GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L05806, doi:10.1029/2006GL028511, 2007

Possible direct cloud-to-ionosphere current evidenced by sprite-initiated secondary TLEs

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Received 19 October 2006; revised 29 December 2006; accepted 19 January 2007; published 6 March 2007.

[1] Video-rate images of sprites observed from Langmuir Laboratory show slow, upward discharges from the cloud to the mesosphere following the sprite discharge. A single high-time-resolution (1000 fps) measurement of the tip of the upward discharge shows that it terminates at the base of the preceding sprite and persists for a total of ~50 ms, compared to the sprite lifetime of ~6 ms. Photometer data show that these events are likely to be predominantly blue. We propose a mechanism by which, in conjunction with intra-cloud activity following the causative CG discharge, charge is moved within the sprite body from the ionosphere to the lower altitude edge of the sprite at ~50 km; this transfer of charge lowers the upper capacitive plate, whereupon a second breakdown is facilitated between the cloud-top and this charged plate, inducing electrical current between the cloud and the mesosphere and initiating the observed luminous discharges. **Citation:** Marshall, R. A., and U. S. Inan (2007), Possible direct cloud-to-ionosphere current evidenced by sprite-initiated secondary TLEs, *Geophys. Res. Lett.*, *34*, L05806, doi:10.1029/2006GL028511.

1. Introduction

[2] Sprites are transient luminous events (TLEs) that occur at altitudes of ~40 to 90 km above thunderstorms [e.g., *Sentman et al.*, 1995]. They are almost always associated with large positive cloud-to-ground lightning flashes (+CGs) [*Boccippio et al.*, 1995], typically those with large charge moments [*Cummer and Inan*, 2000]. Often a second peak in the current moment waveform is detected, and has been attributed to current in the sprite body [*Cummer and Inan*, 2000]. Similarly, long ELF slow-tails observed from great distance, such as at Palmer Station, Antarctica, have been used as an indicator of sprite occurrence [*Reising et al.*, 1996]. Another class of TLEs known as "blue jets" propagate upwards from the cloud top at speeds of ~100 km/s and have been shown to be partially ionized [*Wescott et al.*, 1995, 2001].

[3] Discharges that follow sprites and which occur in the altitude range between the cloud-top and the bottom of the sprite have been previously observed and variously termed "crawlers", "embers", and "palm-trees" [*Heavner*, 2000; *Moudry et al.*, 2001a, 2001b, 2003]. *Siefring et al.* [1999] noted that these events could constitute a direct connection from the ionosphere to the cloud. *Moudry et al.* [2003] contains a thorough summary of these features, and noticed that these features, when observed at 1000 frames-per-second (fps), propagate upwards in discrete steps. These previous observations of these phenomena were realized before the recent evidence of upward discharges over oceanic thunderstorms [*Su et al.*, 2003; *Pasko et al.*, 2002] termed "Gigantic Jets". Gigantic Jets provide the first evidence of discharges from the cloud to the ionosphere, presumably creating a direct current link between the two conductive boundaries, though ELF data (to detect radiation produced by such a current) for these events were not available. While observations of Gigantic Jets have to date been rare, all such observations have occurred over oceanic thunderstorms, and have not been associated with CGs in the thunderstorm. In this paper, we present evidence, analysis and interpretation of "palm tree" events, observed over land-based storms, which are weaker in luminosity and do not extend as high in altitude compared to gigantic jets.

2. Experiments

[4] In the summers of 2004 and 2005, observations of sprites were conducted from Langmuir Laboratory, near Socorro, NM, using two Pulnix TM200 wide field-of-view (FOV) intensified cameras and an array of $N_2 1P$-photometers known as the WASP (Wide-Angle Array for Sprite Photometry), described by *Marshall and Inan* [2005]. One camera had a FOV of 14° by 19°; the second had a FOV of 18° by 24°. The WASP photometers are filtered with a longpass filter with a cutoff of 650 nm. All images presented here were taken with the first, smaller field-of-view imager. These systems were deployed as part of a telescopic high-speed imaging system, described in work by *Marshall and Inan* [2005]. This telescopic system was composed of a Kodak EktaPro intensified high-speed camera, recording at 1000–2000 frames-per-second (fps), attached to the eyepiece of a 16-inch Dobsonian telescope, yielding a field-of-view of ~0.25 × 0.3°.

[5] Furthermore, in 2005 a Very-Low-Frequency (VLF) receiver was deployed at Langmuir for near-field measurements of the ELF/VLF fields radiated by causative CGs and sprites. This receiver utilized crossed magnetic loop antennas and had a flat response from 100 Hz to 40 kHz.

[6] Sprite locations were inferred from National Lightning Detection Network (NLDN) 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. Assuming the sprite to be at the same distance from the observation platform as the causative +CG discharge, sprite altitudes are then determined from star elevation angles. However, the altitudes reported have an uncertainty of 8–15 km, corresponding to displacement of the sprite from the +CG

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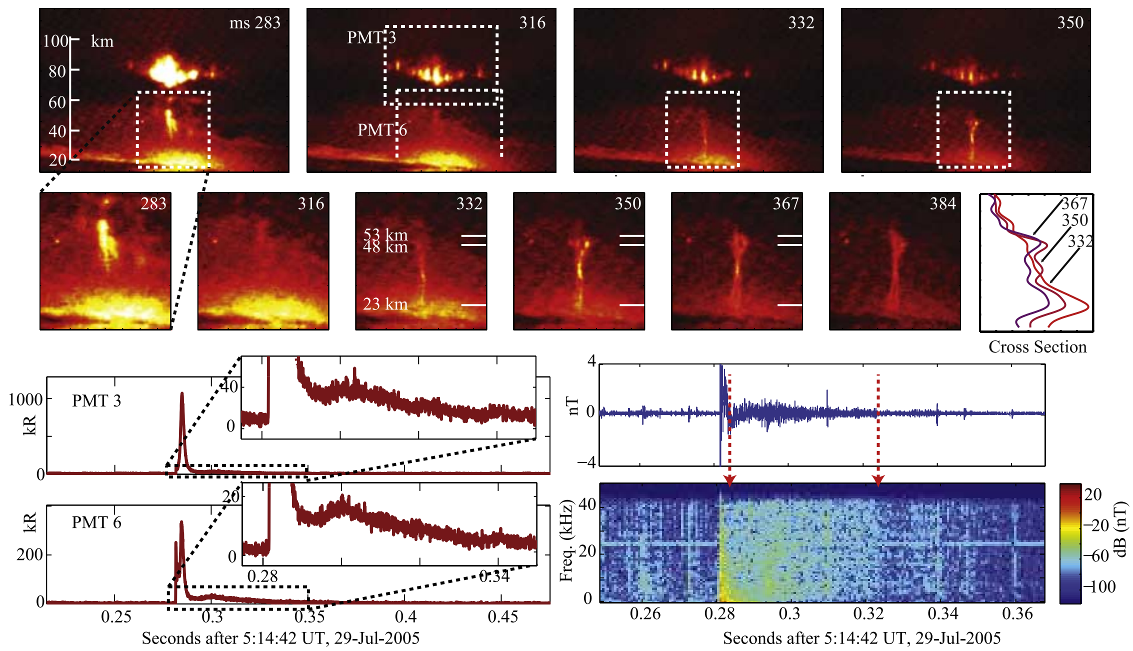

Figure 1. Secondary TLE event of 29 July 2005, 5:14:42 UT. Labels on frames indicate the millisecond after 05:14:42 UT. VLF data at lower right was recorded from Langmuir Laboratory (LL); arrows show the start and stop of the "sferic burst" activity described in the text. Cross section data at right varies from red to purple in time with each frame and demonstrates possible upward propagation. Photometer data at lower left is included to show some luminosity of the secondary TLE in the expanded views.

along the viewing direction by up to 50 km [*Wescott et al.*, 1998a].

3. Data Examples

[7] We refer to the delayed event as a "sprite-initiated secondary TLE" or simply "secondary TLE", noting that they are the same as the "palm trees" of *Heavner* [2000]. Note that these events are distinct from and not related to blue jets. A dramatic example of a sprite followed by a secondary TLE is shown in Figure 1. This event was observed on July 29, 2005 at 05:14:42 UT over southern Arizona, following a 92.8 kA +CG at 05:14:42.280 UT, as reported by NLDN. Following the initial bright sprite, a secondary TLE appears to propagate upward from ~25 km altitude (lower altitudes were obscured by foreground clouds) to an altitude of ~53 km, where we note once again that higher altitudes are obscured. Comparison of the consecutive frames at 332 and 350 ms suggest that the feature propagated upwards, based on the features at higher altitudes. Upon comparison with the frame at 283 ms, it is evident that these features are distinct from those in the original sprite. Further, the rightmost plot shows a vertical cross section of the feature, adding the intensity of a 20-pixel width along the length of the frame. A small altitude increase appears to be evident between frames 332 and 350, and between 350 and 367; however these observations are tenuous and not unambiguous. Further discussion of the implications of propagation can be found in Section 4. Assuming upward propagation from the cloud-top (based on the altitude difference in fields 332 and 350), the tendril had a minimum speed in the first field of 1.5 (±0.2) $\times 10^6$ m/s, 15 times faster than the 10^5 m/s reported for blue jets [*Wescott et al.*, 1995] and 0.5 – 2.7 $\times 10^5$ m/s for the low-altitude structures of the gigantic jet reported by *Pasko et al.* [2002], and an order of magnitude lower than speeds reported for sprite tendrils [*Stenbaek-Nielsen et al.*, 2000; *Stanley et al.*, 1999]. However, this observed speed is more comparable to the 1 $\times 10^6$ m/s for gigantic jets reported by *Su et al.* [2003]. Palm-tree speeds are not reported for the observations in work by *Heavner* [2000] and *Moudry et al.* [2003].

[8] Photometer data for this event (Figure 1) shows an initial peak lasting <1 ms, attributed to the cloud flash, primarily in the lower channel (PMT 6); a longer, ~5 ms peak, stronger at higher altitudes (PMT 3), attributed to the main sprite; and a much longer (~40 ms) persistence, only observed in the channels shown, that can only be attributed to the secondary TLE event. This feature is ~50 times weaker in luminosity than the sprite in PMT 6, and much less in PMT 3; however it appears prominently in the video field. This may be due to its longer persistence, or also to blue emissions that do not show up in the red-filtered photometer channels.

[9] Shown together with the photometer data is broadband ELF/VLF data recorded at Langmuir Laboratory during the 2005 campaign in time series and spectrum; this receiver was not deployed during the 2004 campaign. The sferic begins at 05:14:42.282 UT, noting that 2 ms is the propagation time from the sprite altitude at about 600 km range to the receiver, and shows a strong ELF component in the first 4 ms; weaker ELF components continue for ~20 ms after the parent lightning stroke, a feature that has previously been observed and interpreted as evidence of continuing current [*Reising et al.*, 1996].

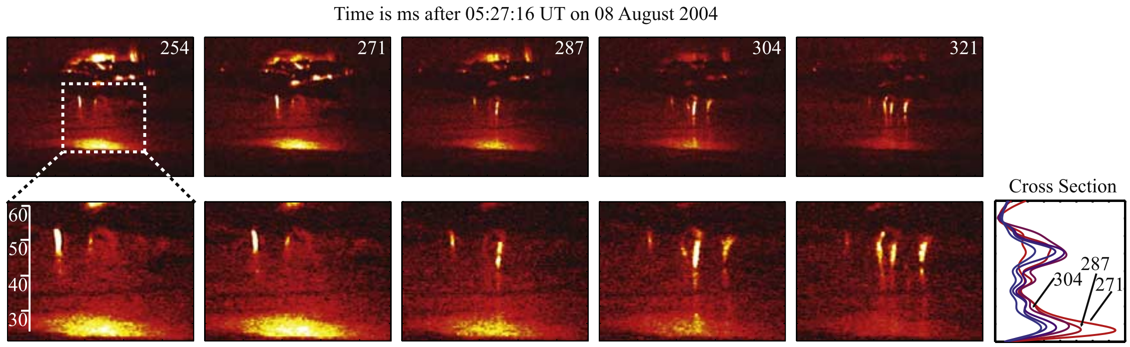

Figure 2. Secondary TLE event of 08 August 2004 at 05:27:16.287 UT. See text for discussion of timing. This example demonstrates the wide variability in these events. Cross section data at right varies from red to purple in time with each frame.

[10] The VLF spectrum is also shown in Figure 1. Of particular interest is the burst-like activity following the CG, or "sferic burst", which is possibly evidence of strong intracloud (IC) lightning activity. Such IC activity can only be observed using VLF when the receiver is near the storm (within ~600 km), since horizontal IC radiation does not propagate well in the earth-ionosphere waveguide [*Johnson et al.*, 1999] and references therein). The presence of IC activity may be an indicator for such secondary TLE events, but is not a sufficient condition, since many sprites that do not exhibit these secondary TLEs do have associated IC activity [*van der Velde et al.*, 2006], and examples in this data set).

[11] Ten similar events were observed in the summer of 2004, each having tendrils that span the distance from the lowest visible altitude (sometimes blocked by foreground clouds) to the base of a fading sprite. These sprites occurred above two storms on August 08 and 09, 2004, above which 20 and 46 sprites were produced in 130 and 200 minutes of observing time for the two respective storms. An example of these events from August 08 is shown in Figure 2. The event in Figure 2 occurred at 05:27:16.287 UT, following a sprite that initiated at 05:27:16.204 UT. The only +CG reported by NLDN within 20 seconds was a 16.6 kA stroke at 05:27:16.351 UT, after the sprite had begun fading; however, a strong sferic was detected with the broadband VLF receiver at Palmer Station at 05:27:16.194 UT (with ~40 ms propagation time) that could have originated near the sprite location. In this event, as in most of those observed, propagation is very difficult to discern, as shown in the cross section at right. Note however that four individual features in this event reach to the lowest visible altitude in the bottom rightmost image frame; this resembles the "fingers" events in work by *Moudry et al.* [2001a]. This event also demonstrates the variability of these events.

[12] Of the twelve total secondary TLE events, the preceding sprite was seen to have average altitude ranges from 48 ± 5 to 94 ± 8 km, where the uncertainty is due to up to 50 km lateral displacement from the causative +CG. Hence, all of these features follow relatively large sprites, most of which reach to low altitudes. The secondary TLE tendril structures in these events had average altitude ranges from 32 ± 4 to 57 ± 6 km, although quite frequently the tops and/or bottoms of these structures were obscured by foreground clouds, so the real altitude ranges may be larger. It is important to note that the 32 km bottom altitude is well above typical cloud-tops; however in most cases the bottoms of the features are obscured by clouds, and furthermore lower altitudes are more difficult to observe due to atmospheric attenuation. Many of the secondary TLE events were fully formed over their altitude range in one video field (16.7 ms), again yielding propagation velocities of at least 1.5 (±0.2) × 10^6 m/s. The slowest observed velocity was in a feature that covered 8 km in one video field, or 0.5 (±0.1) × 10^6 m/s. Photometer data from 2004 showed a similar effect as in Figure 1 in two cases; in other cases, the tendril features were too weak or too small to effect a response in the photometers. We note that the photometers are filtered in the N_2 1P bands above 650 nm, and so while these features in some cases exhibit red emissions similar to sprites, we can say nothing about their overall spectral content. We note that blue jets and gigantic jets are predominantly blue [*Wescott et al.*, 1998a; *Pasko et al.*, 2002], and it is possible that our events have blue content as well - a likely scenario due to their altitude range. Since the cameras are unfiltered black-and-white images, the strong emissions seen in the cameras, combined with the weak red emissions in the photometers, may suggest strong blue content. ELF data from Langmuir was not available for the 2004 events.

[13] For the cases observed, feature sizes ranged from ~300 – 3000 m, though it should be noted that the spatial resolution of the wide field-of-view camera systems is not ideal, and features may be composed of smaller branching structures similar to the Gigantic Jet of *Pasko et al.* [2002]. Furthermore, 6 of the 12 cases exhibited branching visible in these cameras, including the example shown in Figure 1.

[14] In the 2004 event shown in Figure 3, a sprite was seen in the high-speed telescopic system, followed (after some delay, corroborated in timing by photometer and image data) by the tip of the secondary TLE feature (shown in the bottom rows of images in Figure 3), persisting for ~47 ms. The particular secondary TLE event feature seen in this case was ~300 m in diameter, expanding near the top. The cross section data at center-right shows a considerable increase in altitude between frames 527 and 544, and possibly a small increase between 544 and 561. The high-speed images show that this bead-like tip of the secondary TLE feature continued to move very slowly upwards after its initial appearance in the field-of-view (see reference line in Figure 3), advancing a total of ~170 m in 47 ms, for an average speed of ~3800 m/s. This speed is four orders of magnitude slower than typical sprite propagation speeds, and three orders of magnitude slower than secondary TLEs

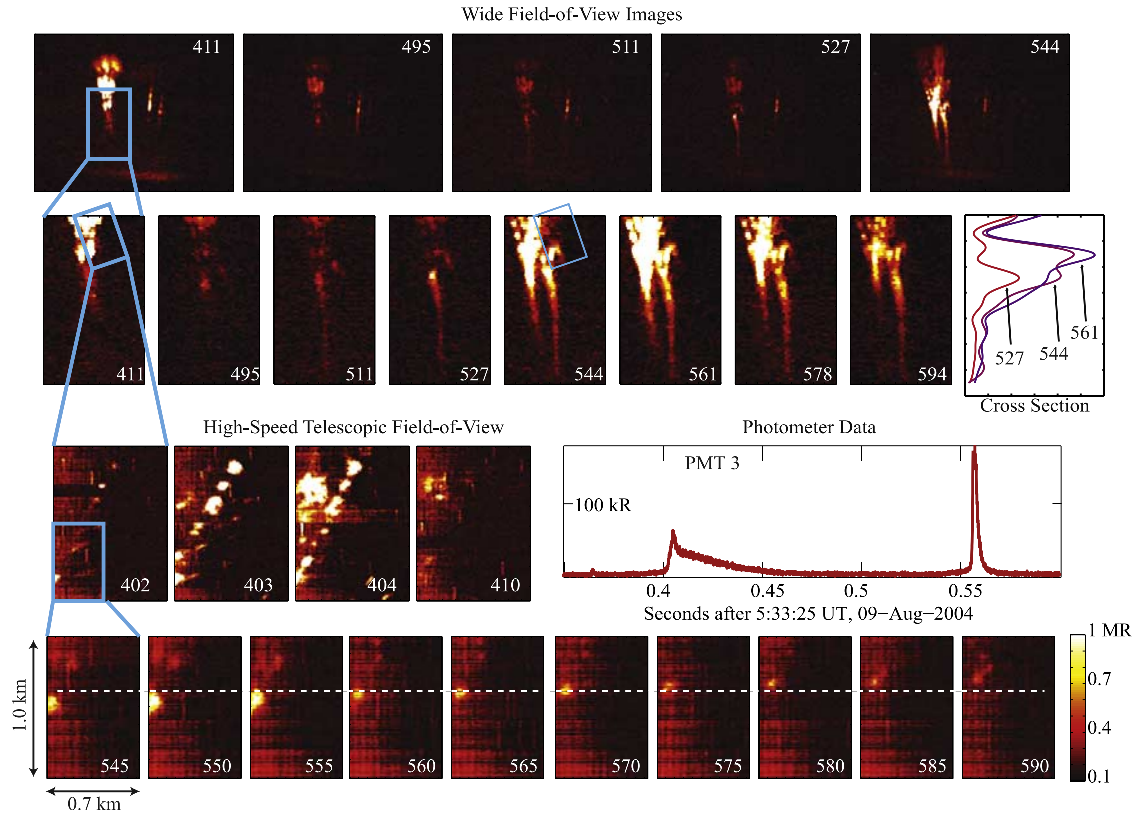

Figure 3. Secondary TLE event of 09-Aug-2004, seen in both (top) wide FOV video and (bottom) high-speed telescopic views. The middle row of high-speed frames are 1 ms integrations; the bottom row are 5-ms integrations done in post-processing. The time markers on each frame are the millisecond stamp of each frame after 05:33:25 UT. Photometer data is shown at middle-right. Cross section data at right varies from red to blue in time with each frame.

observed here, and indeed in the initial stages of this example. We note that the upward propagation of this feature appears to be continuous, unlike the discrete stepping of the features observed by *Moudry et al.* [2003], though the comparison is unfair due to the widely differing fields-of-view. Furthermore, in this case, as in 2 of the other 9 cases observed in 2004, a second sprite followed, at altitudes above the secondary TLE event. In the other two cases, the second sprite followed a second large +CG in the nearby region; however, in the case shown here, no second +CG was reported by NLDN. Furthermore, ELF/VLF data recorded at Palmer Station show a prominent sferic with large ELF content, evident of sprite-causative +CG [*Reising et al.*, 1996], but no second sferic consistent with a causative association with the second sprite. The photometer data for this example, shown in the bottom plot of Figure 3, corroborates the timing sequence described above. However, the secondary TLE event was likely too weak to produce a distinguishable response in the photometers.

4. Discussion

[15] The data presented here may represent a TLE feature that significantly contributes to the electrical charge flow between the thundercloud and the lower ionosphere. While the secondary TLE events herein may be similar to blue jets and Gigantic Jets, there are many differences. These secondary TLE events are not observed with any preference towards the early part of a thunderstorm as blue jets are [*Wescott et al.*, 1998b; *Heavner*, 2000], and are more strongly associated with the largest of sprites. However, like jets, it may be that these features are predominantly blue, as are the jets observed by *Wescott et al.* [1995], whose combined red and green intensity is only 7% of their blue intensity [*Pasko and George*, 2002]. Considering their brightness in the cameras and weak emissions in the red-filtered photometers, this is likely the case, and would suggest similar processes to the upward-propagating gigantic jets of *Pasko et al.* [2002] and *Su et al.* [2003].

[16] We postulate a mechanism for the production of these events, as shown in Figure 4. This mechanism parallels that of *Greifinger and Greifinger* [1976], used by *Pasko and George* [2002] for modeling of blue jets, in which a “moving capacitor plate” model separates regions of the atmosphere dominated by conduction currents above, and displacement currents below. ELF observations coincident with sprites have shown the likelihood of radiating currents within the sprite body [*Reising et al.*, 1996]; these currents move positive charge from the ionosphere towards the thundercloud along the large downward-pointing electric field following a +CG, as in the left plot of Figure 4. According to current sprite theories [e.g., *Pasko et al.*, 1998], a +CG leaves an excess of negative charge in the thundercloud; when positive charge is brought closer to this excess thundercloud charge by the sprite itself (moved from ionospheric altitude down to ~40–50 km altitude), the electric field is enhanced at lower altitudes and a second breakdown is initiated, as depicted in the right plot of

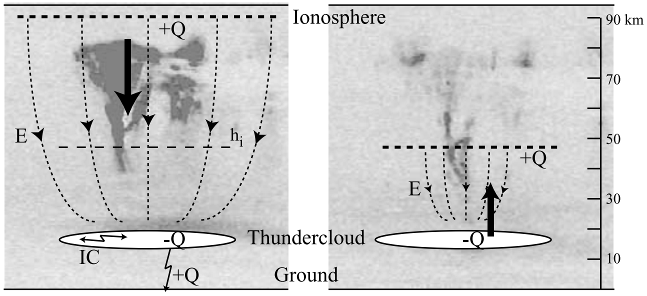

Figure 4. Mechanism of secondary TLE event production following a sprite, overlaid on an observed event. (left) The QE field becomes localized to lower altitudes after the sprite, (right) causing breakdown from the cloud to the lower sprite altitude. The "sprite" visible in the right frame is due to camera persistence.

Figure 4. If the secondary TLE events presented here contain currents, a direct current connection is created between the ionosphere and the thundercloud, via an intermediary altitude at the base of the sprite. Since both events observed in 2005 were accompanied by significant IC activity, it may be the case the charge movement within the cloud may be a necessary precursor to these events, as depicted in Figure 4.

[17] Furthermore, in the cases presented here, the entire process lasts <0.5 s, faster than the charge redistribution time in the thundercloud but much slower than the relaxation time at lower sprite altitudes (80 ms at 50 km - [*Pasko et al.*, 1997]. Thus, if the secondary TLE feature moves negative charge from the cloud-top to the lower edge of sprite altitudes (~40–50 km), this movement of charge may enhance the QE field responsible for the parent sprite and subsequently initiate a second sprite. Such initiation may explain the presence of the second sprite in Figure 3 without a causative sferic or NLDN stroke. However, the time scales involved mentioned above pose a problem for this mechanism in that the QE field needs to be sustained at sprite altitudes for hundreds of ms.

[18] While we have attempted to observe propagation of features in these examples, the images are inconclusive and propagation is still ambiguous. Furthermore, we cannot comment on the discrete or continuous nature of propagation, as seen in work by *Moudry et al.* [2003], for the full altitude range of these events. However, we must note that the specific characteristics of propagation (both direction and speed) do not affect the mechanism proposed above. The proposed mechanism merely suggests breakdown at some point between the upper and lower charge altitudes, ie. the base of the preceding sprite and the cloud-top. The specific altitude of breakdown, and the propagation direction and speed, can only be resolved by a more sensitive, high-speed imaging system.

[19] **Acknowledgments.** This work was supported by a Texas Instruments Stanford Graduate Fellowship and by ONR grant N00014-03-1-0333. We thank Victor Pasko of Pennsylvania State University for useful discussions.

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