A survey of streamer and diffuse glow dynamics observed in sprites using telescopic imagery

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[1] While the fine structure in sprites can assume a wide variety of shapes, sizes, and timescales, certain patterns such as upward branching, downward branching, beading, columns, bidirectional streamers, and propagating large-scale diffuse glow regions are repeatedly observed. Example cases of these streamer and diffuse glow dynamics observed in sprites are presented using video data obtained by a telescopic imaging system in July–August 1998 and are compared to predictions of current sprite and streamer theories. The previously unreported propagating diffuse glows move slowly ($\sim 10^4$ m/s) and are broader than that predicted for a streamer formation at the same altitude. Sudden brightening of slowly developing negative streamers may be indicative of a return stroke process in which the streamers connect with charge in a lowered ionosphere. Meteoric dust particles in the upper atmosphere may be responsible for the fine beading that exists in many negative streamers and may cause plasma enhancements that initiate double-headed streamers. Beads at the base of columns can glow for over 100 ms while slowly drifting upward ($\sim 10^4$ m/s). Columns may initiate from downward branching positive streamers. Faint positive streamers are observed at the base of and/or preceding large bright sprite events. Some sprites may initiate as double-headed streamers formed in localized regions of enhanced electron density. A transition between the streamer formation region and the diffuse glow region is observed at ~80-km altitude. No fine structure is observed in telescopic images of the diffuse glow region also referred to as the "sprite halo" [*Barrington-Leigh and Inan*, 2001]. *INDEX TERMS:* 2439 Ionosphere: Ionospheric irregularities; 3324 Meteorology and Atmospheric Dynamics: Lightning; 2427 Ionosphere: Ionosphere/atmosphere interactions (0335); *KEYWORDS:* sprite, streamer, lightning

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1. Introduction

[2] Sprites are large luminous discharges which appear in the altitude range of ~40 km to 90 km above thunderstorms [e.g., *Sentman et al.*, 1995]. Video observations have revealed fine structure in sprites, including upward and downward branching [*Sentman et al.*, 1996; *Taylor and Clark*, 1996; *Stanley et al.*, 1996; *Fukinishi et al.*, 1996]. High speed imaging of sprites has captured the temporal development of some of the fine structures seen in sprites such as the upward and downward branching and slowly moving beads [*Stanley et al.*, 1999; *Stenbaek-Nielsen et al.*, 2000] revealing that in general sprites are initiated as columns with downward branching at their bases followed by upward branching from the column. Telescopic imaging of sprites has shown that the fine structure covers a wide range of features which are primarily vertically oriented but also slanted at varying degrees, including branching tree-like shapes and well defined but isolated columns [*Gerken et al.*, 2000]. It has been observed that a diffuse glow region may occur in the upper altitudes (~70–85 km) of sprites. This diffuse glow region may exist independently or either precede or accompany streamer formation region at lower altitudes. The diffuse glow region, or "sprite halo", and the streamer formation region are able to exist independently due to the strong variation with altitude of the timescale for electrical relaxation of the postlightning quasi-electrostatic field above thunderclouds [*Barrington-Leigh and Inan*, 2001]. A theoretical explanation of observed spatial fine structures and diffuse glow in sprites was put forth in the context of a streamer-based model of electrical breakdown above thunderstorms [*Raizer et al.*, 1998; *Pasko et al.*, 1998]. Characteristic structure widths for each altitude have been predicted, ranging from ~10 m at 70 km to ~100 m at 85 km [*Pasko et al.*, 1998]. The tortuous path of cloud-to-ground lightning has been modeled as a fractal antenna resulting in a highly nonuniform radiation pattern at sprite altitudes and possibly accounting for fine structure [*Valdivia et al.*, 1997]. Fractal techniques have also been applied to the sprites streamers themselves as a means of predicting general shapes of bulk sprite volumes [*Pasko et al.*, 2000; *Petrov and Petrova*, 1999]. In this paper we

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present examples of various types of fine structure found in sprites and compare these structures to that predicted by existing streamer and sprite models.

2. Description of Experiment

[3] During the months of July and August 1998, Stanford University deployed a telescopic imaging system, consisting of a ~41 cm diameter, f/4.5 Dobsonian-mounted Newtonian reflecting telescope with an intensified CCD camera attached to its eyepiece and a bore-sighted wide field of view (FOV) camera mounted on its top. The system was deployed at the Langmuir Laboratory (LL), located in the Magdalena Mountains of central New Mexico and operated by the New Mexico Institute of Mining and Technology. The FOV of the telescope (0.5 in CCD) was 0.7 degrees by 0.92 degrees while that of the bore-sighted camera (0.33 in CCD, 50 mm lens, f/1.4) was 9 degrees by 12 degrees. Both cameras were unfiltered with a broadband spectral response which peaked between ~450 and 850 nm. The narrow FOV camera was field-selected, creating images exposed for ~17 ms while the wide FOV camera was in interlaced frame mode creating images exposed for ~33 ms. GPS video time-stamping and IRIG-B code were used for timing. Images presented are deinterlaced NTSC TV images and time-stamping occurs at the end of the first field of each frame. Electromagnetic signatures of causative lightning discharges known as radio atmospherics (or sferics) were recorded using crossed-loop magnetic antennas and ELF/VLF receiving system located at Stanford University. A more detailed description of this experiment and the method of instrument calibration are presented by *Gerken et al.* [2000].

3. Examples of Fine Structure

[4] Hundreds of cases of fine structure in sprites have been observed by the Stanford telescopic imager. While widely ranging in morphology, certain trends have been found such as upward and downward branching, beading, and streamer/diffuse glow transition regions. We use selected cases from 13 July, 19 July, and 6 August 1998 to illustrate these morphologies.

3.1. Case I: 05:15:00 13 July 1998

[5] This event illustrates the rich diversity of morphologies possible in the fine structure of a single sprite event, including faint downward-branching streamers, upward-branching tree-like structures, nonbranching streamers, beads, and a propagating region of diffuse glow. One or more of these broad categories of features appear in the majority of sprites observed with the telescopic imager on this and other days.

[6] Faint downward branching streamers, also referred to as "sprite tendrils" [e.g., *Wescott et al.*, 1998; *Stanley et al.*, 1999; *Stenbaek-Nielsen et al.*, 2000], are observed in several sprites. They occur either at the base of the sprite or prior to a bright sprite event. Both types occur in the 05:15:00 13 July 1998 event shown in Figure 1. The monochromatic digitized video images presented in this and subsequent figures have been false-colored in order to better show the dynamic range of the data. The false-color scale ranges from blue at minimum brightness to red at maximum brightness (Figure 1) [*Gerken et al.*, 2000]. None of the narrow field images presented here were saturated in the camera, however the dynamic ranges have been scaled in order to enhance relatively dim fine-scale features. In the first narrow field of view panel (N1) faint downward-branching streamers precede the main sprite event and are not evident in the wide field of view image. The second narrow field of view panel (N2) similarly has a downward-branching structure but this one is at the base of a bright sprite as can be seen from the corresponding wide field of view image. Each video frame, however, corresponds to 17 ms of photon integration which means that in fact both sets of downward streamers could have

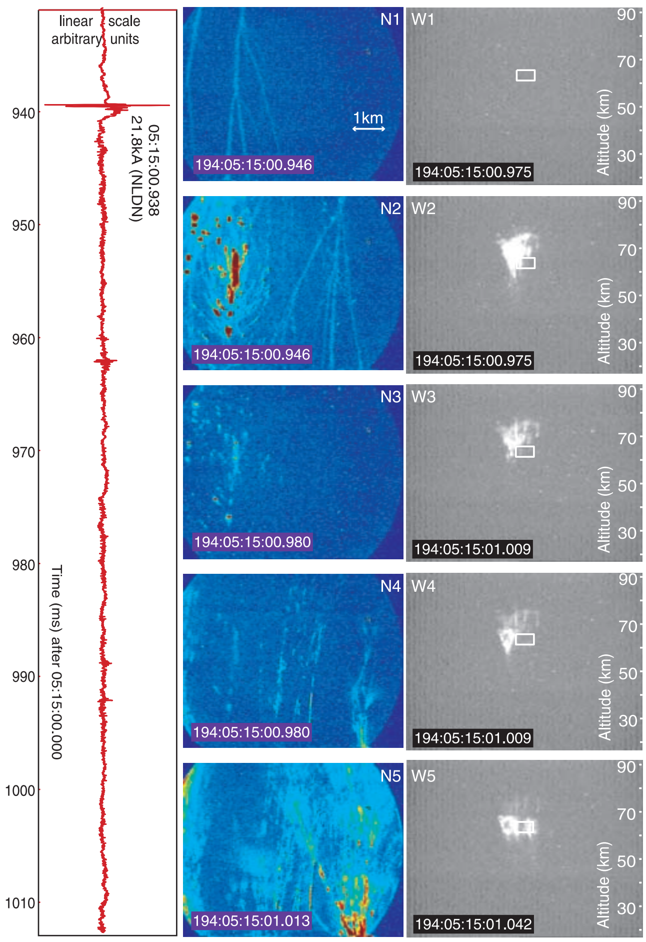

Figure 1. This sprite event exhibits several types of features including faint downward positive streamers, bright upward negative streamers, beading, and a propagating diffuse glow. The leftmost panel contains the Stanford ELF recording during the event. The middle column shows the telescopic field of view (panels N1–N5) and the rightmost column shows the wide field of view (panels W1–W5). The narrow field of view with respect to the wide field of view is depicted by a white rectangle in the wide field of view images. Images presented are deinterlaced NTSC TV images and time-stamping occurs at the end of the first field of each frame.

preceded the bright sprite structures. Sprite features have been observed by high-speed imagers to develop within a few milliseconds [*Stanley et al.*, 1999; *Stenbaek-Nielsen et al.*, 2000]. In both cases the streamers maintain a fairly constant half-maximum width of ~120–130 m (10–11 pixels) as is observed in theoretical models of the filamentary stage of streamers [*Vitello et al.*, 1994]. The brightness also varies little and is ~10 kR as determined by the camera calibration described by *Gerken et al.* [2000]. No beading is apparent. Relatively little branching is observed in these structures with the streamers apparently propagating several kilometers before splitting. The streamers appear to bifurcate at close to the same angle each time with two primary streamers continuing creating a fractal-like pattern (although triangulation would be necessary to determine the actual angle). Streamer bifurcation was modeled by *Pasko et al.* [1998] who proposed that the streamers split when their radius exceeds that necessary for stable propagation. The regular branching may imply that the local ambient electric field (external to the streamer) is uniformly vertical and that the branches follow the field lines created by the superposition of the ambient field and the electric field of the streamer head (as illustrated by *Raizer* [1991], p. 332). Although it should be possible to reconstruct these field lines from the streamer images, triangulation is necessary since the angle of branching cannot be determined from a single two-dimensional image.

[7] An upward-branching structure is shown in the second narrow field of view panel (N2) where the downward branching had occurred in the previous panel (N1). The downward branches were likely initiated above the field of view and propagated downward (and out of the field of view) while the upward branching structures apparent may have been initiated below the field of view and have propagated into it. Since the associated sferic was produced by a positive cloud-to-ground (CG) lightning stroke, the electric field set up above the storm after the CG is directed downward. The downward branching structures are thus likely to be positive streamers while the upward branching structures are negative streamers. A streamer is a transient filamentary plasma structure which propagates as an ionization wave with charge separation and an enhanced, localized electric field in its wave front (streamer "head" region). The polarity of a streamer is determined by the charge in the streamer head—a positive streamer accelerates electrons into its head and travels in the direction of the external electric field while a negative streamer expels electrons from its head and travels in the opposite direction (for further explanation, see *Raizer* [1993]).

[8] The telescope's field of view covers ~60–65 km altitude range in these images. As described by *Gerken et al.* [2000], each sprite altitude was calculated using the elevation of the background starfield and the range of the associated +CG as determined by the National Lightning Detection Network (NLDN). The spatial resolution of the system is determined by the range of the object being imaged (e.g., at a range of 500 km, each pixel maps to ~12.5 m by ~12.5 m).The charge moment at the time of the sprite for the associated sferic is calculated to be ~1000 C km using the model developed by *Cummer and Inan* [2000]. *Pasko et al.* [2000] calculated the electric field versus altitude for 10 C × 10 km and 100 C × 10 km CG's as well as the breakdown electric field and critical electric fields for stable positive and negative streamer propagation. According to these calculations, even for a relatively large 100 C discharge, the electric field only exceeds the breakdown field at an altitude of 80 km or higher. This is consistent with the images of positive streamers presented in this example which appear to have been initiated at an elevation greater than 65 km. However, the negative streamers appear to have been initiated at an altitude below 60 km where the breakdown field is not exceeded. Since the positive streamers precede the negative streamers it is possible that they play a role in the initiation of the negative streamers due to the enhanced electric field in the vicinity of the streamer head [*Dhali and Williams*, 1987]. Such a circumstance is consistent with high-speed camera images [*Stanley et al.*, 1999] in which it was observed that sprites began as downward branching forms and subsequently developed into upward branching structures.

[9] The upward branching negative filaments found in the second telescopic panel (N2) have much higher peak brightness (~240 kR over a video field) than the positive streamers preceding them. Streamer emission has an exponential dependence on the electric field in its head [*Kulikovsky*, 1997]. For a given streamer radius and velocity, the electric field found in the streamer channel is higher in a negative streamer whereas the field in the streamer head is higher in a positive streamer [*Babaeva et al.*, 1997]. Tree-like structures similar to the ones shown in this example are probably the time-integrated images of an upward-moving streamer with many streamers emanating from its tip. Much beading is observed. As opposed to the positive streamers discussed previously, beads often persist for several frames either remaining stationary or drifting slowly as was observed previously [*Stenbaek-Nielsen et al.*, 2000].

[10] In the third panel (N3) of telescopic images, some of the beads continue to glow. The only other structure present is a faintly glowing portion of the negative streamer that continues to glow in the fourth and fifth panels (N4 and N5). By the fourth panel (N4), most of the beaded structure has faded away. New almost vertical filaments are formed with no branching. These bright filaments are ~60 m wide and have a brightness of ~50 kR. The direction of propagation is not evident. The filaments consist of a number of long luminous segments with dark spaces between. In the following panel (N5), these filaments remain present and grow brighter with some of the segments merging to form long channels. The rightmost group of filaments diverges from vertical in a cone expanding with altitude, indicating upward propagation. These filaments may be in close proximity to each other and are therefore repelled as one would expect in the case of charged conductors.

[11] In the fifth panel (N5) beading as well as faint broad diffuse glow is present. A glowing region near the middle of the panel proceeds to move upward in the 6 subsequent fields, lasting over 100 ms. The movement of this diffuse glow is show in Figure 2 with a superimposed stationary dashed white line for reference. The glowing region covers an area of ~4.80 × 1.75 km and propagates at a velocity of ~10^4 m/s, three orders of magnitudes less than streamer velocities reported by *Stanley et al.* [1999]. Other examples of this sort of glow were also found in telescopic images of

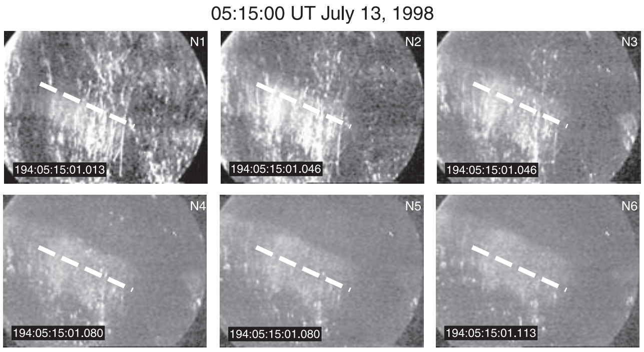

Figure 2. Propagating diffuse glow during the 0515:00 UT 13 July 1998 event. The dashed white line has been superimposed for reference. The glowing region covers an area of $\sim$4.80 $\times$ 1.75 km and propagates at a velocity of $\sim 10^4$ m/s, three orders of magnitude less than streamer velocities previously reported.

sprites. The glow generally occurs in the presence of many fine filaments as is the case here. Most likely these filaments and other preceding ionizing channels temporarily raise the local electron density to the level where a glow discharge is maintained instead of a streamer structure as is often observed at higher altitudes ($\sim$85 km). Each example of this type of propagating diffuse glow has been found to propagate upward. Frequently, multiple horizontal striations are observed in the glowing region.

[12] Propagation of this horizontally striated diffuse glow may be due to a diffusion-dominated mechanism similar to that observed in striated glow discharges [*Stewart*, 1956; *Raizer*, 1993]. A striated state is preferable in a glow discharge. This is due to the fact that it is more likely for an electron to gain enough energy for ionization without losses through excitation in a short distance with a steep potential gradient than over a slowly increasing potential gradient. Additionally, excitation losses are low in the flat potential region between striations [*Allis*, 1976] resulting in a striated glow discharge having a lower average electric field than a homogeneous one.

[13] If an instability is triggered such that striations are set up, the charge density becomes arranged sinusoidally in the direction of the ambient electric field lines. Although there is a high degree of charge neutrality, the electrons diffuse somewhat and charge separation occurs (refer to *Raizer* [1993], Figure 9.5, p. 235). This charge separation enhances the ambient field on one side of the charge density peaks while diminishing it on the other side. Electron temperature is almost in phase with the electric field, and since the ionization rate is more sensitive to electron temperature than to electron density, ionization is increased in these regions of field enhancement. Thus the sinusoidal variation of the ionization rate is a quarter phase off from that of the charge density variations and in general the striations are in motion [*Raizer*, 1993]. While the phase velocity of these charge density striations is generally pointed in the direction of the ambient electric field, the group velocity is always pointed in the opposite direction from that of the ambient field [*Allis*, 1976]. This property means that even though the striations themselves may be traveling in the direction of the electric field, the enhanced regions of glow viewed by an observer will be seen traveling the opposite direction [*Raizer*, 1993]. In the case of a glow discharge tube the bright regions are observed to travel from cathode to anode while in the case of sprites they would travel toward the ionosphere (in a field set up by a positive CG) as is indeed observed.

[14] Studies of breakdown phenomena in liquids have shown that shock waves can be created by streamers forming rings of ripples emanating from the streamer tips. These shock waves have been found to have slower velocities than the causative streamers [*Devins et al.*, 1981; *Yamada et al.*, 1990]. A similar phenomenon may be present in the atmospheric breakdowns such as that observed in this example.

3.2. Case II: 04:07:48 19 July 1998

[15] This event (Figure 3) is an example of a very slowly propagating upward (negative) streamer structure preceding a bright sprite. As opposed to the last case where a sferic was recorded in ELF at the same time as the initial streamers (to within the 17 ms resolution of a video field), the closest sferic recorded prior to this sprite was 30 ms before the start time of the telescopic video field in which the event was observed (N1). No lightning strokes are reported by the National Lightning Detection Network (NLDN) for the

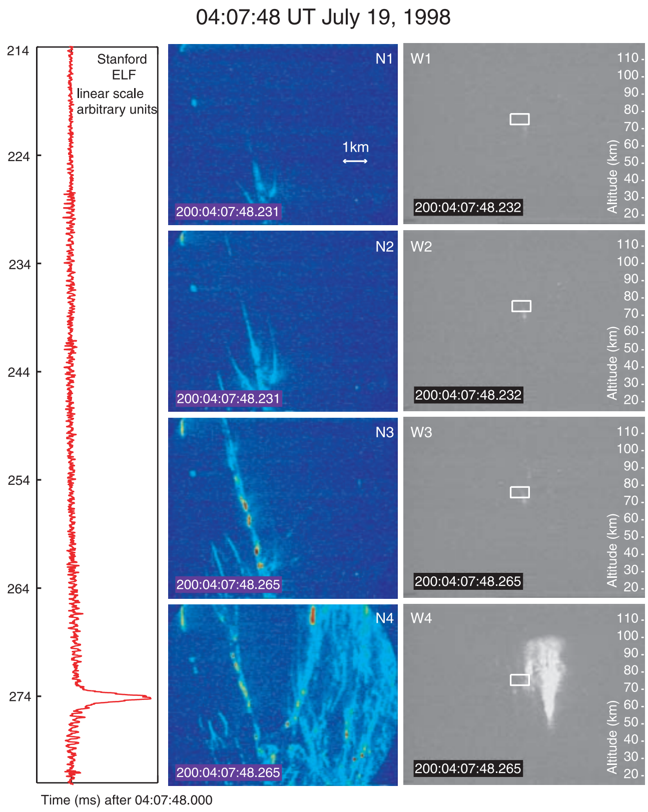

Figure 3. Slowly propagating streamers preceding a bright sprite event at 0407:48 UT 19 July 1998. No sferic signature is observed in the Stanford ELF recording for 30 ms prior to the appearance of the bright sprite and no CG is reported by NLDN during the second of this event. An ELF peak is observed in conjunction with the bright sprite.

associated storm within the full second during which the sprite was observed so that the delay between causative sferic and sprite initiation is ambiguous. The first three panels of the wide field of view camera (W1–W3) show that initially a very small and dim sprite occurred and was followed by the sudden development of a large bright sprite in the fourth panel (W4). The subsequent frames show further development of this bright sprite. There is a large ELF pulse recorded at Stanford simultaneous (within the ~17 ms resolution of a video field), with the bright sprite event which appears to have been radiated by the sprite itself [*Cummer et al.*, 1998].

[16] The telescopic images capture two streamer structures in this event that develop very slowly prior to the bright sprite. The first narrow field of view panel (N1) shows a forked structure in the middle bottom portion of the field. The middle branch of this forked structure has a width of ~120 m as seen in the second panel (N2). Based on the measurements from two successive video fields, the middle branch propagates upward at a velocity of $\sim 10^5$ m/s, two orders of magnitude less than the velocities measured by *Stanley et al.* [1999], and at the lower limit of that predicted by *Raizer* [1998]. Observations have shown that there is a minimum velocity possible for streamer propagation which is on the order of magnitude corresponding to the electron drift velocity [*Raizer*, 1998]. Simulations indicate that lowering the ambient voltage (i.e., electric field) lowers the streamer velocity [*Dhali and Williams*, 1987], and such may be the case for the example in hand. A low voltage electric field may be increasing in time between the clouds and the ionosphere in response to a continuing current flow to ground from a previous lightning stroke.

[17] Simultaneous to the upward development of the forked structure, another streamer appears to start at the top of the field of view and extends down toward the middle branch. It is possible that this extension is actually a part of the upward streamer with a dark space in the middle. In such a case the velocity of this streamer would be higher than that stated in the previous paragraph. Finally, in the third panel (N3), the middle branch reaches its maximum brightness and beading occurs. It appears that the middle branch reached a charge source that caused a "return stroke" to propagate downward following the path of the original streamer. Typically this sort of a process appears like a reversed streamer at a much higher ionization than the original streamer [*Raizer*, 1991, p. 343]. If the causative CG lightning has slow charge removal ($\geq$1 ms) then the time dependence of the lower boundary of the ionosphere begins to play a significant role in streamer dynamics. If the lower ionosphere has a high conductivity, the boundary is able to quickly descend to 80-km altitude [*Pasko et al.*, 1999]. The upper edge of the field of view in this example is in fact at ~80 km so that it is possible that the upward going streamer encountered the lower boundary of the ionosphere, leading to the initiation of a return stroke from the ionosphere.

[18] The second slowly developing feature present in this sprite event is a downward propagating streamer that begins at the upper left-hand corner of the narrow field of view. The streamer expands downward over the four fields shown with a velocity of magnitude $\sim 10^4$ m/s and is much brighter than the upward going streamers. There is a small bead below the streamer which brightens and moves upward in the direction of the bright downward streamer. In the third panel (N3) a dim streamer reaches upward beneath the bead and continues to propagate in the fourth panel (N4). Although these features appear to be along the same channel, such is not necessarily the case since only two dimensions are imaged. Columnar structures have been observed in other sprite events but beads are generally found in closer proximity to the base of the column [*Wescott et al.*, 1998; *Gerken et al.*, 2000]. An upward propagating diffuse glow structure similar to that described in Case I was apparent in subsequent fields (not shown).

3.3. Case III: 0433:10 UT 19 July 1998

[19] This sprite event exhibits the fine beading that often occurs in the middle regions of sprites. In the wide field of view images, the event is made up of a series of sprites which move from right to left. The image shown in Figure 4 depicts the second sprite in the series. The beads are strung along upward-branching channels at fairly regular intervals and range in size from ~70 to 150 m. Most of the beads last 2–3 video fields but remain stationary from field to field.

[20] It has been proposed that beads and other structures found in sprites may in fact be initiated by dust particles [*Zabotin and Wright*, 2001; *Wescott et al.*, 2001]. Dust particles of meteoric origin in the mesosphere and stratosphere most likely have many microspires that locally enhance the quasi-static electric field following a CG. Microscopic protrusions are also found on massive cathodes and it has been observed that the electric fields on these protrusions are enhanced by a hundredfold or more. The current caused by thermionic emissions at the protrusion tip can create enough Joule heat to explode the metal [*Raizer*, 1993]. In the case of sprites, a similar thermal explosion of meteoric dust particles would create an effective plasma source which in turn could initiate a streamer. This mechanism may be responsible for sprite initiation, and the branching, discontinuous streamers, and bright beading observed in telescopic imagery of sprites [*Zabotin and Wright*, 2001].

[21] The charge moment change at the time of the sprite in this example is calculated to be ~700–2000 C km (the calculation is limited by the time resolution of a video field). These streamers initiate in an electric field below the breakdown threshold predicted by *Pasko et al.* [2000] for a charge moment of 100 C $\times$ 10 km and are at the boundary altitude for negative streamer propagation. It may be that dust particles initiate streamers at altitudes lower than that predicted for a dust-free environment. A similar phenomenon has been experimentally recorded in laser breakdown of liquids where beading occurred along the breakdown axis as a result of defects such as microscopic bubbles, contaminants, or soot [*Teslenko*, 1982].

[22] Another closely related phenomenon is that of beading in cloud-to-ground lightning channels. Beads in cloud-to-ground lightning have been found to exist 75–300 ms after the decay of the lightning channel, having diameters ranging from 50 cm to several meters [*Boichenko*, 1996]. *Boichenko* [1996] has developed a theoretical explanation

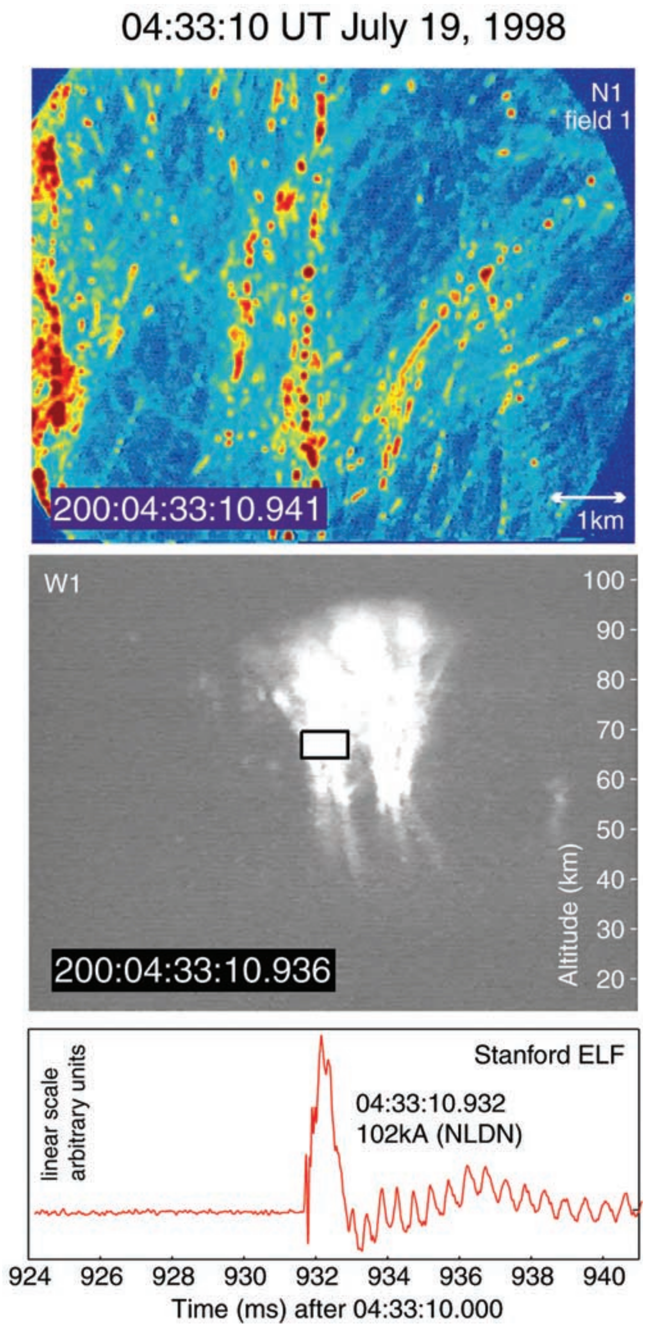

Figure 4. Example of fine beading in negative streamers during a large sprite at 0433:10 UT 19 July 1998. The beads may have been initiated by meteoric dust. It may be that dust particles initiate streamers at altitudes lower than that predicted for a dust-free environment.

for the observations of persistent beads in cloud-to-ground lightning suggesting that inhomogeneities of the atmosphere or of some parts of the lightning bolts could cause energy to be irregularly deposited within the channel. Such inhomogeneities may in fact be dust-related.

[23] Beading appears to primarily be a negative streamer phenomenon since little beading has been observed in the positive streamers of sprites. This asymmetry in bead formation has also been found experimentally in laboratory pulsed gas discharges [*Zobov and Siderov*, 1990]. Models of positive and negative streamers in air have shown that positive streamers have a higher electric field in their head and a higher electron density, but a lower channel electric field [*Babaeva and Naidis*, 1997]. It has been found in studies of breakdown in dielectric liquids that positive streamers appeared with a lower crest voltage, lower light emission and higher velocity than negative streamers [*Yamada et al.*, 1990; *Massala and Lesaint*, 2001]. It is possible that the more slowly propagating negative streamer with a higher channel field allows for a greater enhancement of the electric field surrounding dust microspires and thus accounts for the asymmetry of bead formation.

3.4. Case IV: 0543:10 UT 19 July 1998

[24] This event is an example of a single "columniform" sprite [*Wescott et al.*, 1998] imaged by the telescope (Figure 5). Other frames of the wide field of view camera (selected fields shown) indicate that this sprite is the middle part of a sequence of "dancing" sprites moving from right to left across successive frames. First, a collection of ~15 columniform sprites occurs at approximately the same altitude (~80 km) as the telescopically imaged column. Next, several large carrot-shaped structures form beneath the wake of fading columns and some of the columns are re-ignited. The "carrot" sprites [*Winckler et al.*, 1995] are about fives times the height of the columns. A couple of the columns appear to become part of the carrot structures. As the carrots fade over the subsequent frames, the single columniform sprite shown in the telescopic images emerges. This column exists by itself for three successive frames. Finally, five frames later a collection of ~10 columniform sprites appears at ~70 km altitude and then subsequently fades away.

[25] Figure 5 displays four fields from the wide field of view camera at the top. The middle two fields (W2 and W3) show a bright column in the center of the image with the wake of the carrots on the right. The middle row of panels (N1–N7) shows a sequence of slices through the narrow field of view containing the bright single columniform sprite. As shown in these panels, the columniform sprite starts as a faint positive streamer which branches once in the field of view and has a slightly brighter segment on the top. In the subsequent fields the branching streamer is not present and the upper segment becomes much brighter, extends downward, and develops a single bead at its base with a dark space occurring between the bead and the bright segment. This bead and the dark space above travel upward along the channel as the bright segment fades and contracts upward. The bead has the longest lifetime of any features present and travels upward at a rate of $\sim 10^4$ m/s. The entire sequence has a long lifetime lasting ~120 ms, which could either be the result of chemical changes or persistent electric field/current flow. The tapering of the column at its top is inconsistent with the expected profile variation of a streamer with respect to altitude [*Pasko et al.*, 1998]. A similar contraction phenomenon is observed in positive glow discharges when the current is increased [*Raizer*, 1991]. The column width of 150 m is slightly larger than predicted for this altitude [*Pasko et al.*, 1998] and has been previously documented [*Gerken et al.*, 2000]. The column appears

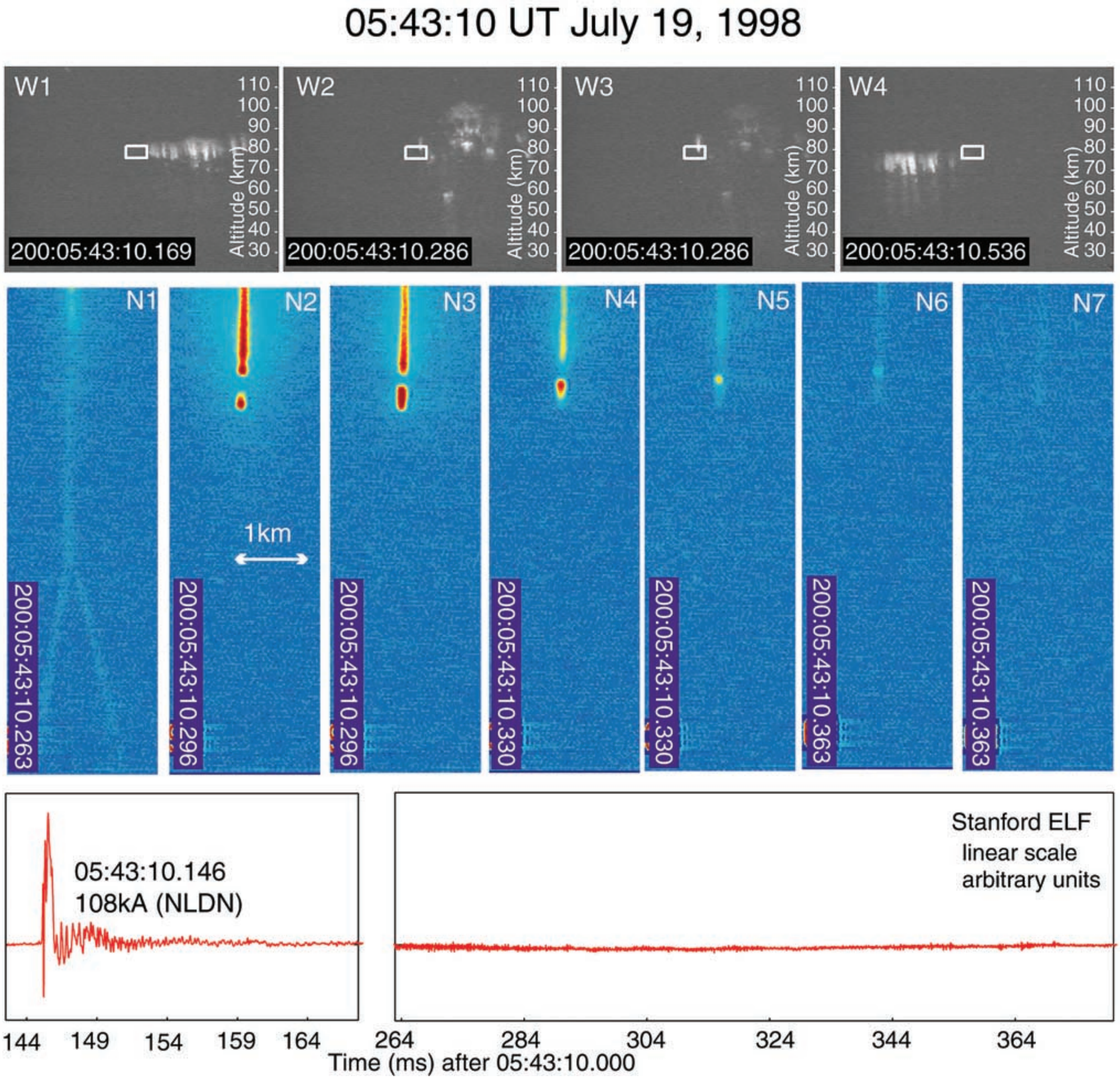

Figure 5. Example of a columniform sprite with initial downward branching and a slowly moving bead at 0543:10 UT 19 July 1998. The wide field of view panels on top of the figure (W1–W4) are selected frames containing bright features from the dancing sprite sequence of which the column sprite was a part. The telescopic images sequentially range from 0543:10.263–05:4310.380 UT. The sferic record at the bottom left shows the sferic related to the causative cloud-to-ground lightning stroke which occurred over 100 ms prior to the column sprite. The sferic record at the bottom right shows the recording during the interval of the column sprite as displayed in the telescopic images.

to have boundaries which are sharper than the resolution of the camera.

[26] This sort of column/bead structure has been previously documented [*Wescott et al.*, 1998; *Gerken et al.*, 2000]. Studies conducted by means of high-speed imagers suggest that columniform sprites initiate the so-called carrot sprites [*Stanley et al.*, 1999; *Stenbaek-Nielsen et al.*, 2000], appearing to originate from downward positive streamers and subsequently moving upwards in branching negative streamers following the original channel. However, it is unclear as to why in some instances collections of bright columniform sprites occur while in others only a few large carrots form [*Wescott et al.*, 2001].

[27] Although previously documented [*Wescott et al.*, 1998], it is unusual to find a single columniform sprite as exemplified by the case in hand. Columniform sprites are most frequently observed in clusters. *Cho and Rycroft* [2001] investigated the distribution of energy deposition from an electromagnetic pulse (EMP) due to a horizontal lightning discharge. They found that the EMP formed local

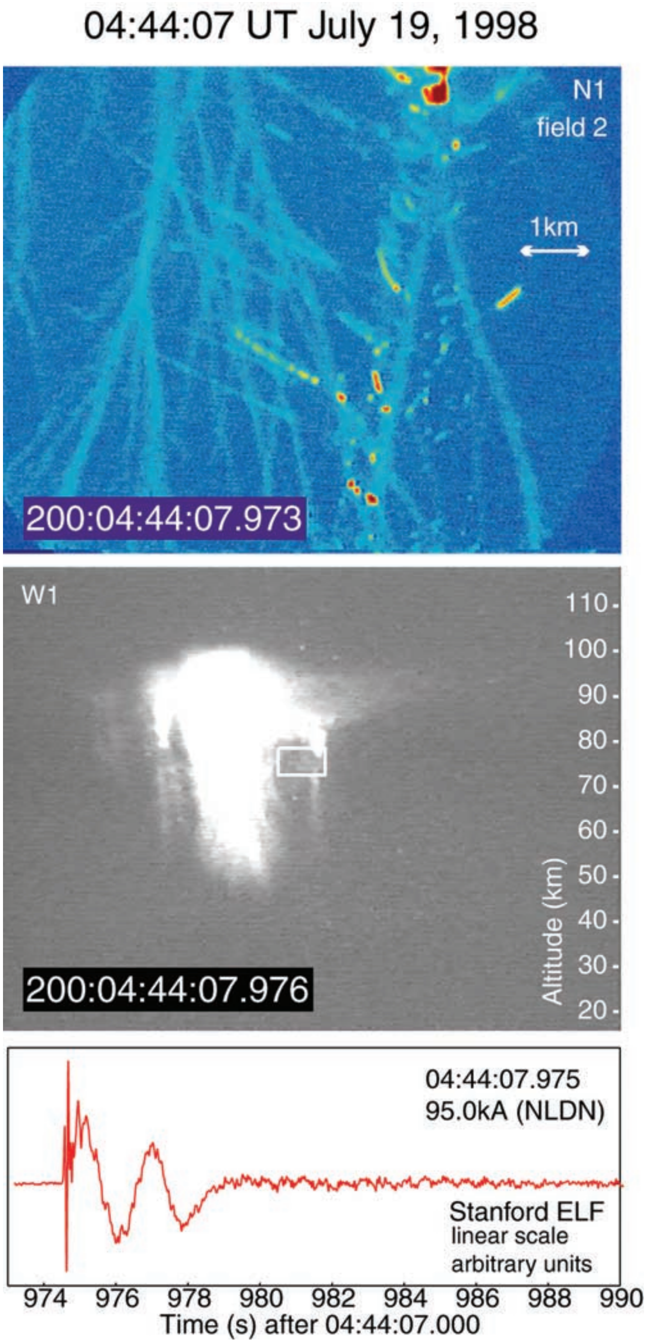

Figure 6. Faint downward branching positive streamers during a large bright sprite event at 0444:07 UT 19 July 1998. Faint positive streamers are frequently observed either preceding a bright sprite or at the base of a bright sprite.

maxima due to interference between direct waves radiated by the discharge current, those reflected by the ground, and those reflected from the ionosphere. These maxima caused the formation of "stalactites" of ionization enhancements spread ~10 km apart between ~75–85 km altitude. *Cho and Rycroft* [2001] suggest that it would be possible to initiate clusters of columniform sprites from field enhancements due to these stalactites thus accounting for the high altitude at which columniform sprites are found and possibly also the fact that they have been observed as the first stage in carrot sprite formation. In general, a positive streamer develops more easily than a negative one and requires a lower voltage since its electron avalanche propagates in the direction where the electric field becomes stronger [*Raizer*, 1998, p. 253].

[28] The bottom panel in Figure 5 displays the sferic record associated with this sprite event. While there is a sferic at the time of the initial sprite of the sequence (left bottom panel), no sferic activity is present during the interval

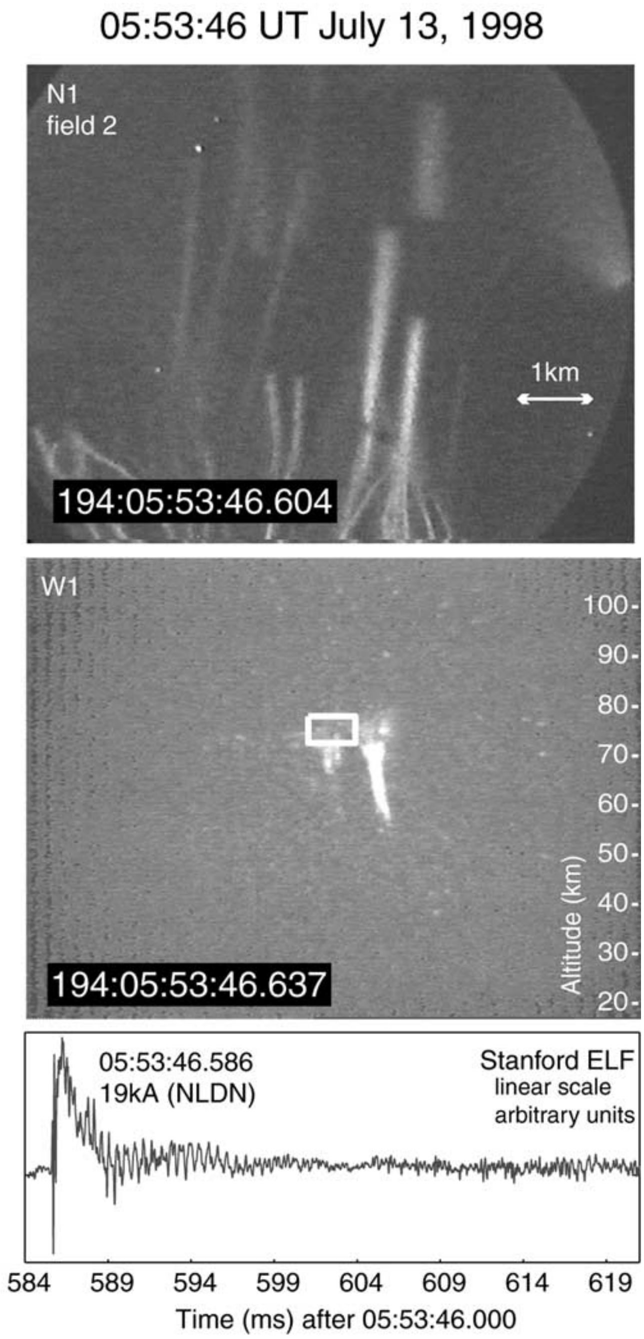

Figure 7. Bidirectional streamers in a small sprite event at 0553:46 UT 13 July 1998. The positive streamers branch while the negative streamers expand indicating that this bidirectional streamer may have been initiated with a radius below that necessary for negative streamer propagation but above the critical radius for positive streamer propagation.

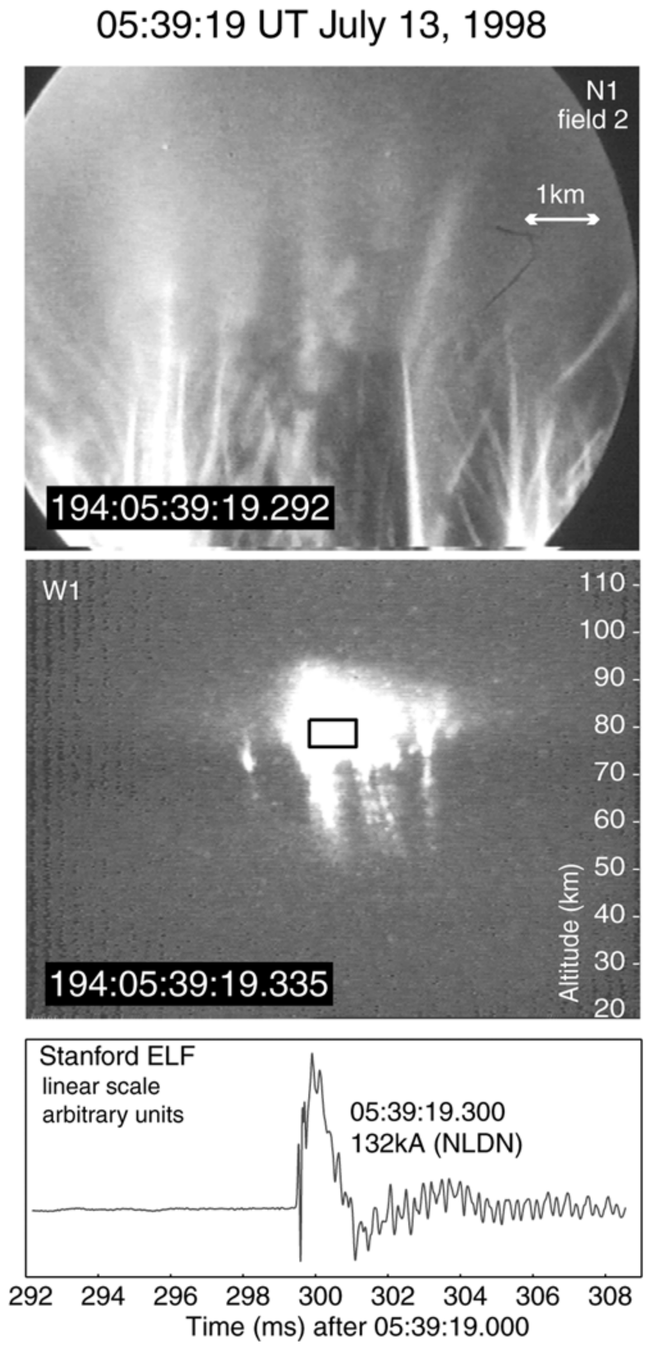

Figure 8. Transition between the streamer region and the diffuse glow region as seen in a large sprite event at 05:39:19.335. The transition region only exists over a narrow region of 1–2 km in height at an elevation of ~80 km, consistent with model predictions that the transition region should exist between 75 and 85 km.

in which the lone column exists (right bottom panel). The entire sequence lasts ~450 ms. The long delay between sferic and much of the sprite activity suggests the presence of continuing currents either within the thunderstorm [*Bell et al.*, 1998] or to ground [*Cummer and Fullekrug*, 2001].

3.5. Case V: 0444:07 UT 19 July 1998

[29] This case is an example of faint positive streamers found at the base of a small carrot sprite on the side of a large bright sprite event as shown in the wide field of view panel (W1) of Figure 6. Faint positive streamers are frequently observed either preceding a bright sprite or at the base of a bright sprite. These streamers can occur in a dense filamentary structure [*Gerken et al.*, 2000] or as more isolated tendrils with fewer bright spots. As was also the case in Figure 1, bifurcating branching angles in this example are similar to that modeled by *Pasko et al.* [1998]. The streamers observed in the telescopic image (N1) range in width from ~80 to 145 m. Some beading does occur and it appears to be following an upward branching path. This upward branching path may be part of another sprite structure in front of the tendrils or alternatively may be a negative streamer traveling back up the original positive streamer channel and branching upwards. The top portion of the rightmost tendril group is in the base of the bright region of the carrot sprite and is much brighter than the faint downward branches.

3.6. Case VI: 0553:46 UT 13 July 1998

[30] Figure 7 shows an example of an unusual sprite structure exhibiting only downward branching. The upper nonbranching columns expand with altitude as predicted [*Pasko et al.*, 1998; *Raizer*, 1998]. This sprite develops over several fields. It initiated with a downward "wishbone" shape which then grows an upward column and develops further downward branching around the "wish-

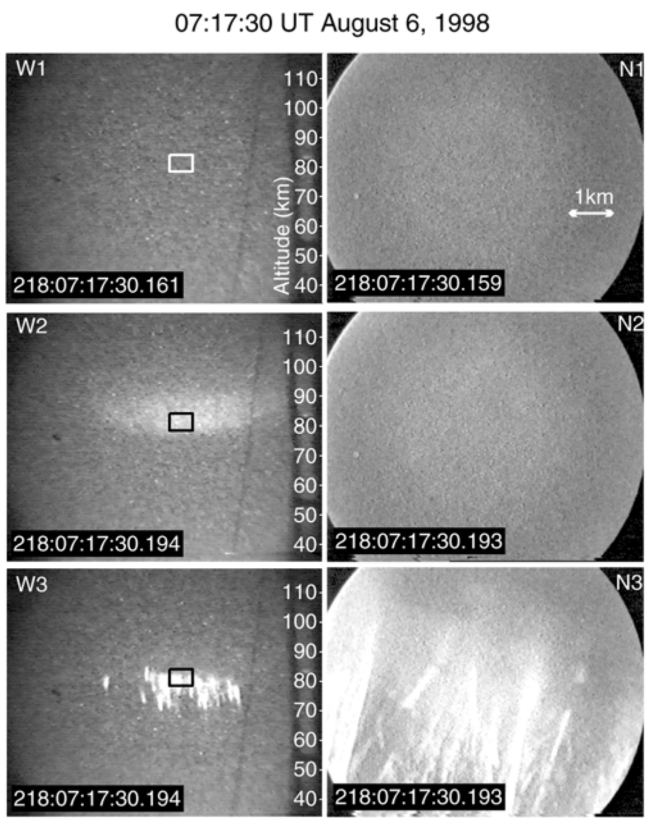

Figure 9. Diffuse glow region (or "sprite halo") observed during an event at 0717:30 UT 6 August 1998. As expected, no structure is observed in the telescopic image - only a faint overall brightening.

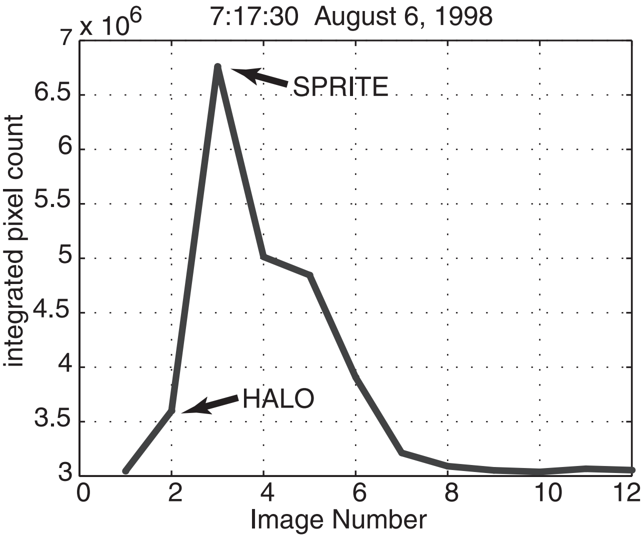

Figure 10. Integrated pixel count during the sprite halo event shown in Figure 9. Pixel counts were summed over each image for 12 successive images. It is apparent that the telescopic images do brighten at the time of the sprite halo although no structure is seen.

bone". The upward columns range in width from ~200 to 210 m and the downward branches range in width from ~71 to 100 m. Lasting for over 100 ms, the columns move upward at a velocity of magnitude $\sim 10^4$ m/s in subsequent fields (not shown) and are therefore assumed to be negative streamers. There appears to be a different threshold radius between the positive and negative streamers since the positive streamers branch and the negative streamers expand although presumably originating from the same point. It has been shown that a streamer which starts with a radius below some critical threshold expands while those with too large a radius it will contract [*Vitello et al.*, 1994] or branch [*Pasko et al.*, 1998]. This sprite event may be a grouping of double-headed streamers initiated by some sort of plasma enhancement such as heated dust particles. Double-headed streamers have been modeled [*Vitello et al.*, 1994] to evolve slower with lower streamer propagation velocities, and peak electric fields than the corresponding single-headed streamer case. This behavior is explained by the fact that less negative space charge is needed to produce the necessary internal electric fields when the positive charge is nearly fixed in space than when it is a moving mirror charge beyond the cathode [*Vitello et al.*, 1994].

[31] The negative streamer columns have abrupt termination points which slowly move upward in subsequent fields (not shown). There is a less luminous broader segment above the rightmost column which may be part of the same channel. It is interesting that there are several structures in the telescopic image with the same morphology - branching on the bottom, column on top, indicating that in this case, streamer morphology is not a random process but rather one which corresponds to a particular atmospheric/ionospheric condition. A localized plasma enhancement may have been present in this region and may have caused several double-headed streamers to form.

3.7. Case VII: 0539:19 UT 13 July 1998

[32] Figure 8 shows the transition region between streamer formation and glow discharge in a sprite. Unlike the previous example in which the streamers abruptly terminated at the top, these streamers fade to broadly expanding, less luminous diffuse glows. The transition region only exists over a narrow region of 1–2 km in height at an elevation of ~80 km, consistent with model predictions by *Pasko et al.* [1998] that the transition region should exist between 75 and 85 km. Since no branching is evident the polarity of the streamers is ambiguous. A clue may exist in the fact the tips are tapered. As previously mentioned it has been modeled that streamers initiated with too small of a radius will expand until they reach their critical radius [*Vitello et al.*, 1994]. It may be that the diffuse glow existed first at high altitude and that streamers were initiated by seed electrons as the glow expanded to lower regions into the streamer regime. These streamers would then be positive downward propagating streamers which expanded to a stable radius. This diffuse glow region has been identified as the sprite "halo" [*Barrington-Leigh et al.*, 2000] and will be discussed in greater detail below in Case VIII. If the streamers were negative and upward propagating it would be expected that the streamers would expand into the glow region smoothly as has been modeled [*Vitello et al.*, 1994].

3.8. Case VIII: 07:17:30 6 August 1998

[33] The final example of sprite features is one of the diffuse glow region in sprites, or the so-called "sprite halo". As previously mentioned, this diffuse glow region may exist independently or may either precede or accompany a streamer region and generally occurs at an altitude of ~70 to 85 km. The diffuse glow region is expected to be produced by a large charge moment change occurring over a relatively short timescale [*Barrington-Leigh and Inan*, 2001].

[34] Figure 9 shows a sequence of three fields of a sprite event. The wide field of view images, on the left, display first one field prior to the event, then a sprite halo between ~80 and 90 km altitude, and finally a structured sprite below at ~70–85 km altitude. Subsequent images contain further development of the structured sprite. The field of view of the telescope is positioned in altitude such that it observes the lower half of the sprite halo and the top of the structured sprite. As expected, the telescopic images (on the right) show no decameter-scale structure in the sprite halo. The overall brightness level does however increase at the time of the sprite halo. This faint diffuse glow is difficult to detect visually on the images but if the pixel counts are integrated over each image and plotted versus time, the brightening due to the sprite halo is readily observable. A plot of integrated pixel counts for several images of this sequence is shown in Figure 10. The first three images correspond to those shown in Figure 9 and the rest are subsequent images displaying sprite development and decay. As can be seen, the integrated count for the image containing the sprite halo is significantly greater than that of the image preceding or following the sprite event but much less than that of the structured sprite.

[35] Sprite halos are often observed to have upwardly concave shapes. This is due to the enhanced ionization of the descending space charge region [*Barrington-Leigh and Inan*, 2001]. The enhanced ionization leads to higher electric fields outside the diffuse glow region and thus affects streamer formation. Sprite halos may be another explanation for streamer initiation at elevations below that predicted by models which do not take into account the effects of a descending ionospheric disturbance.

4. Conclusions

[36] Sprite structure can assume a wide variety of shapes, sizes, and timescales, but certain structures such as beading, faint downward branching, propagating diffuse glows, and columns appear repeatedly. Using telescopic imagery, we have shown examples of the following observations of decameter-scale streamer and diffuse glow formations:

1. Within some sprite events, several different types of structural features appear while in others only one morphology occurs.
2. Propagating diffuse glows are observed to move slowly and are broader than predicted for streamer formation.
3. While many streamers move at velocities greater than the time resolution of regular video rate imaging, some have been found to move as slowly as 10^4 m/s.
4. Sudden brightening of slowly developing negative streamers may be indicative of a return stroke process in which the streamers connect with charge in a lowered ionosphere.
5. Fine beading exists in many negative streamers and may possibly be a result of meteoric dust particles in the upper atmosphere.
6. Columniform sprites may originate from positive branching streamers.
7. Beads at the base of columns can glow for over 100 ms while slowly drifting upward ($\sim 10^4$ m/s).
8. Faint positive streamers are observed at the base of large bright sprite events.
9. Some sprites having branching positive streamers and nonbranching negative streamers may be double-headed streamers initiated from plasma enhancements such as vaporized meteoric dust.
10. A transition region between streamer formation and diffuse glow is observed at ~80-km altitude.
11. No structure is observed in telescopic images of the diffuse glow region, or "sprite halo".

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