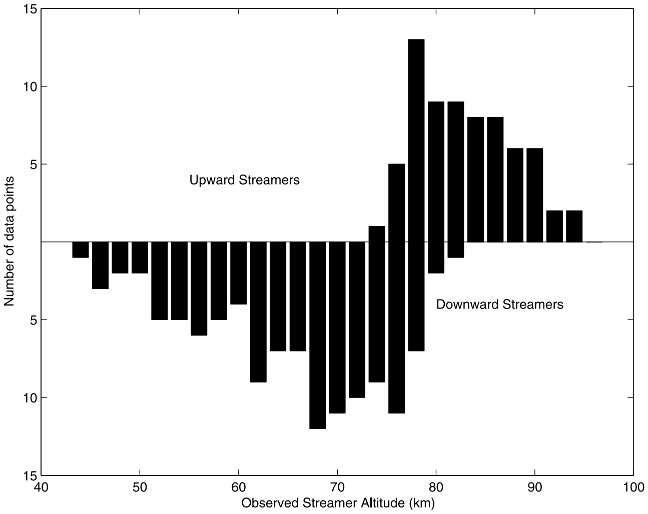

Figure 3. Distribution of number of time series entries versus streamer tip altitude for the 10 upwards and 10 downwards propagating streamer tips. The downward section has more data points because the downward streamers last longer. In all cases we find the downward propagating streamers occur first, while the upward propagating streamers start at a lower altitude leading to the 75–80 km altitude overlap between the two distributions.

ward propagating streamers. The difference is consistent with the shorter duration and altitude covered by the upward streamers which tend to decelerate 'harder' and terminate 'sooner.'

4. Discussion

[19] A streamer is a type of corona discharge [*Bazelyan and Raizer*, 1998]. When observed in the laboratory, the continuously glowing envelope breaks up into patches, and long filamentary emissions are observed in the region in between the electrodes. Streamers have much lower currents and ionization fractions of the ambient air than spark discharges or short circuit arcs which can occur between electrodes in an air filled gap. Streamer motion is typified by an ionization wave with a '...strongly magnified electric field near its leading edge–the streamer tip' [*Raizer et al.*, 1998]. *Liu and Pasko* [2004] show that these streamer tips are the source of intense optical emission. They predict that the regions of emission expand radially and accelerate as they propagate down.

[20] Since the vast majority of sprites are associated with positive cloud to ground lightning [*Rodger*, 1999, and references therein] the ambient electric field in the mesosphere during sprite initiation is directed downward. Streamers propagating in the direction of this electric field (downward) are referred to as positive, while those propagating opposite this electric field (upward) are referred to as negative. Our observations show that positive streamers generally propagate very close to the downward direction, while negative streamers propagate over a wider range of angles with respect to the local vertical.

[21] *Liu and Pasko* [2004] show that streamers branch when the streamer head exceeds a certain threshold. The details of this threshold size '...are quite sensitive to the preionization ahead of the streamer, which generally acts to suppress the occurrence of the instability' leading to the branching. While the division of the streamer tips is beyond the scope of this paper, in general we see branching as they become brighter. There may also be a tendency for the speeds of the streamer tips to abruptly change when they divide.

[22] The streamer speeds reported here agree with those of *Stanley et al.* [1999], *McHarg et al.* [2002], *Moudry et al.* [2003], and *Cummer et al.* [2006]. The reason we can resolve the streamer tips is the short, ~ 1 μs, phosphor persistence used in the Video Scope image intensifier. With a 50 μs integration time, the smearing of the streamer tip in our images is approximately two pixels, assuming a propagation speed of 10^7 m/s and a range to the sprite of 500 km. To totally 'freeze' the streamer tip will require smaller exposure times.

[23] The good temporal resolution in our images allows determination of the location of the streamer head as function of time and hence instantaneous velocity and acceleration can be derived. The downward and upward velocities observed are of order 10^7 m/s and the acceleration can be positive or negative. *Liu and Pasko* [2004] predict streamers accelerate with the length of the streamer channel. The absolute value of the average acceleration observed, 10^{10} m/s^2, is in good agreement with the theoretical predictions of *Liu and Pasko* [2004]. The experimental evidence for both positive and negative accelerations indicates that the energy provided to the streamer tip by the applied electric field sometimes falls below that necessary to overcome the energy loss mechanisms due to ionization, excitation, attachment, scattering, etc [*Gallimberti*, 1972]. At higher altitudes, the lower ionospheric boundary screens out the applied field, which may explain why deceleration was observed more frequently in upward propagating steamers [*Pasko et al.*, 1997].

[24] *Liu and Pasko* [2005] note that time averaging of luminosity from the streamer tip may cause the observed

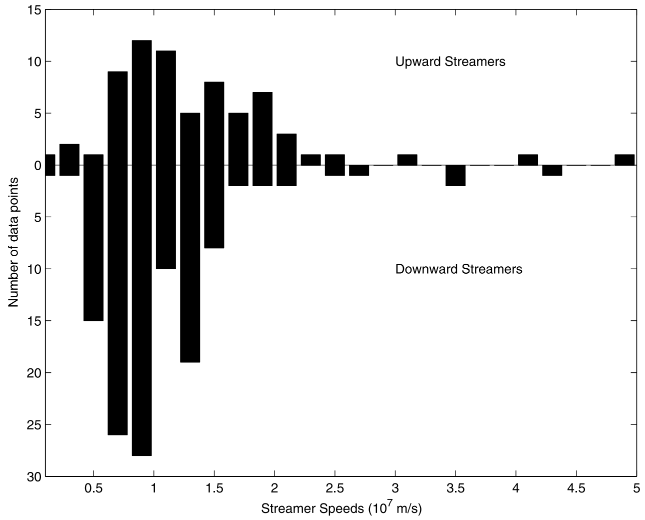

Figure 4. Distributions of number of data points versus observed streamer tip speeds. The peak of both upward and downward streamer speeds is near 10^7 m/s.

filamentary nature of sprites observed at slower time resolutions. *van Veldhuizen and Rutgers* [2002] and *Yi and Williams* [2002] show that when the exposure time is reduced to 1 ns, streamers in full pressure air show streamer tips similar to the streamer tips reported here. *Ebert et al.* [2006] show time resolved streamer imagery in full pressure air which is in remarkable agreement with our images of streamers at 75 km altitude. The 300 ns image of streamers in Figure 1 of *Ebert et al.* [2006] is analogous to the picture of a sprite taken at TV frame rates (33 ms per image). This is not surprising since streamer development scales as 1/n, and the difference between full pressure air and densities at sprite altitudes is approximately 10^5. Thus 300 ns maps to 30 ms, well in line with TV frame rate integration times. Likewise the image of a laboratory streamer with a 50 ns integration in Figure 1 of *Ebert et al.* [2006] maps to a sprite image with a 5 ms integration time. Finally the 1 ns integration time of *Ebert et al.* [2006] clearly shows streamer head development in line with the streamer heads in sprites shown in our Figures 1 and 2.

[25] In terms of sprite morphology, as for example reported by *Moudry et al.* [2003], our observations indicate that columnar sprites (C-sprites) have only downward propagating streamers, and the body of the C sprite is the trail afterglow of a downward moving streamer head. Carrot sprites on the other hand start as C sprites, but with subsequent upward propagating streamers. The branches are the afterglow of the upward propagating streamer heads. The upward streamers tend to have a larger horizontal velocity component than the downward streamers and they become diffuse at the upper end yielding a carrot like overall appearance.

[26] The thesis that sprite emissions start with the passage of a highly energetic streamer with a subsequent ‘afterglow’ resulting from energy cascading down leading to various longer termed emissions is surely too simplistic. We have examples which clearly show a brightening of the sprite well past the time of passage of streamer heads (see Animation S2 of the auxiliary material). This brightening was seen across the entire sprite body. The energy source for this brightening is unknown, but presumably is not associated with the energy deposited by the passage of streamer heads.

[27] In summary, the 10,000 fps images have time resolved the formation of sprite tendrils and branches to show that they are formed by very bright, almost point like streamer tips. The streamer tips move at velocities near 10^7 m/s and create in their wake a stationary afterglow which forms the main sprite body. Similar to *Stanley et al.* [1999] and *Cummer et al.* [2006], we see sprite initiation near 80 km with downward moving streamers while upward propagating streamers, when present, always start later, from a lower altitude, and appear to start from existing bright structures in the sprite body.

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