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Measurement of sprite streamer acceleration and deceleration

J. Li[1] and S. A. Cummer[1]

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[1] Measurements of streamer velocity reflect the detailed internal microphysics of sprite development that is connected to the effects streamers create in the mesosphere. We report intensified high speed video observations of streamer development acquired at 5,000 to 10,000 frames per second that include the entire altitude range of sprites (~40–90 km). Downward streamers accelerate to a maximum velocity 3–10% of the speed of light c and then immediately decelerate at an almost constant rate close to 10^{10} m/s^2. This deceleration process dominates the downward streamer propagation in both time and distance. Measurements of the complete dynamics of sprite streamers from initiation to termination can give useful insight into their internal processes. **Citation:** Li, J., and S. A. Cummer (2009), Measurement of sprite streamer acceleration and deceleration, *Geophys. Res. Lett.*, *36*, L10812, doi:10.1029/2009GL037581.

1. Introduction

[2] Sprites are caused by lightning discharges and are observed in the altitude range of ~40–90 km above thunderstorms [*Sentman et al.*, 1995]. Previous measurements of sprite optical emissions have revealed its fine structure [*Gerken et al.*, 2000; *Gerken and Inan*, 2002], which has been interpreted in terms of positive and negative streamer coronas similar to the small-scale streamers existing at high atmospheric pressures [*Pasko et al.*, 1998; *Pasko*, 2007]. High speed video observations [*Stanley et al.*, 1999; *Stenbaek-Nielsen et al.*, 2000; *Cummer et al.*, 2006; *McHarg et al.*, 2007] have further confirmed the streamer nature of sprites. Understanding the influence sprites may have on the mesosphere can thus be answered by understanding how streamers behave at high altitudes.

[3] Previous studies have focused on the properties of sprite streamers with both theoretical modeling and experiments. *Raizer et al.* [1998] modeled the streamer propagation in an inhomogeneous atmosphere by treating the lightning source as an electrical dipole. Including the internal chemical and photoionization processes, *Liu and Pasko* [2004, 2005] have developed a model to simulate the propagation of streamers in constant electric fields at different altitudes. However, the small time scale of streamer propagation and complex inhomogeneous atmosphere make it difficult to collect the data to validate these existing models. One possible solution is applying the similarity relations to the small-scale streamers created by lab experiments [*Liu and Pasko*, 2004, 2006], which are usually conducted in homogeneous media at high atmospheric pressures [*Ebert et al.*, 2006; *Luque et al.*, 2008; *Briels et al.*, 2008]. However, not only the significant pressure difference between ground level and high altitudes introduces notable non-similar behavior of streamers due to quenching of excited species responsible for photoionizing radiation [*Liu and Pasko*, 2006], but also there is no existing lab experiment conducted in nonuniform electric fields and inhomogeneous medium that can be directly applied to estimate the sprite streamer velocity at different altitudes.

[4] Streamer models need quantitative measurements to constrain them before they can reliably predict high altitude streamer behavior and impact. High speed video has been proven to be valuable for such measurements. *Stanley et al.* [1999] firstly adopted high speed imaging technique with 1 ms and better time resolution and measured initial streamer velocities in excess of 10^7 m/s. Also with 1 ms resolution images, *Moudry et al.* [2002] reported examples of fast and slow expansion of streamers with average velocities of ~10^7 m/s in a bright sprite and ~10^6 m/s in the bottom part of a dim sprite. *McHarg et al.* [2002] reported the propagation velocity of downward and upward luminosity on the order of 10^7–10^8 m/s range with a multi-anode photometer. *McHarg et al.* [2007] recorded 0.1 ms resolution high speed video images and reported that the initial state of streamer development in the highest altitude portion of sprites was dominated by acceleration on the order of 10^{10} m/s^2 with velocities varying between 10^6 and 10^7 m/s.

[5] Although all these previous studies have revealed many important features of sprite streamers, the streamer velocity during the entire sprite extent has not been reported, especially the lower altitude portion that occupies a substantial part of the entire sprite volume. In this work, we report the measurement from high speed video images with 0.1–0.2 ms time resolution of streamer propagation from initiation to termination altitudes. We find that the downward development of sprite streamers is dominated by a nearly constant deceleration that follows the initial acceleration, and that this deceleration is remarkably consistent across most sprites. We also report measurements of an atypical slowly developing sprite. Collectively, these measurements provide important data on sprite dynamics and can be used to constrain the existing models.

2. Instrumentation and Observations

[6] During the summer campaign in 2005, we recorded the sprite optical emissions by a high speed camera at Yucca Ridge field station (40.70°N, 105.03°W), Colorado. 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. It was equipped with a 75 mm lens and had a field of view approximately 13 degrees. The phosphor persistence

[1]Electrical and Computer Engineering Department, Duke University, Durham, North Carolina, USA.

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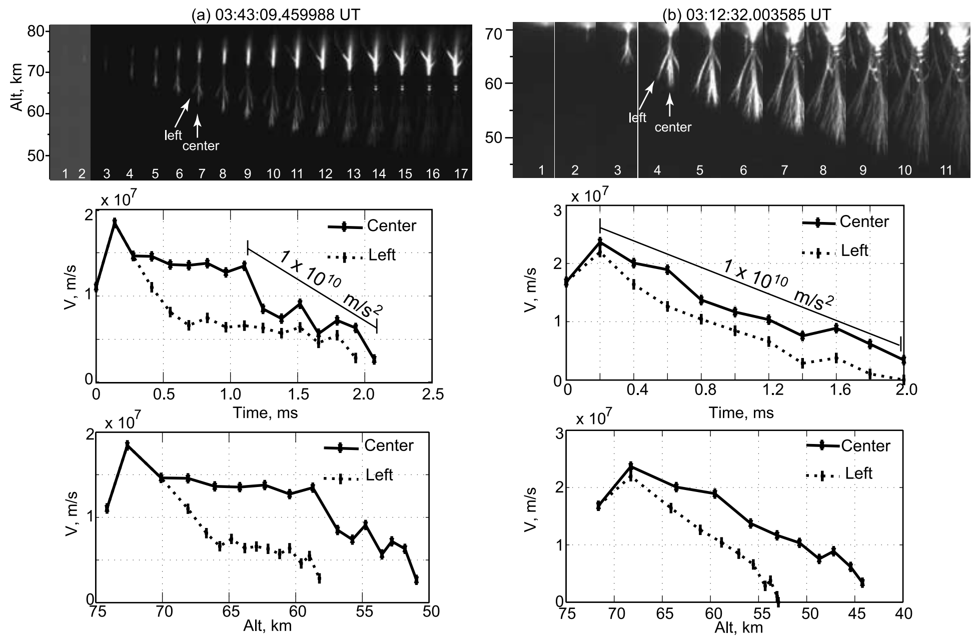

Figure 1. Examples of downward streamer observed on (a) Aug 13 2005, 03:43:09 UT, and (b) Aug 13 2005, 03:12:32 UT. In each subplot, the three panels show the high speed sprite images, the streamer head velocity versus time, and velocity versus altitude.

of the intensifier was measured with controlled sources to have a half-life between 0.35 ms (dim features) and 0.70 ms (bright features). Although this persistence affects the appearance of the sprites, it does not affect the ability to measure the positions of streamer tips. This camera was used to record sprite images at frame rates from 1,000 to 10,000 frames per second (fps) at image sizes of is 800 $\times$ 600, 640 $\times$ 480, or 512 $\times$ 384 pixels with 4096 gray levels (12 bits). The camera time stamped every image with the end of the integration time as computed from an external GPS-synchronized 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. Experimental details and initial analysis were previously reported by *Cummer et al.* [2006].

[7] On August 13, 2005, our high speed camera captured 7 sprites produced by two thunderstorms about 300 km and 450 km away from the observation site. The resulting spatial resolution is about 140 meter/pixel for the sprite images (640 $\times$ 480) during the first thunderstorm (300 km) and about 260 meter/pixel for the sprite images (512 $\times$ 384) during the second thunderstorm (450 km). All of these sprites were produced by positive cloud-to-ground lightning. This produces a downward electric field in the mesosphere and thus downward propagating positive streamers.

[8] To track an individual streamer head, we define the edge of the streamer as the point where the luminosity is at least two times the background noise level. The termination altitude is determined at the location where the minimum detectable luminosity (at least 2 times the noise level) appears at the location in successive images. In cases where complicated branching prevents the tracking of individual streamers, we measure the velocity from the lowest altitude streamer. The altitudes presented here are estimated by using the background star fields assuming that the sprite is directly above the National Lightning Detection Network reported location of its parent lightning discharge. The effect of atmospheric refraction is taken into account. The unknown offset between sprites and their parent lightning discharges (a few tens of km [*Wescott et al.*, 2001]) contributes an overall altitude uncertainty of approximately ±3 km, which corresponds to an offset about ±10 km for lightnings 300–400 km away from the observation site. However, this uncertainty is nearly constant at all altitudes and it thus does not affect the velocity magnitude.

3. Downward Streamer Propagation

[9] Distinct downward streamers were observed in all recorded sprites. Here we analyze the streamer propagation in both typical sprites and one dim, long lasting unusual case. Figure 1 shows two typical sprites detected on August 13, 2005. The event observed at 03:43:09 UT exhibits simple structure. The sprite producing lightning discharge was 300 km away from the observation site. The high speed camera recorded the sprite images at 7,200 fps or 0.138 ms time resolution. In this example, the spatial resolution is 125 meters/pixel, which results in an uncertainty in the velocity of 0.9×10^6 m/s. The sprite streamer is first visible at 74.3 km altitude with an initiation velocity of 1.1×10^7 m/s. In two time steps, the streamer head reaches its maximum velocity of 1.9×10^7 m/s. Note that our wider field of view prevents us from measuring the detailed acceleration process observed by *McHarg et al.*, 2007; however it enables us to track the streamer development over its entire vertical extent.

[10] The streamer then splits into two streamers at 66 km altitude. The center streamer travels at a constant speed

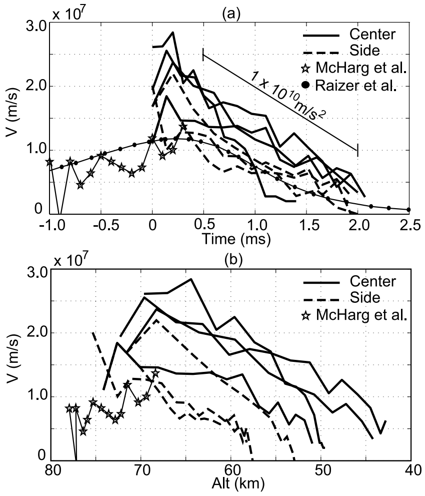

Figure 2. The 7 streamer velocities measured from 4 typical sprites: (a) streamer velocity versus time and (b) streamer velocity versus altitude. Solid and dashed lines represent the velocity of streamer head in the center and on the side of sprites. Stars represent measurements read from *McHarg et al.* [2007]. Dots represent the model predictions adopted from *Raizer et al.* [1998].

about 1.5×10^7 m/s from 70 km to 58 km altitude. After that, the streamer head velocity decreases until terminating at ∼50 km altitude. The corresponding deceleration rate is about 1.0×10^{10} m/s^2. Compared to the center streamer, the streamer head on the left travels at a slower speed, terminates at a higher altitude, and has a slightly different velocity profile. Nevertheless, in both streamers the deceleration phase begins between 60 and 70 km altitude, and this phase dominates the duration and vertical extent of the sprite.

[11] Figure 1b shows another typical sprite detected on 03:12:32 UT that was previously reported by *Cummer et al.* [2006]. The lightning discharge occurred 283 km away from the observation site. Images are recorded at 5000 fps (0.2 ms resolution) and in 640 × 480 pixels. The spatial resolution is about 140 meters/pixel and the corresponding velocity resolution is 0.7×10^6 m/s. The sprite initiates at 72 km in the bottom part of a sprite halo with an initial velocity of 1.6×10^7 m/s. The streamer head reaches its maximum velocity of 2.4×10^7 m/s in two time steps. On image 3, the streamer head splits and we again measure the velocity for streamers both in the center and on the left side. After reaching peak velocity at 68 km altitude, both streamer heads exhibit almost constant deceleration close to 1.0×10^{10} m/s^2 until termination. Again, the deceleration phase dominates the duration and vertical extent of the sprite.

[12] Figure 2 shows the velocities of 7 different downward streamers from 4 different typical sprites including the examples shown in Figure 1. The measured parameters for these 7 streamers are summarized in Table 1. Among the total 7 streamers, 4 of them were in the center of the sprites and the other 3 were towards the side. The measurements show similar properties for all the streamers from different sprites. Figure 2a shows the velocity versus time, and each streamer head exhibits the same acceleration-deceleration process. After initial detection, the streamer heads quickly reach their maximum velocities within several hundred microseconds. The maximum acceleration rate is approximately 10^{10} m/s^2, which is consistent with the results reported by *McHarg et al.* [2007], though it is not well resolved in our data because of the wide field of view. After reaching the maximum velocity between 1.0×10^7 and 3.0×10^7 m/s, every streamer begins to decelerate almost instantaneously. In only one case does a streamer exhibit something close to a constant velocity. This deceleration is an almost linear decrease in velocity with time close to 10^{10} m/s^2 (note the slope on Figure 2a). The streamers away from the center of the sprite exhibit slower velocities than the streamers in the center of the sprites, which we suggest is because these streamers are traveling in a weaker electric field. Nevertheless every downward streamer still shows almost the same deceleration regardless of where it propagates.

[13] Figure 2b shows the velocity versus altitude. All streamers initiated between 70–80 km altitude and accelerated to their maximum velocity in only <5 km from their apparent initiation altitude. After that, the streamer velocity decreases with decreasing altitude before reaching the termination altitude between 45 km and 55 km. Again, the streamers away from the center of the sprite are slower and they terminate at higher altitudes. We again attribute this to lower background electric fields away from the region of sprite initiation. It is interesting to note that the set of downward streamers that initiated out of a bright halo (the 0312 UT event) are not noticeably different from the others. We also found that the two fastest streamers in Figure 2 are from the two sprites that exhibit the most streamer branching, which suggests faster streamers may branch more than slow streamers.

[14] On Figures 2a and 2b we also overlay the measurements of the early stages of streamer development from *McHarg et al.* [2007]. Their narrower image field enabled more precise measurement of the acceleration stage but did not extend low enough to see the deceleration in most cases. In Figure 2b, the velocity versus altitude profiles from these two sources are remarkably consistent. In the narrower measurements the streamer was first observed at higher altitude and slower velocities, and it accelerated down to about 68 km. Our wider field measurements observed the same acceleration to between 70 and 65 km altitude, at which point deceleration took over for all observed streamers. The same consistency appears in Figure 2a when we time shift the measurements of *McHarg et al.* [2007] earlier by approximately 1 ms. This indicates that our wide field

Table 1. Observed Streamer Tip Duration and Altitudes, and Impulse Lightning Charge Moment Change

Event Time (UT)	Streamer Type	Streamer Time From RS (ms)	Streamer Tip Alt. (km)	2 ms Charge Moment Change (C km)
03:12	center	1.5–3.5	72–43	415
03:12	side	1.5–3.5	72–53	415
03:25	center	2.0–4.1	73–42	462
03:25	side	2.0–4.0	75–58	462
03:43	center	5.2–7.4	74–51	310
03:43	side	5.2–7.4	72–58	310
04:14	center	1.6–3.0	70–49	395

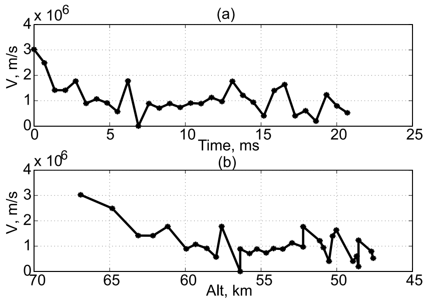

Figure 3. Examples of downward streamer observed on Aug 13 2005, 03:29:52 UT: (a) streamer velocity versus time and (b) streamer velocity versus altitude.

and thus less sensitive measurements may have missed the first 0.5–1 ms of the streamer development. Nevertheless, the two independent measurements of different portions of sprite streamer development are completely consistent. In Figure 2a, we also compare our measurements with model predictions reported by *Raizer et al.* [1998]. We aligned the predicted and measured velocities based on the time of the peak velocity. Although the model predicts slower acceleration than observed, the model predictions and measurements are in generally good agreement, with very similar peak velocities and deceleration rates.

4. An Unusually Dim and Slow Sprite

[15] Different from the typical sprites above, one unusually slowly developing sprite was imaged on Aug 13, 03:29:52 UT. The process of downward streamer development lasted more than 20 ms. The streamers are very dim and propagate extremely slowly comparing to examples introduced above. The images were recorded at 7,200 fps with a spatial resolution about 125 meters/pixel. Due to the long time duration and low propagation speed of the streamers, we computed the streamer velocity every 5 images. This decreases the minimum detectable velocity and reduces the time resolution. Figure 3 shows the streamer velocity versus time (Figure 3a) and altitude (Figure 3b). The first visible light appears at 67 km altitude, which is lower than the typical sprite initiation altitude. One possible reason is that the sprite is too dim to be detected at its initiation stage. Different from previous examples, the maximum velocity is only 3×10^6 m/s and no obvious acceleration is observed in this case. The velocity decreases from 67 km to 58 km altitude. The deceleration rate is about 5×10^8 m/s^2. After that, the streamer head travels at a constant velocity below 1.0×10^6 m/s. Comparing to those typical events, this unusual event is one order of magnitude slower in speed and two order of magnitude slower in deceleration rate. It also forms the lower bound of the streamer velocity and deceleration rate in our data set.

5. Summary

[16] In this work, we have analyzed the velocity, acceleration rate, and deceleration rate of downward streamers over the full altitude extent of sprites. The downward streamers from four typical sprites exhibit very similar properties. The streamer propagation is dominated in duration and length by a nearly constant deceleration that typically begins between close to 65 km altitude after reaching a maximum velocity of $1–3 \times 10^7$ m/s. This deceleration rate is close to 1×10^{10} m/s^2 for typical sprites. Streamers near the center of sprites propagate faster and terminate at a low altitude than streamers towards the edge, probably reflecting lower electric fields, but they exhibit very similar velocity profiles. We also show measurements from an unusually dim sprite with downward streamer velocities close to 1×10^6 m/s that appears to be very atypical.

[17] When combined with previous high speed measurements presented by *McHarg et al.* [2007] of only higher altitudes, a consistent and complete picture of sprite streamer development emerges, from initiation and acceleration followed by a rapid change to deceleration and ultimately termination. This complete picture will enable detailed comparisons with simulations in order to understand the electrical environment in which sprite streamers propagate and the impact they may have on the mesosphere.

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S. A. Cummer and J. Li, Electrical and Computer Engineering Department, Box 90291, Duke University, Durham, NC 27708, USA. (jl108@ee.duke.edu)