RADIO SCIENCE, VOL. 41, RS6S43, doi:10.1029/2005RS003353, 2006

High-speed measurements of small-scale features in sprites: Sizes and lifetimes

R. A. Marshall[1] and U. S. Inan[1]

Received 28 August 2005; revised 12 May 2006; accepted 23 June 2006; published 4 October 2006.

[1] We report on the results of observations with a combination of high-speed and telescopic imaging to capture high spatial resolution images of sprite streamers and beads at high frame rates, revealing the evolution and propagation of these structures on a decameter scale at millisecond and higher resolution. In July and August 2004, sprites were observed from Langmuir Laboratory, in the mountains of New Mexico, using a >1000 frames-per-second intensified CCD imager mounted to a Dobsonian reflecting telescope. We present a number of examples of sprite features, along with photometric data on sprites and sprite halos, taken with the Wide-angle Array for Sprite Photometry (WASP). Results show a variety of structures, including evidence of formation and evolution of both streamers and beads. Examples and statistics presented indicate that most bead structures have sizes of 10–300 m, similar to previous telescopic observations, and endure typically for a few milliseconds to 10 ms, with rare cases of up to 50 ms. Similarly, streamer-like structures are observed to have diameters of 10–300 m but persist for shorter timescales, typically 2–3 ms, with occasional cases of up to 10 ms. Attempts to measure propagation of streamers indicate that higher frame rates are required in order to observe speeds on the order of previous wide-field-of-view observations and modeling predictions.

Citation: Marshall, R. A., and U. S. Inan (2006), High-speed measurements of small-scale features in sprites: Sizes and lifetimes, *Radio Sci.*, *41*, RS6S43, doi:10.1029/2005RS003353.

1. Introduction

[2] Sprites are a type of transient luminous event that occurs at altitudes of 40–90 km above thunderstorms [e.g., *Sentman et al.*, 1995] and are usually associated with large positive cloud-to-ground lightning flashes (+CGs) [*Boccippio et al.*, 1995]. They commonly extend for tens of kilometers in both vertical and lateral dimensions but persist for rarely more than a few milliseconds [*Winckler et al.*, 1996; *Marshall and Inan*, 2005]. Telescopic imaging of sprites reveals a variety of structures on scales ~10–300 m [e.g., *Gerken et al.*, 2000; *Gerken and Inan*, 2002, 2004], the most ubiquitous of which have come to be known as beads and streamers [e.g., *Gerken et al.*, 2000; *Stenbaek-Nielsen et al.*, 2000]. Furthermore, in their short lifetimes of a few milliseconds, sprites exhibit complex evolution and propagation characteristics, consistent with the observed streamer types of structures being naturally occurring examples of plasma streamers. This assertion is corroborated by both modeling [*Pasko et al.*, 1998; *Raizer et al.*, 1998] and experimental work [*Stanley et al.*, 1999; *Moudry et al.*, 2002]. However, quantitative assessment of this interpretation, with respect to internal consistency relative to characteristic dimensions and speeds as described by *Pasko et al.* [1998], has not yet been possible because of a lack of spatial resolution in current high-speed image data [*Stanley et al.*, 1999; *Stenbaek-Nielsen et al.*, 2000] or lack of time resolution in telescopic imaging [e.g., *Gerken et al.*, 2000]. In this paper, we report the results of an experimental effort to document the evolution and propagation of streamers and other sprite features, using a high-speed telescopic imaging system. We present a number of examples of both streamer and bead formations, as well as a statistical analysis of their sizes and lifetimes.

2. Description of Experiment

[3] In July and August 2004, observations of sprites were conducted from Langmuir Laboratory, near

[1]Space, Telecommunications and Radioscience Laboratory, Stanford University, Stanford, California, USA.

0048-6604/06/2005RS003353$11.00

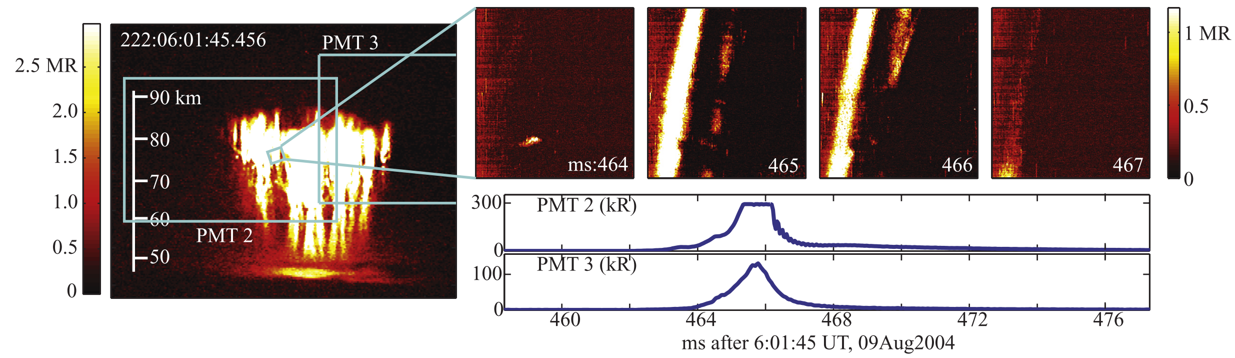

Figure 1. Sprite event of 9 August 2004, 0601:45 UT, with the sprite shown at left, four telescopic images at 1 ms resolution, and two channels of photometer data. Note that PMT 2 is saturated. The photometer intensity values are averages over the photometer fields of view, which are larger than the sprite body; as such, the Rayleigh values are diminished from the actual brightness.

Socorro, New Mexico. The instruments deployed include an intensified high-speed telescopic imaging system, an array of photometers, and two wide-field-of-view intensified imagers. The telescopic system consists of a 16-inch Dobsonian telescope with a Kodak Ektapro motion analyzer model 1012 and a Kodak Ektapro intensified imager controller mounted to the eyepiece of the telescope. The CCD of the motion analyzer used with the telescope resulted in a field of view of $\sim$0.25° × 0.3°. The imaging CCD has an array of 192 × 239 pixels, and the system is capable of 1000 frames per second (fps) at full resolution and higher frame rates with reduced resolution. One of the wide-field-of-view imagers was coaligned with the telescope, which was composed of a Pulnix TM200 CCD camera with a GenII image intensifier and a 50-mm lens yielding a $\sim$9° × 12° field of view. The telescopic system was complemented by the Wide-angle Array for Sprite Photometry (WASP), an array of six Hamamatsu HC104 photomultiplier tubes (PMTs), each fitted with a long-pass 665 nm filter and a lens yielding a $\sim$3° by 6° field of view. The fields of view of each PMT are made nearly adjacent so that the 2 × 3 array of PMTs has an overall field of view of $\sim$6° × 16°. Photometer data are recorded at 25 kHz and are used to complement the timing resolution of the high-speed imaging system; both systems were synchronized with the output of the same Truetime XL-AK GPS receiver, accurate to 20 ns. A second wide-field-of-view imager was coaligned with the WASP for field-of-view calibration.

[4] Sprite locations were inferred from National Lightning Detection Network stroke data by matching the +CG nearest in time to the sprite and using the coordinates of the +CG as the approximate center of the sprite location. However, knowing that sprites can be displaced laterally from the location of the causative +CG discharge up to 50 km [*Wescott et al.*, 1998], the exact pointing angle was determined by the azimuths of stars appearing in the field of view. Assuming the sprite to be at the same distance from the observation platform as the causative +CG discharge, sprite altitudes were then determined from the star elevations; however, the altitudes reported have an uncertainty of 8–15 km, corresponding to the possible displacement of the sprite from the +CG along the viewing direction.

[5] The high-speed imager and wide-field-of-view cameras were calibrated by exposure to a diffuse light source whose output was calibrated to a National Institute of Standards and Technology photodiode of known response. Assuming that most of the sprite emissions are in the N_2 1P band system [*Hampton et al.*, 1996], the spectral output of the calibration source was scaled by the N_2 1P spectrum and the response of the S20 photocathode of the camera intensifier, then integrated over the spectrum to find the response of the imaging system. The high-speed imager was found to saturate at 1.2 MR when operated at 1000 fps, and the wide-field-of-view camera coaligned with the telescope saturated at about 3 MR. All sprite images reported here were seen to saturate in both cameras.

3. Results

[6] Overall, 17 sprites were captured at high frame rates (1000 or 2000 fps) in the telescopic system during July and August 2004, yielding numerous examples of fine structure in sprites. From this data set, we are able to measure the lifetimes of individual sprite features such as beads and streamers, as well as their rise (brightening) and decay (fading) times. Furthermore, sizes of individual features can be compared with previous results [e.g., *Gerken et al.*, 2000], and the evolution of these features can be qualified. While streamer speeds cannot be strictly measured in this data set, we can assert the

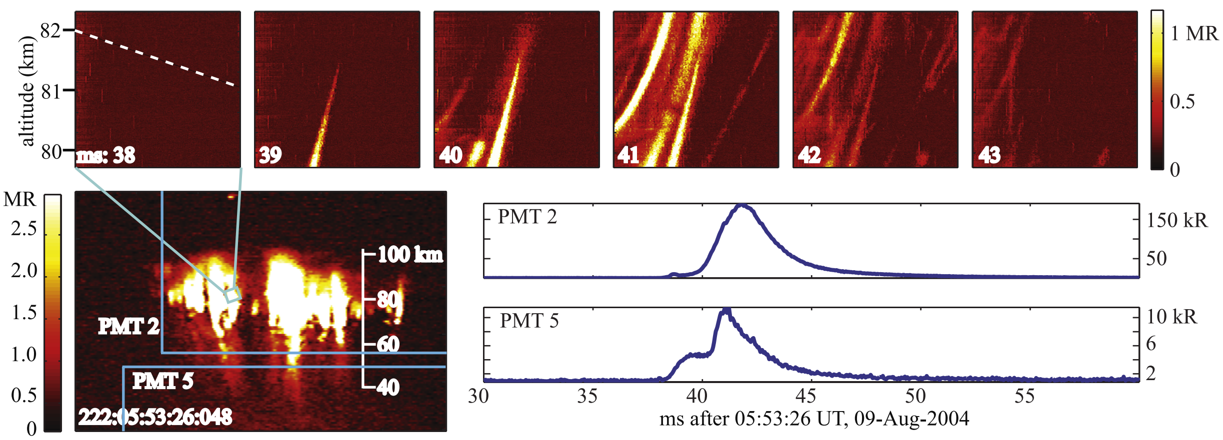

Figure 2. Sprite event of 9 August 2004, 0553:26 UT, with six telescopic frames and two channels of photometer data. Note the "tapered" streamer that merges to a point as well as the adjacent "curved" streamer; see the text for discussions of these interesting features.

likelihood of propagation in some instances and compare with previous measurements of *Stanley et al.* [1999] and *Moudry et al.* [2002]. A number of examples are given below, organized into streamer properties and bead properties.

3.1. Streamer Properties

[7] The vast majority of sprites contain numerous vertically striated structures, which are commonly referred to as streamers or tendrils. Previous measurements of sprite streamers have exhibited characteristic diameters in the range 10–300 m [*Gerken et al.*, 2000], and propagation speeds have been estimated to be about 10^7 m/s [*Moudry et al.*, 2002; *Stanley et al.*, 1999].

[8] Figure 1 shows an example of a typical wide streamer captured by the high-speed telescopic system on 9 August 2004. The telescopic frames are spaced by 1 ms; as such, the streamer appears with no intermediate forms (i.e., subfine structure) within each frame and persists no more than three frames. This bright streamer has a width of ~350 m at its widest point. The scattered structures adjacent and parallel to this streamer are of interest; they may be remnants of a very fast (persisting no more than 1 ms) streamer or individual bead-like structures that formed parallel to the streamer structure. One of these structures appears prior to the streamer and is completely faded out in the following frame, contrary to the typical ~6 ms lifetimes of beads shown in section 3.2. Here (and in all subsequent discussions), it should be noted that depth cannot be determined in the data presented, so we can say nothing about the proximity of apparently adjacent features in each image. The photometer data show that the lifetime of the entire sprite is ~2–3 ms, comparable to the lifetimes of the individual features shown. Note that PMT 2 is saturated, and the subsequent "ringing" is a commonly seen saturation effect.

[9] In Figure 2, various types of streamers are evident with a variety of sizes, all within a few kilometers of each other laterally (again, depth cannot be determined). This example is also briefly discussed by *Marshall and Inan* [2005]. In the second frame, a tapered structure appeared which is ~250 m wide at the base and merges to a fine point ~1.5 km above the bottom of the frame. This structure appears to be propagating upward, as evidenced by the third frame, contrary to conclusions

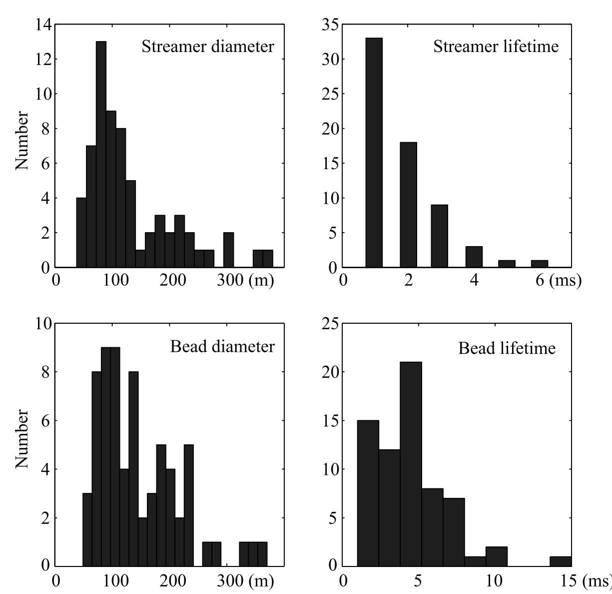

Figure 3. Histograms of streamer and bead sizes and lifetimes.

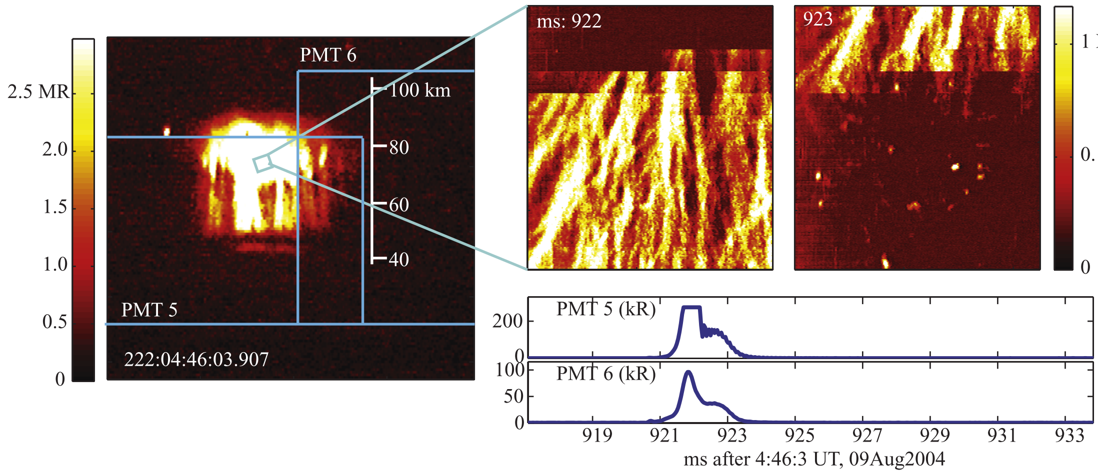

Figure 4. Sprite event of 9 August 2004, 0446:03 UT. The streamers were only apparent in these two telescopic frames, corroborated by the duration of the photometer pulse. The horizontal delineation of the streamer structure is a by-product of the readout scheme of the high-speed camera.

drawn by *Gerken and Inan* [2002] of similar structures, which were interpreted to originate at the sharp pinpoint location and propagate downward from the upper diffuse region of the sprite. In our case, the streamer structure was low in the sprite body, and other streamers appeared at higher altitudes. However, it should be noted that this example may be interpreted such that the tapered feature did indeed propagate downward and was merely brightened in the third frame. On the other hand, there appears to be a rounded streamer tip evident in the third frame, which then propagated through the field of view in the next frame, and this observation corroborates the idea of upward propagation in this region. Additionally, the ~300 m diameter and circular streamer tip shape are similar to model predictions of streamer tips [*Liu and Pasko*, 2004]. Also of interest is the curved streamer that appeared in the third and fourth frames, which may be evidence for complex electric field structure in and around the sprite. Finally, in the final frame, a branching structure is faintly visible on the left; this structure appears to be downward branching, counter to the upward propagating structures in previous frames. This difference may be indicative of the fact that both directions of propagation are possible at the same altitudes, as observed by *Gerken and Inan* [2002]; however, the two types of propagation may occur at different temporal stages of the sprite evolution, as observed here. Photometer data for this example show the sprite lifetime to be ~6–7 ms, comparable to the individual features shown; furthermore, a double-peak feature is seen in the lower photometer trace (PMT 5). However, neither the telescopic frames nor the wide-field-of-view video images can determine the cause of this double peak.

[10] In these and other examples of streamer structures, propagation is not directly observed; the field of view at a typical range of ~400 km to the sprite is only ~2.5 km so that at 1 ms resolution, a structure would need to propagate at less than 2.5×10^6 m/s in order to be resolved. On the basis of the size of the tapered streamer in Figure 2, we can conclude that it must have propagated at a minimum speed of 1.5×10^6 m/s to traverse the field of view in one frame. Streamers in previous measurements and model predictions are seen to propagate at $\sim 10^7$ m/s; hence a minimum of fourfold increase in either time resolution or viewing angle is necessary to observe such propagation.

[11] Figure 3 shows statistics for streamer and bead sizes and lifetimes observed during this experiment; the beads will be discussed in section 3.2. Statistics were

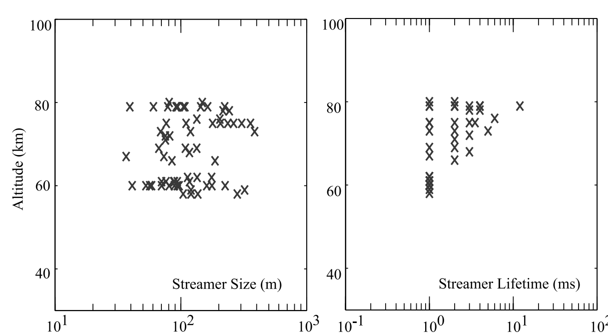

Figure 5. Streamer sizes and lifetimes versus altitude. A weak correlation is seen for streamer lifetimes such that there is a minimum altitude for a given streamer lifetime; no correlation is found for streamer sizes.

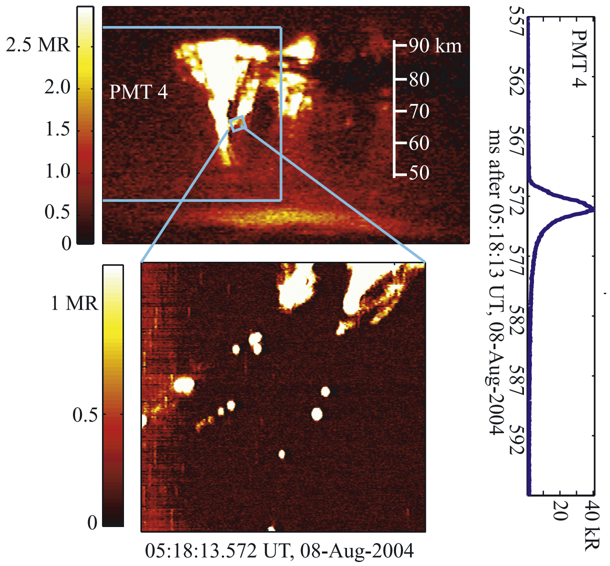

Figure 6. Sprite event of 8 August 2004, 0518:13 UT. Beads such as those shown were evident in five successive frames, with no streamer structure.

collected for all events observed in the high-speed imager and were taken as a representative set for each event; that is, for the event in Figure 2, each of the main streamers was used in the statistical set, but in the event of Figure 4, a few streamers of a variety of sizes were used to represent the event. Overall, we see that very few of the observed streamers persisted longer than 1–2 ms. Most streamer structures fell in the size range of 70–120 m diameter, with a distinct second peak from 150–230 m. Very few streamers are seen to be larger than 250 m and none were found to be <60 m in diameter, despite the ~10 m resolution of the imaging system. It is possible that any smaller streamers were also fainter and did not exceed the detection threshold of the system. These size statistics agree with previous results of streamers observed in sprites [*Gerken et al.*, 2000; *Gerken and Inan*, 2002].

[12] *Pasko et al.* [1998] and *Liu and Pasko* [2004] show that streamer sizes should scale with reduced electric field E/N at high altitudes so that larger streamers exist at higher altitudes. Predicted sizes vary by more than an order of magnitude between 60 and 80 km altitude [*Pasko et al.*, 1998]. Furthermore, sprite persistence times are likely a measure of the persistence of the quasi-electrostatic field at sprite altitudes, predicted to be ~1–2 ms at sprite altitudes, depending on assumed atmospheric conductivity profile [*Pasko et al.*, 1998]. The dielectric relaxation time τ_s in the streamer [*Pasko et al.*, 1998] is much smaller (<1 μs), and optical relaxation times are on the order of microseconds [*Liu and Pasko*, 2004] for the emission bands seen in sprites, primarily N_2 1P band system, so that the E field persistence likely dominates in observations. Furthermore, depending on the conductivity profile, the lifetimes may have either little altitude dependence or strong altitude dependence [*Pasko et al.*, 1998].

[13] Correlations between streamer sizes, lifetimes, and altitudes (based on the calibrated altitude using star

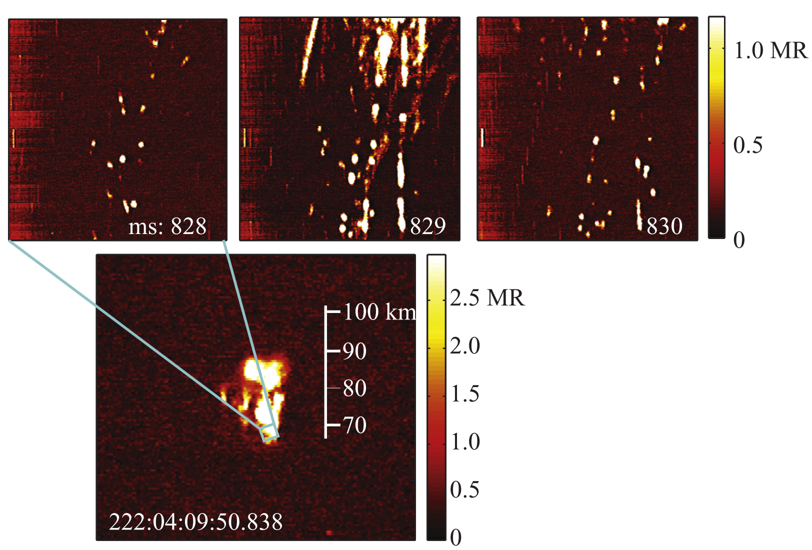

Figure 7. Sprite event of 9 August 2004, 0409:50 UT. In this case, there appear to be beads and streamer-like structures in the same region during one frame and beads alone in other frames. Photometer data were not available for this event.

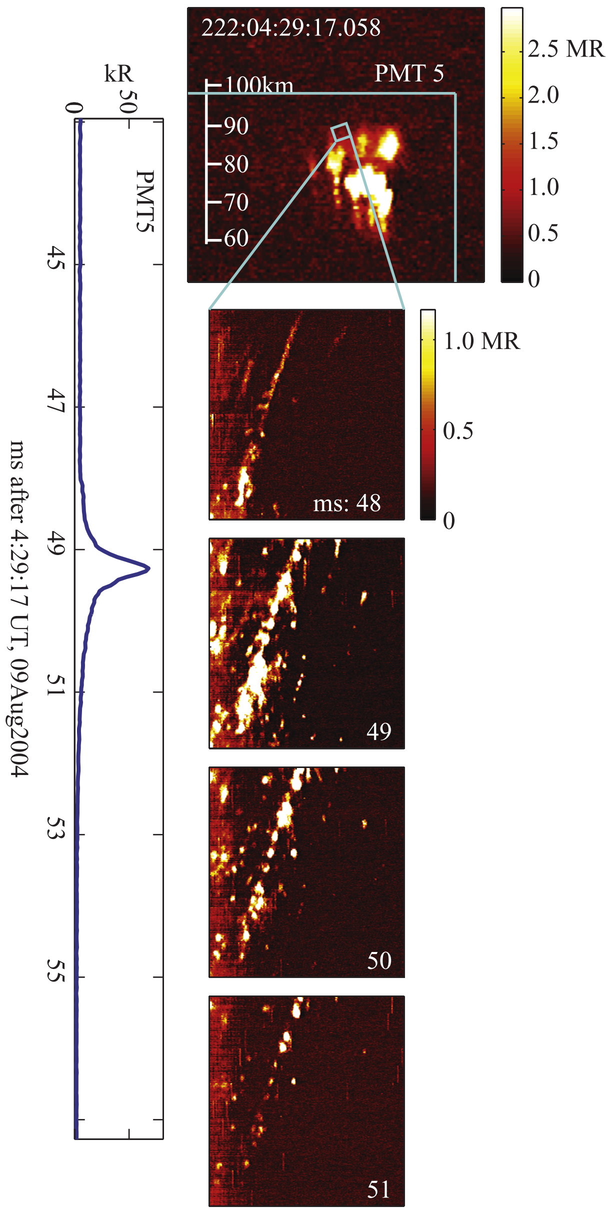

Figure 8. Sprite event of 9 August 2004, 0429:17 UT. Beads and streamers appear to be difficult to differentiate in these four telescopic frames.

fields), shown in Figure 5, exhibit very weak or no correlations. Streamer lifetimes show a very weak correlation with altitude in this data set, such that those that persist the longest are always observed at higher altitudes. Such a dependence is contrary to the predictions of *Pasko et al.* [1998], where the *E* field persistence time is longer at lower altitudes for any conductivity profile. Streamer sizes show no correlation with altitude. It should be noted that the imaging system is only able to view a subset of altitudes, from 60 to 80 km, as it was typically pointed toward the predicted center of a sprite.

3.2. Bead Properties

[14] Bead formations appear to be a very common form of fine structure for sprites and have been of interest to the sprite community for some time [e.g., *Sentman et al.*, 1996; *Moudry et al.*, 2003], as there currently is no theoretical understanding of their formation. Beads vary in size from ~10 m (limited by the resolution of the camera) to over 300 m in diameter and seem to have a predominantly circular shape in images. In rare cases, beads appear to propagate slowly in the vertical direction [*Gerken et al.*, 2000]; however, in all cases seen in this data set but one, beads are static, appearing quickly and fading slowly without movement. At the same time, it is very common for beads to appear lined up along vertically oriented columns, as if they were broken-up streamers. *Gerken and Inan* [2002] suggested that in such cases, the beads may form in fossil streamer channels, where very short lived streamers had previously appeared. *Gerken and Inan* [2002] also showed examples in which faint streamers were evident, time integrated over a 17 ms video field, and bright beads appeared on top of the faint streamer channels.

[15] Figure 4 shows an example of sprite features where beads appear in vertical columns, similar to those of *Gerken and Inan* [2002]. The high-speed camera used for these measurements exposes all pixels for the full 1 ms exposure time; however, there are 12 blocks of 16 horizontal lines each that are read out at 83 μs intervals; that is, the luminosity in the first block is 1 ms integration but offset 83 μs before that of the second block. Hence we see in this two-frame sequence that the sprite streamers were initiated just prior to the readout time of the third block, which we will call $t_{1.3}$ (first frame, third block); the structures take two to three readout periods (~166–249 μs) to reach full brightness and fade in the readout time of the fifth block in the second frame, $t_{2.5}$, resulting in a total persistence time of ~1.08 ms. Hence, using the readout feature of the camera, we achieve a better-than-resolution (i.e., better-than-frame-rate) measurement of the lifetime of the sprite features. This short lifetime is corroborated by the photometer traces, lasting less than 2 ms (once again, PMT 5 is saturated, and the subsequent ringing is a saturation effect). Following complete fading, scattered bead structures are seen across the field of view; these did not persist into the following frame. By superposing the two frames (not shown), we can see that these beads line up along columns where the branching streamers had previously appeared, in agreement with *Gerken and Inan* [2002].

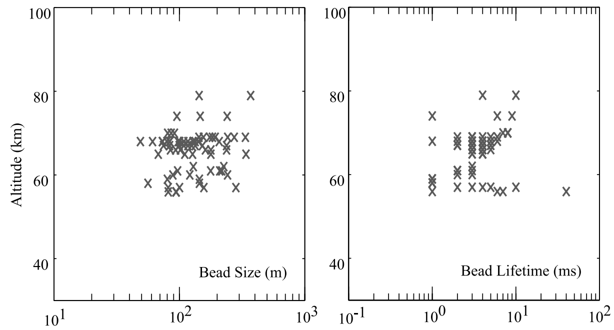

Figure 9. Bead sizes and lifetimes versus altitude. From this data set, no correlation is seen between sizes and altitude or between lifetimes and altitude.

[16] Figures 6, 7, and 8 show further examples of beading in sprites. In the example of Figure 6, only one frame is shown, but the beads in this case persist for ~6 ms. They form in vertical channels, though no evidence for fossil streamer channels in evident; these channels may exist below the noise level of the imaging system. Furthermore, these beads show a variety of sizes (from 30 to >200 m) at apparently similar altitudes. The photometer trace shows the sprite lifetime to be ~5–6 ms, similar to that of the structures appearing in the high-speed system.

[17] In Figure 7, beads appear without evident streamer structure in the first and third frames, but vertically stratified structures similar to streamers appear in the second frame. This observation suggests the possibility that these beads appear without preceding streamers, since streamers seem to occur after the beads; however, we note once again that it may be possible that the luminosity of weak streamer channels fell below the instrument threshold. Photometer data were not available at the time of this observation.

[18] In Figure 8, many bead and streamer-like structures appear in a narrow region, making them nearly indistinguishable. Such a spatial distribution poses problems for the electric field near these structures. According to established plasma streamer theory [e.g., *Bazelyan and Raizer*, 1997] and simulations [e.g., *Pasko et al.*, 1998; *Liu and Pasko*, 2004], electric fields are highly enhanced in the region near a streamer tip. For streamers of the same polarity, this enhancement creates strong opposing fields in nearly adjacent streamer tips. If the electric field structure is similar in beads, as would be the case, for example, if beads are initiated by meteoric dust particles [*Zabotin and Wright*, 2001], there would need to be a minimum separation between structures caused by the opposing electric fields. For the case in hand, the photometer data show the sprite lifetime to be ~2–3 ms, and the main luminous peak is only ~0.7 ms wide, despite the beading shown lasting for ~6 ms. Since the beads are typically quite small compared to the photometer field of view, their contribution is washed out over the spatial integration.

[19] Figure 3 shows a histogram of bead sizes and lifetimes beside those of streamers. In the case of beads, we see typically longer lifetimes, averaging ~6 ms, with rare cases >10 ms. Very few beads persisted for less than 1–2 ms. Bead sizes show a wide variety, ranging primarily from 50 to 240 m in diameter, with a few examples of beads >300 m in diameter. Statistics for beads were gathered in a similar fashion to those of streamers, described above. Figure 9 shows the correlations between bead sizes and lifetimes versus altitude. To our knowledge, no model predictions are available on how bead properties should vary with altitude. What we observe in this data set is that there is no correlation between either bead size and altitude or bead lifetime and altitude. Of the 17 events captured in the telescopic high-speed system, 15 had corresponding photometer data. Of these, six were composed entirely of streamer structures, such as in Figure 2; the remaining nine had either all beads or some combination of beads and streamers. The photometer data corroborate the sprite lifetime to within 1 ms for all of the exclusively streamer examples; however, in the presence of beads, the photometer traces are on average 2–3 ms shorter than the bead durations, as exemplified by Figure 8.

4. Summary

[20] We have presented examples of sprite features recorded at 1000 frames per second and higher using a telescopic imaging system. These features include a variety of morphologies of streamers and beads studied in unprecedented detail because of either limited time or limited spatial resolution in previous observations. Streamers are seen to have lifetimes of <1–50 ms, though typically ~6–7 ms, while streamers rarely persist more than ~2–3 ms. Both types of features have diameters of tens of meters up to ~350 m. Resolving propagation effects at predicted speeds requires imaging at higher frame rates. Future experiments at 5000–10,000 frames per second and possibly higher will likely reveal features of streamer and bead evolution that will help to delineate the different circumstances in which these structures are initiated.

[21] **Acknowledgments.** This work was supported by a Texas Instruments Stanford Graduate Fellowship and by ONR grant N00014-03-1-0333. The authors wish to thank Bill Winn, Steve Hunyady, and Sandy Kieft of Langmuir Laboratory for hosting the experiment; Bill Abrahams of Speed Vision Technologies for the use of their high-speed imager; and Ken

Cummins and John Cramer of Vaisala, Inc., for access to NLDN lightning data.

References

Bazelyan, E. M., and Y. P. Raizer (1997), *Spark Discharge*, CRC Press, Boca Raton, Fla.

Boccippio, D. J., E. R. Williams, S. J. Heckman, W. A. Lyons, I. T. Baker, and R. Boldi (1995), Sprites, elf transients, and positive ground strokes, *Science*, *269*, 1088–1091.

Gerken, E. A., and U. S. Inan (2002), A survey of streamer and diffuse glow dynamics observed in sprites using telescopic imagery, *J. Geophys. Res.*, *107*(A11), 1344, doi:10.1029/2002JA009248.

Gerken, E. A., and U. S. Inan (2004), Comparison of photometric measurements and charge moment estimations in two sprite-producing storms, *Geophys. Res. Lett.*, *31*, L03107, doi:10.1029/2003GL018751.

Gerken, E. A., U. S. Inan, and C. P. Barrinton-Leigh (2000), Telescopic imaging of sprites, *Geophys. Res. Lett.*, *27*(17), 2637–2640.

Hampton, D. L., M. J. Heavner, E. M. Wescott, and D. D. Sentman (1996), Optical spectral characteristics of sprites, *Geophys. Res. Lett.*, *23*(1), 89–92.

Liu, N., and V. P. Pasko (2004), Effects of photoionization on propagation and branching of positive and negative streamers in sprites, *J. Geophys. Res.*, *109*, A04301, doi:10.1029/2003JA010064.

Marshall, R. A., and U. S. Inan (2005), High-speed telescopic imaging of sprites, *Geophys. Res. Lett.*, *32*, L05804, doi:10.1029/2004GL021988.

Moudry, D. R., H. C. Stenbaek-Nielsen, D. D. Sentman, and E. M. Wescott (2002), Velocities of sprite tendrils, *Geophys. Res. Lett.*, *29*(20), 1992, doi:10.1029/2002GL015682.

Moudry, D., H. Stenbaek-Nielsen, D. Sentman, and E. Wescott (2003), Imaging of elves, halos and sprite initiation at 1 ms time resolution, *J. Atmos. Sol. Terr. Phys.*, *65*, 509–518.

Pasko, V. P., U. S. Inan, and T. F. Bell (1998), Spatial structure of sprites, *Geophys. Res. Lett.*, *25*(12), 2123–2126.

Raizer, Y. P., G. M. Milikh, M. N. Shneider, and S. V. Novakovski (1998), Long streamers in the upper atmosphere above thundercloud, *J. Phys. D Appl. Phys.*, *31*, 3255–3264.

Sentman, D. D., E. M. Wescott, D. L. Osborne, D. L. Hampton, and M. J. Heavner (1995), Preliminary results from the Sprites94 aircraft campaign: 1. Red sprites, *Geophys. Res. Lett.*, *22*(10), 1205–1208.

Sentman, D. D., E. M. Wescott, M. J. Heavner, and D. R. Moudry (1996), Observations of sprite beads and balls, *Eos Trans. AGU*, *77*(46), Fall Meet. Suppl., Abstract A71B-07.

Stanley, M., P. Krehbiel, M. Brook, C. Moore, W. Rison, and B. Abrahams (1999), High speed video of initial sprite development, *Geophys. Res. Lett.*, *26*(20), 3201–3204.

Stenbaek-Nielsen, H. C., D. R. Moudry, D. D. Sentman, and F. T. Sâo Sabbas (2000), Sprites and possible mesospheric effects, *Geophys. Res. Lett.*, *27*(23), 3829–3832.

Wescott, E. M., D. D. Sentman, M. J. Heavner, D. L. Hampton, W. A. Lyons, and T. E. Nelson (1998), Observations of 'Columniform' sprites, *J. Atmos. Sol. Terr. Phys.*, *60*, 733–740.

Winckler, J. R., W. A. Lyons, T. E. Nelson, and R. J. Nemzek (1996), New high-resolution ground-based studies of sprites, *J. Geophys. Res.*, *101*, 6997–7004.

Zabotin, N. A., and J. W. Wright (2001), Role of meteoric dust in sprite formation, *Geophys. Res. Lett.*, *28*(13), 2593–2596.

R. A. Marshall and U. S. Inan, Space, Telecommunications and Radioscience Laboratory, Stanford University, 350 Serra Mall, Room 306, Stanford, CA 94305, USA. (ram80@stanford.edu)