High-speed telescopic imaging of sprites

R. A. Marshall and U. S. Inan

Space, Telecommunications and Radioscience Laboratory, Stanford University, Stanford, California, USA

Received 12 November 2004; revised 16 December 2004; accepted 28 January 2005; published 2 March 2005.

[1] Telescopic video observations of sprites at high frame rates show very complex structures in both space and time, including bead and streamer-like formations and propagation. Observed streamers rarely persist for more than 1–2 ms, while observed beads persist up to tens of ms and do not appear to propagate in this data set. Additionally, images show that streamer-like channels often contain many bead-like structures. While the time resolution cannot directly observe propagation, images show that the so-called "streamers" presented here do seem to exhibit signs of propagation. These results are compared to previous measurements and discussed in the context of streamer modeling and laboratory streamers.
Citation: Marshall, R. A., and U. S. Inan (2005), High-speed telescopic imaging of sprites, *Geophys. Res. Lett.*, *32*, L05804, doi:10.1029/2004GL021988.

1. Introduction

[2] Sprites are transient luminous events that occur at altitudes of ~40 to 90 km above thunderstorms [*Sentman et al.*, 1995]. They are usually associated with large positive cloud-to-ground lightning flashes (+CGs) [*Boccippio et al.*, 1995], typically those with large charge moments [*Cummer and Inan*, 2000].

[3] Telescopic imaging of sprites has shown spatial structure of streamers and beads at decameter scales [*Gerken et al.*, 2000; *Gerken and Inan*, 2002, 2003]. However, these images, taken at regular video frame rates, do not resolve the evolution of these fine structures and necessarily blur any evolution on scales less than 17 ms, the duration of one video field. Independently, video observations of sprites at high frame rates have resolved streamer propagation and sprite evolution [*Stanley et al.*, 1999; *Stenbaek-Nielsen et al.*, 2000; *Moudry et al.*, 2002] and have made measurements of streamer velocities [*Moudry et al.*, 2002; *Stanley et al.*, 1999]. These observations, however, lack the ability to spatially resolve the finer structures of sprites, being limited in spatial resolution to 250 m. In this paper, we report the first observations of sprites with high-resolution in both space and time, using telescopic high-speed imaging.

2. Description of the Experiment

[4] In July and August 2004, observations of sprites were conducted from Langmuir Laboratory, near Socorro, NM, using a 41-cm aperture, f/4.5 Dobsonian Telescope. A Kodak Ektapro Motion Analyzer Model 1012, with a Kodak Ektapro Intensified Imager Controller, was mounted to the eyepiece of the telescope. The CCD of the Motion Analyzer used with the telescope resulted in a field-of-view of 0.25° by 0.3°. Coaligned with the telescope was a Pulnix TM200 CCD camera with a GenII Image Intensifier, and a 50-mm lens yielding a 9° by 12° field-of-view.

[5] The Motion Analyzer stores 1600 images at a resolution of 192 by 239 pixels. The Imager is capable of 1000 frames per second (fps) at the full resolution, and can also provide higher frame rates with reduced resolution. Events observed in the wide field-of-view camera are used to trigger the high-speed imager, the output of which is recorded on VHS videotapes.

[6] The Wide-angle Array for Sprite Photometry (WASP), an array of six Hamamatsu HC104 photomultiplier tubes (PMTs), was deployed alongside the telescopic high-speed system. Each PMT is fitted with a longpass 665 nm filter and a lens yielding a 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 6° by 16°. The PMT signals are filtered and sampled at 25000 samples per second, and are sensitive to a noise level of 1 kiloRayleigh (kR) or 10^9 photons-cm^{-2}s^{-1}str^{-1} in the wavelength band of response. A second Pulnix TM200 CCD camera and GenII Image Intensifier combination is coaligned with the WASP, using a 25-mm lens yielding a field of view of 18° by 24°.

[7] Sprite locations were inferred from National Lightning Detection Network (NLDN) stroke data, by matching the nearest +CG to the sprite in time and using the coordinates of the +CG as the center of the sprite location. However, sprites can be displaced laterally from the location of the causative +CG discharge up to 50 km [*Wescott et al.*, 1998], yielding error in pointing angle; the exact pointing angle is thus determined by star fields. Assuming the sprite to be at the same distance from the observation platform as the causative +CG discharge, sprite altitudes are then determined from the star fields; however, the altitudes reported have an uncertainty of 8–15 km, corresponding to displacement of the sprite from the +CG along the viewing direction. Furthermore, since the eyepiece of the telescope is mounted on its side and is situated 19° from horizontal, high-speed images are effectively rotated by this angle, and lines of constant altitude are thus angled downwards across the images from left to right. For this reason, a dashed white line across the image shows a line of constant altitude.

[8] The high-speed imager and wide field-of-view cameras were calibrated by exposure to an Eather Lamp whose output was calibrated to a NIST photodiode of known response. The response of the S20 photocathode of the high-speed imager is multiplied with the output of the lamp and the N_2 $1P$ band structure (consisting of discrete bands), and compared to the NIST photodiode response. The high-

0094-8276/05/2004GL021988$05.00

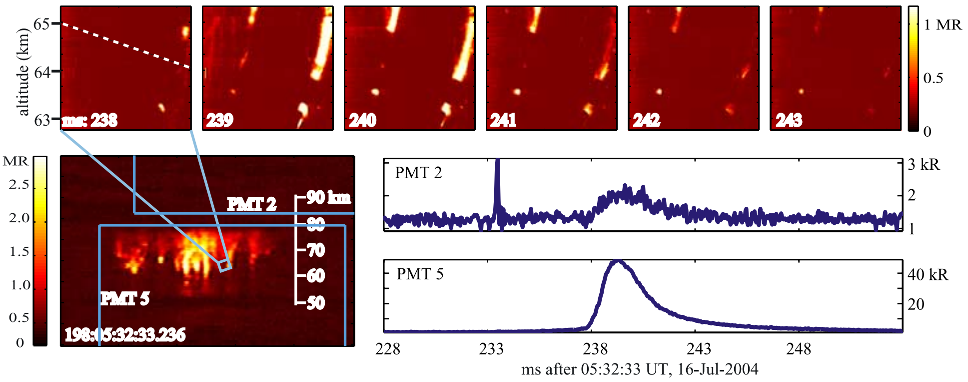

Figure 1. Sprite event of 05:32:33 UT, July 16, 2004. The top six panels show consecutive frames of the high-speed imager; the bottom left shows the wide field-of-view sprite image and the relative location of the narrow field-of-view; the bottom right shows two channels of photometer data. Note that Rayleigh intensities in the photometer channels are averaged over the photometer field-of-view, which is much larger than the sprite.

speed imager is found to saturate at 1.2 MegaRayleigh (MR) when operated at 1000 fps, and the wide field-of-view camera co-aligned with the telescope saturates at about 3 MR. All sprite images reported here were seen to saturate in both cameras.

3. Data and Analysis

[9] Four examples of high-speed sprite images are presented, along with their defining characteristics. Figure 1 shows a sequence of six images of a sprite initiated by a +CG discharge of peak current 101.4 kA occurring at 05:32:33.215 UT on July 16, 2004 in a thunderstorm over northern Mexico. The images are spaced in time by 1 ms; the previous frame showed no illumination. Figure 1 also shows the wide FOV sprite image and two channels of PMT data, demonstrating the sprite luminosity and possibly a halo or elve event prior to the sprite. The illustrated features of this sprite event persisted for only 7 ms in the high-speed camera. A wide (200–300 m) streamer is evident at upper right, possibly initiating from a point at about 65 km altitude and appearing to propagate both upwards and downwards; this propagation is exhausted in one 1-ms frame (marked 239 ms). At the same time, beads appear in both streamer channels which do not propagate, and furthermore persist for longer (8 ms; two frames have been omitted) than the luminosity of the streamer columns (3–4 ms). There are also branched streamers appearing in the second frame, persisting for only one frame (1 ms). We note here that the 65 km altitude is much lower than published altitudes of 75 km for sprite initiation [*Stanley et al.*, 1999], but is nevertheless within the uncertainty of the sprite altitude.

[10] Figure 2 shows a sequence of images of a sprite initiated by a 37.2 kA +CG flash at 05:18:13.516 UT on August 8, 2004, the middle of three sprites within 30 ms of one another, in a thunderstorm over eastern New Mexico. Once again, the images across the top are spaced in time by 1 ms. Two channels of PMT data are also shown, along with the wide field-of-view image of the sprite. Evident are two chains of beads, which appear to not propagate and persist for 4–6 ms. The beads appear to form along distinct channels, suggesting the presence of non-luminous ionization columns. Furthermore, these beads vary in size from 10 meters (limited by camera resolution) up to hundreds of meters in diameter.

[11] Figure 3 shows a sequence of images of a sprite initiated by a 121.7 kA +CG flash at 07:48:16.053 UT on August 22, 2004 in a thunderstorm over eastern New Mexico. The images in this example were recorded at 2000 fps, representing an exposure time and resolution of 0.5 ms. PMT data was not available at this time. The high-speed images show two streamer-like columniform structures, the more distinct of which has a 400 m diameter, and reaches full luminosity over the course of three frames

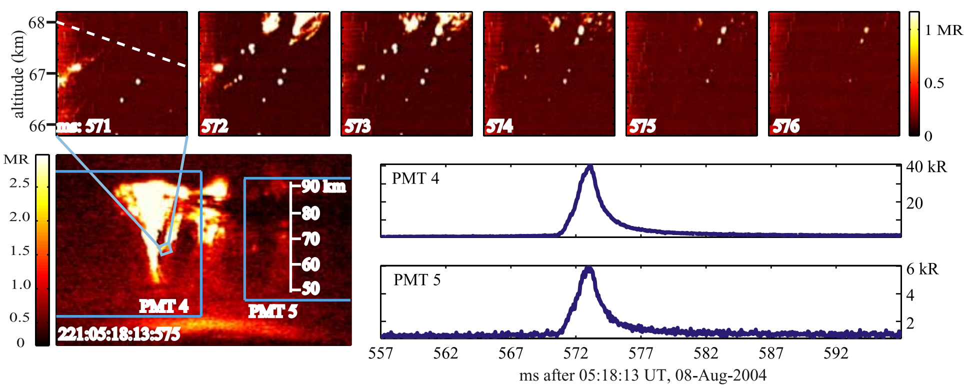

Figure 2. Sprite event of 05:18:13 UT, August 08, 2004, with telescopic frames, wide field-of-view sprite image, and two channels of photometer data. The relative fields-of-view and altitudes are shown on the sprite image.

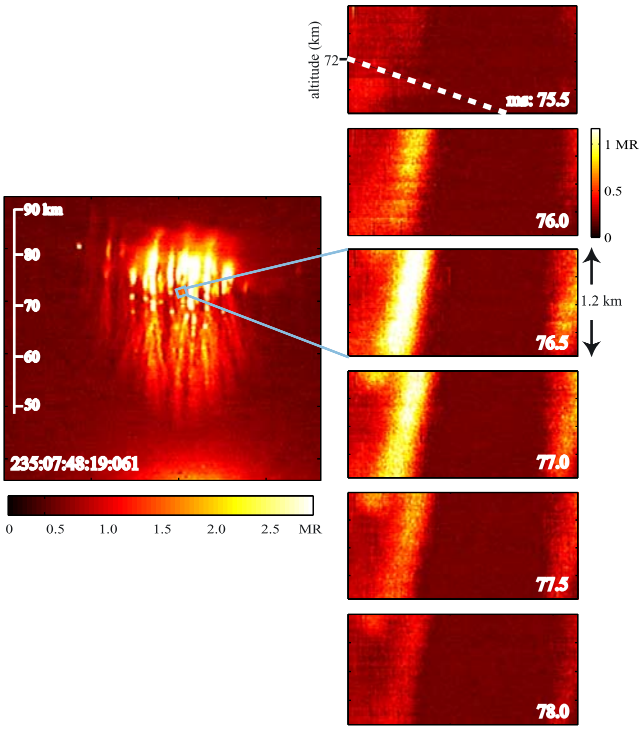

Figure 3. Sprite event of 07:48:16 UT, August 22, 2004, with telescopic frames recorded at 2000 fps and a wide field-of-view sprite image. Photometeric data were not available for this event.

(1.5 ms) and fades over the following three frames. This columniform structure does not readily appear to propagate through the field-of-view; however, due to the spatial and temporal resolution limits of this system, it is difficult to ascertain the presence of propagation.

[12] Figure 4 shows a sequence of images of a sprite initiated by a 86.7 kA +CG flash at 05:53:26.030 UT on August 9, 2004 in a thunderstorm over southwest Texas. In this example the first structure to appear is a very sharp, tapered structure that appears from the bottom of the field-of-view. If this feature propagated during this 1-ms exposure, the velocity of propagation for this streamer must have been over 1.64×10^6 m/s to have propagated that far in 1 ms. In the next frame it seems to have propagated further, and its velocity in this frame is estimated to be 3.1×10^5 m/s, averaged over the 1 ms frame duration. In subsequent frames the streamer fades while others appear surrounding it, including the curved structure with a similar evolution, and a faint tendril with a diameter of only 20 m. The tapered streamer has a width on the order of 10–20 m at the tip, limited by the resolution of the high-speed imager, and at the edge of the field-of-view the streamer has a width of 250 m. The streamer width appears to vary linearly with length. The other streamers that appear in this event exhibit constant thickness. This tapered streamer is similar to those reported by *Gerken and Inan* [2002]. However, *Gerken and Inan* [2002] interpreted those streamers as widening while propagating downwards from a diffuse region, while such is evidently not the case in our example. The streamer most certainly appears to be propagating upwards; there are streamer structures above the tapered structure in the telescopic field-of-view; and this structure is at too low altitude in the sprite body to emanate from the diffuse region.

4. Summary and Discussion

[13] We have presented four examples of narrow field-of-view, high-speed images of sprite structure. These and other examples show many features, including a predominance of bead structure that does not appear to propagate; and cases of beads forming in channels, as in Figure 1. These data are consistent with previous observations [*Gerken et al.*, 2000] of beads forming in fossil streamer channels, though similar channels are not visible in these observations. It is possible that these beads are initiated without fossil channels, but the physical mechanism for such an occurrence is unknown.

[14] There is also a wide variety of streamer structure evident in these observations. Bead and streamer structures have sizes ranging from 10 m (resolution limited) to hundreds of meters in narrow altitude ranges. The tapered streamer in Figure 4 varies significantly (by a factor of 10) in width over an altitude range of only 2 km, a variation much too rapid to fit the predicted streamer widths of *Pasko et al.* [1998], in which streamer radius scales with ambient density (which varies exponentially with a scale height of 6 km); this issue has previously been raised by *Liu and Pasko* [2004]. Furthermore, within the narrow field-of-view of Figure 4, streamers with a wide variety of widths are evident to co-exist at the same altitude, ranging from less than 30 to over 300 m, as observed by *Gerken et al.* [2000].

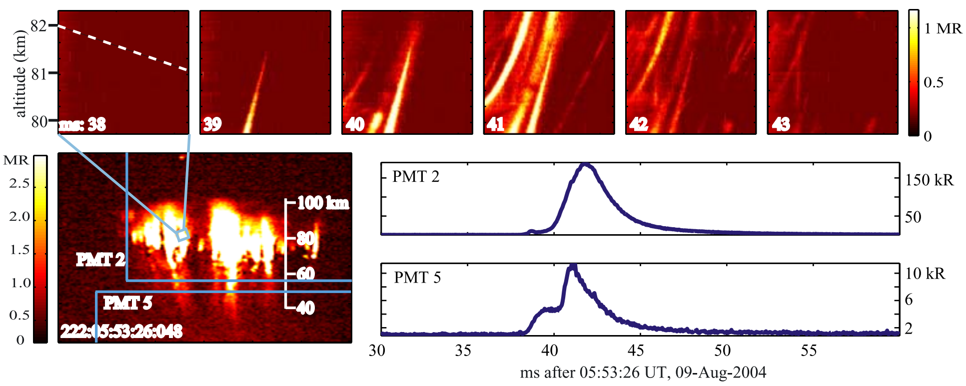

Figure 4. Sprite event of 05:53:26 UT, August 09, 2004, with telescopic frames, wide field-of-view sprite image, and two channels of photometer data.

[15] The vertically-stratified structures in sprites have commonly been suggested to be plasma streamers [*Pasko et al.*, 1998; *Raizer et al.*, 1998]. Observations [i.e., *Moudry et al.*, 2002] and modeling of streamers in the mesosphere [*Raizer et al.*, 1998; *Pasko et al.*, 1998] have revealed general agreement on the velocities of these structures. The results presented herein also generally agree with the hypothesis of streamer propagation, though accurate measurements of velocity can be made for only a few examples in our data set.

[16] The results presented here demonstrate the need for, and feasibility of, even higher frame-rate telescopic and wide field-of-view imaging of sprites. The conclusions concerning streamer propagation are based on interpretation and not on strict measurements; further, the initiation of streamers is not well documented due to the fact that even the frame rates used here appear to be too low. Images of similar spatial scale captured at better than 0.1 ms resolution should be capable of measuring streamer propagation with speeds on the order of 10^7 m/s. Since the images presented saturate even at 0.5 ms exposure, exposures of one-tenth this time would still yield bright, resolvable images of sprite structures.

[17] **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 and Rick Sutherland of Speed Vision Technologies for the use of their high-speed imager; Ken Cummins and John Cramer of Vaisala, Inc. for access to NLDN lightning data; Jack Doolittle of Lockheed Martin Advanced Technology Center for assistance in calibration; and Michael Smith of Stanford and Mark Stanley of Los Alamos National Labs for assistance in preparation and execution of the experiment.

References

Boccippio, D. J., E. R. Williams, S. J. Heckman, W. A. Lyons, I. Baker, and R. Boldi (1995), Sprites, ELF transients and positive ground strokes, *Science*, *269*, 1088.
Cummer, S. A., and U. S. Inan (2000), Modeling ELF radio atmospheric propagation and extracting lightning currents from ELF observations, *Radio Science*, *35*, 385.
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 (2003), Decameter-scale morphologies of sprites, *J. Atmos. Sol. Terr. Phys.*, *65*, 567.
Gerken, E. A., U. S. Inan, and C. P. Barrington-Leigh (2000), Telescopic imaging of sprites, *Geophys. Res. Lett.*, *27*, 2637.
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.
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.
Pasko, V. P., U. S. Inan, and T. F. Bell (1998), Spatial structure of sprites, *Geophys. Res. Lett.*, *25*, 2123.
Raizer, Y. P., G. M. Milikh, M. N. Scheider, and S. V. Novakovski (1998), Long streamers in the upper atmosphere above thundercloud, *J. Phys. D Appl. Phys.*, *31*, 3255.
Sentman, D. D., E. M. Wescott, D. L. Osborne, D. L. Hampton, and M. J. Heavner (1995), Preliminary results from the Sprites94 Campaign: Red sprites, *Geophys. Res. Lett.*, *22*, 1205.
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*, 3201.
Stenbaek-Nielsen, H. C., D. R. Moudry, E. M. Wescott, D. D. Sentman, and F. T. Sâo Sabbas (2000), Sprites and possible mesospheric effects, *Geophys. Res. Lett.*, *27*, 3829.
Wescott, E. M., D. D. Sentman, M. J. Heavner, D. L. Hampton, W. A. Lyons, and T. Nelson (1998), Observations of 'Columniform' sprites, *J. Atmos. Sol. Terr. Phys.*, *60*, 733.

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