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Imaging of elves, halos and sprite initiation at 1 ms time resolution

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Abstract

Elves, halos and sprites were observed during August 1999 with a 1 ms high speed imager. The higher time resolution compared to conventional television cameras (17 or 20 ms) allowed excellent images of the three phenomena temporally separate from each other to be obtained. Analysis of images of elves and halos indicates that the causal lightning-generated electromagnetic pulse and quasi-electro static fields are homogeneous and any small-scale (sub-10 km) structure, if visible, is most likely due to a structured atmosphere. Observations of sprites initiated to the side of a halo, without a halo, and from beads left over from a previous sprite, respectively, all suggest sub-pixel (< 0.5 km) background structures in atmospheric pressure or composition as being the dominant factors in determining the sprite "seed" location, or site of sprite initiation.

Keywords: Elves; Halos; Sprites; Mesosphere; Lightning; Optical emissions

1. Introduction

Sprites are large, brief, structured flashes of light observed above very active thunderstorms (Sentman and Wescott, 1995; Lyons, 1996). They last 3–5, in a few cases >100 m, and initiate near 70–75 km altitude (Stanley et al., 1999). They develop downward and sometimes also upward from that altitude (Stanley et al., 1999; Takahashi et al., 1996). Sprites occur primarily as a response to large, positive, cloud-to-ground lightning flashes in the underlying thunderstorm (Boccipio et al., 1995). Currently, identification of specific characteristics of lightning flashes and mesospheric conditions that produce sprites has not been made; and the importance of sprites in the global electrical circuit and in the chemistry of the mesosphere has not been established.

Often preceding sprites are the unstructured elve and halo (Barrington-Leigh, 2000; Barrington-Leigh et al., 2001; Wescott et al., 2001). Elves persist for less than a ms, and appear as an expanding ring of light at around 90 km altitude centered above the associated causative lightning (Barrington-Leigh et al., 2001). The model for elves (Inan et al., 1997) attributes the phenomenon to interactions of an electromagnetic pulse generated by lightning with the lower ionosphere. This model appears to explain the characteristics of elves as observed by photometers (Barrington-Leigh et al., 2001).

Halos are pancake-like in appearance, centered at 70–80 km altitude, and are 50–70 km in diameter (Wescott et al., 2001). The optical emissions from halos are very diffuse and generally unstructured, and last a few (2–10) ms. Most of these characteristics have been modeled by Barrington-Leigh et al. (2001) as emissions due to a quasi-electrostatic field generated by positive cloud-to-ground lightning.

Sprites and halos have been observed primarily with 17 ms time resolution (many pixel) CCD cameras and with 1 μs time resolution (1–16 pixel) photometers, giving either good temporal or spatial resolution, but not both. Images from the first high speed (0.3–1 ms time resolution) camera observations of sprites and halos were first published by Stanley et al. (1999) and Barrington-Leigh et al. (2001), respectively. Elves were not observed with cameras, with perhaps one exception (Barrington-Leigh

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et al., 2001). Most elves have been observed with photometers (Barrington-Leigh et al., 2001).

For the 1999 Sprites NASA Balloon campaign, the University of Alaska Fairbanks deployed a 1 ms high speed imager into the field. Initial results from the campaign and from the high speed imager have already been described (Bering III et al., 2002; Stenbaek-Nielsen et al., 2000). We report here on the dim structures initiating some sprites, but also observe details of sprite development not previously seen, in particular, very dim tendrils ultimately forming large sprites.

Sprite initiation has been suggested to be due to electromagnetic pulse structure, quasi-electrostatic field focusing, or background inhomogeneities. Early theories of sprites included electromagnetic pulse (EMP) from a fractal-like lightning antenna radiating a highly non-uniform pattern and exciting structured optical emissions (Valdivia et al., 1997), or streamer breakdown caused by a quasi-electrostatic (QE) field initiated from EMP-induced ionization patches in the ionosphere (Raizer et al., 1998). Theories of sprites due to quasi-electrostatic fields from lightning (Pasko et al., 1997) appear to more completely explain halos than sprites, as Barrington-Leigh et al. (2001) have shown. Both Raizer et al. (1998) and Pasko et al. (1998) have suggested that streamers accelerated by the quasi-electrostatic field are responsible for the sprite structure. These streamers are to be initiated by a single free electron (Pasko et al., 1998) or in the bottom of a halo, where the electric field is the strongest (Barrington-Leigh et al., 2001). Other possibilities for sprite seeds include meteors (Wescott et al., 2001) or the initiation of streamers from meteoric dust (Zabotin and Wright, 2001). Thus far the velocities and spatial structure of sprites, as reported by Stanley et al. (1999) and Gerken et al. (2000), appear to match the velocity and streamer diameter modeled by Raizer et al. (1998) and the large-scale structure modeled by Pasko et al. (2000, 2001), but the questions of how sprites/streamers are initiated and the factors determining the specific sites of the breakdown remain unanswered. Analyses of images of elves, halos and sprites obtained from the high speed imager allow new light to be shed on these questions, and are the subject of this paper.

2. Instruments and data

Sprite images with 1 ms time-resolution were recorded in August 1999 from the University of Wyoming Infrared Observatory (WIRO) on Jelm Mountain, southwest of Laramie, WY, as part of the 1999 Sprites NASA Balloon Campaign (Bering III et al., 2002). The images were obtained with a newly developed, computer controlled, low light-level, 1000 frames per second ("high speed") intensified CCD imager. We used a 105 mm, f/0.9 lens for a 6.4 × 6.4 degree field of view. The CCD resolution is 256 × 256 pixels at 8 bits (256 gray levels), arranged into four quadrants of 128 × 128 pixels each. Each quadrant of the CCD is read out in parallel through separate electronics, and consequently, individual images often show slight differences between quadrants. The end-to-end spectral response of the system is 500–900 nm with maximum sensitivity near 700 nm. Saturation (gray level 255) is 3 MR, and minimum detectable enhancement above system noise is of the order of 20 kR.

During data acquisition, the high speed imager data are continuously read into a 4096 frame (∼4 s) circular buffer. When a sprite or other bright event is observed visually on a scene camera boresighted with the high-speed imager, we save by a keyboard command the buffer, or part thereof, to disk. The save operation typically requires a few 10 s of seconds.

The scene camera is an ICCD-TV with a 10 × 14 degree field of view. The camera is similar to those used in earlier sprite campaigns (Sentman et al., 1998; Heavner et al., 2000). The camera operates at regular TV framing rate (60 fields per second) giving ∼17 ms time resolution. The video is recorded continuously on tape with a GPS timestamp and look-angle information (azimuth and elevation) included on each field. The time stamp and azimuth are used during subsequent analysis to determine the most likely causative lightning strike as registered by the National Lightning Detection Network (NLDN) (Cummins et al., 1998). The lightning location (latitude/longitude), equivalent to the presumed location of the sprite, is used to calculate the approximate sprite range from the observing station. The high speed imager does not have GPS timing, so the time stamp on each video field of the TV scene camera is used for approximate (±17 ms) time assignment of the 1 ms data.

In addition to the high-speed imager and associated scene camera we also had a multi-channel high-speed photometer on the same mount, and a separate wide field of view SIT TV camera. For the analysis presented here, we only use data from the high-speed imager. Initial results from the photometer, indicating upward and downward sprite propagation velocities of up to 1.4×10^8 m/s are presented elsewhere (McHarg et al., 2002).

On the evening of August 18, 1999 UT (August 17 local time), we recorded 26 sprite events above an intense storm over Nebraska. On average, the storm was 500–700 km from our site in Wyoming, a distance ideal for the 6.4 × 6.4 degree field of view of the high-speed imager since a sprite of several 10's km vertical extent would subtend an appreciable fraction of the image. All full-sized images presented in this paper have an equivalent vertical extent of ∼60 to ∼70 km at the range of the events, and were integrated for 1 ms. The events recorded on 18 August 1999 were quite varied, with examples of elves, halos and sprites all being imaged. They ranged from single halos or sprites to complex events with multiple elve/halo/sprite sequences, but few had all three types simultaneously occurring in the same event. Elves were observed only in association with halos and sprites. We did not identify any solitary elves in our data, but, as discussed previously, our triggering on visually

Fig. 1. Example of three successive images 1 ms apart, showing background, elve and halo. Event is at 06:04:18 UT on August 18, 1999.

bright phenomena precludes the acquisition of the solitary elves, which are very dim.

3. Elves

3.1. Models of elves

Elves are modeled to be due to the EMP from a lightning return stroke: a vertical cloud-to-ground lightning current (Inan et al., 1997; Fernsler and Rowland, 1996), and should appear as a ring of light in the ionosphere expanding radially outward at apparent speeds greater than the speed of light, lasting less than 1 ms. The outward expansion and short duration of elves has been observed with photometers (Barrington-Leigh et al., 2001). Integrated over 1 ms, the expanding disk smears out to a uniform diffuse emission in our high speed images.

Valdivia et al. (1997) propose that the structure in "sprites" arises from the positively/negatively interfering EMPs from intracloud fractal lightning following a cloud-to-ground discharge. The model was applied to the intracloud portion of lightning discharge in order to allow for the observed delays between NLDN-recorded return strokes and sprites. In this model, the intracloud lightning was taken to be a fractal radiating antenna, yielding spatial interference patterns in the mesosphere. These in turn produce horizontally structured regions of optical emissions varying by as much as 30 dB, over scale distances of 10 km for the parameters used by Valdivia et al. (1997). We believe that for CG flashes, the model can also be applied to the intracloud portions of the lightning very close (spatially and temporally) to the channel leading to ground, since (1) peak radiative electric fields from lightning occur within 25 μs of onset (Uman, 1987, p. 197), and (2) peak return stroke currents occur within less than 200 μs for 95% of positive cloud-to-ground strokes (+CGs), and within less than 18 μs for 95% of −CGs (Uman, 1987, p. 124). The resulting fields/emissions in the mesosphere would have relatively small both spatial and temporal separation from those of the return stroke. We call this the modified fractal antenna model, modified in the sense that only a small amount of temporal delay (itself unspecified in the model) would be expected from the return stroke for the conditions described here.

A comparison of observed structure in elves with that predicted by the straight-lightning channel model (Barrington-Leigh et al., 2001) and by the modified fractal-antenna lightning model (Valdivia et al., 1997) as described above, allows us to estimate the degree of homogeneity of the EMP fields in the mesosphere created temporally close to the return stroke. It should be noted that variations in atmospheric composition may also be expected to play a role.

3.2. Observations of elves

Fig. 1 shows three images 1 ms apart of the events at 06:04:18 UT on August 18, 1999. The first image, with a contrast enhanced greyscale to bring out dim features, shows the background. Several stars are visible. On the second image, an elve is visible in the upper quadrants, followed 1 ms later (third field) by a halo near the center.

In the high-speed images we see elves associated with halos and sprites in 9 of the 26 events. Of the 9 events where halos were entirely in the lower 60% of the image, all but 1 had elves visible in the top part of the image, indicating that we were looking too low to see elves the rest of the time. We cannot estimate the height of the elves without assuming some shape and extent for the emissions. No solitary elves have been identified. Elves last less than 1 ms, are considerably less luminous than halos, and as indicated earlier would generally not be visible in the video (30 frames per second) used to trigger a save of the high-speed imager data. Post-campaign laboratory analysis of the video (TV rate) data did not produce any elves that could be identified as such. However, this does not necessarily preclude the possibility that elves may occur as solitary events. There are many unidentified, short-lived events in the photometer records that could be elves (McHarg, private communication, 2001). Similarly, on the balloon payload there appear to be many events possibly linked to solitary elves (Bering, private communication, 2001; Bering et al., 2001). This clearly warrants further investigation, but is beyond the scope of the present paper.

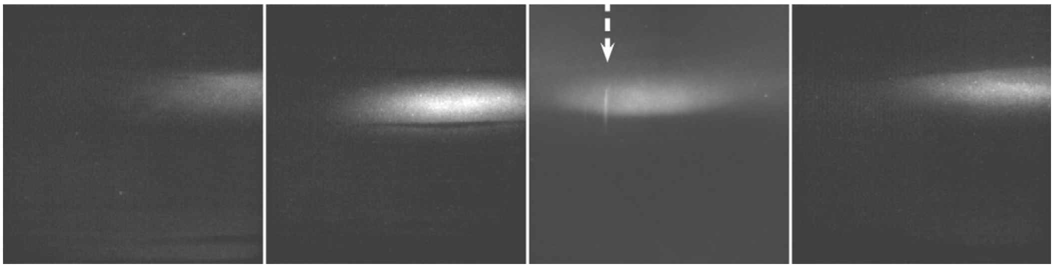

Fig. 2. Examples of unstructured halos. Events are, from left to right, at 04:38:42, 05:02:05, 06:15:07 and 06:32:07 UT on August 18, 1999. The bottom edge of the second halo is at the same elevation angle as an intervening cloud closer to the observing site, visible as a dark band. A sprite is visible in the third halo.

3.3. *Analysis of elve observations*

In order to check for horizontally alternating quasi-periodic strong/weak emissions predicted by the modified model of Valdivia et al. (1997) described above, horizontal strips (both 20 and 64 pixels wide) were selected across the elve in the image. The pixels in the rows selected were summed into a single horizontal profile to increase signal, on which a Fourier transform was performed. No strong periodicities were detected at the 95% confidence level. The same analysis was performed on four other elves with similar results. No indication of structure was found in any of the five events analyzed.

This analysis indicates that there is no strong quasi-periodic interference pattern of the EMP in the lower ionosphere, and that the EMP affecting the mesosphere lacks spatial structure, as can be expected from a vertical lightning discharge. In turn, this uniformity of elves has implications for sprite initiation, as discussed below.

4. Halos

4.1. *Halo models*

Halos are brighter, but spatially smaller than, elves, and last several ms. They appear in an image as diffuse emissions in the shape of a "pancake" up to ~70 km in diameter near 75 km altitude. Most early models of "sprites" employing the quasi-electrostatic field from lightning return stroke (e.g. Pasko et al., 1997) now appear to be good models of halos instead. Recent work by Barrington-Leigh et al. (2001) shows that emissions from the interaction of the QE field with the background atmosphere at mesospheric heights match the altitude, size and duration of halos well. So far no models predict structured halos.

4.2. *Observations of halos*

There were 23 halos imaged by the high speed imager on August 18, 1999, of which 20 had an obvious parent cloud-to-ground stroke in the NLDN data, as determined by spatial proximity and < 1s temporal precedence. The other halos may still be associated with CG flashes, as the NLDN does not record all +CGs, especially those of complex forms. The halos tended to fall into two distinct categories with respect to their spatial structure. Fig. 2 shows single images from four different halos that are fairly representative of approximately half of the 23 halos observed on August 18, 1999. These halos are smoothly varying spatially, with no discernible structures. A small sprite onset originating from a halo is visible as a thin vertical line in the third example of Fig. 2, indicated by an arrow.

The other half of all halos in our dataset for August 18, 1999 are represented by the examples shown in Fig. 3. In contrast to the halos shown in Fig. 2, the halos in this group are structured to various degrees. The first halo in Fig. 3 has a lobe (a large-scale structure) to the left of, and separate from, the main portion of the halo. The second halo has some structure on its left side but is otherwise rather uniform (also a large-scale structure).

The third image of Fig. 3 shows the most structured Halo in our dataset. The structure is not due to intervening clouds—as is clear from images of the subsequent sprite. There is Rayleigh-scattered light above the clouds at the very bottom of the image (top row, 3rd image). One ms later, two larger sprites appear (not shown), one each from the two brightest "beads" within the halo, near the centerline of the CCD. The brighter of the two comes from the dimmer bead. One ms later they form a single carrot sprite (not shown). Note that the outline of this halo is still in the shape of a "pancake".

The fourth halo in Fig. 3 shows a complicated image with both a halo and sprites. The halo started 2 ms earlier, and sprites 1 ms earlier than the image shown. The halo appears uniform and dim in the 1st ms (not shown), develops some apparently horizontal striations in the 2nd ms (not shown), which brighten in the 3rd ms (shown). These striations are visible around the brightest of the sprites and the two smaller sprites to the right of it. Note that the one darker stripe immediately "above" the second brightest sprite is an intervening thin cloud close to the observing site.

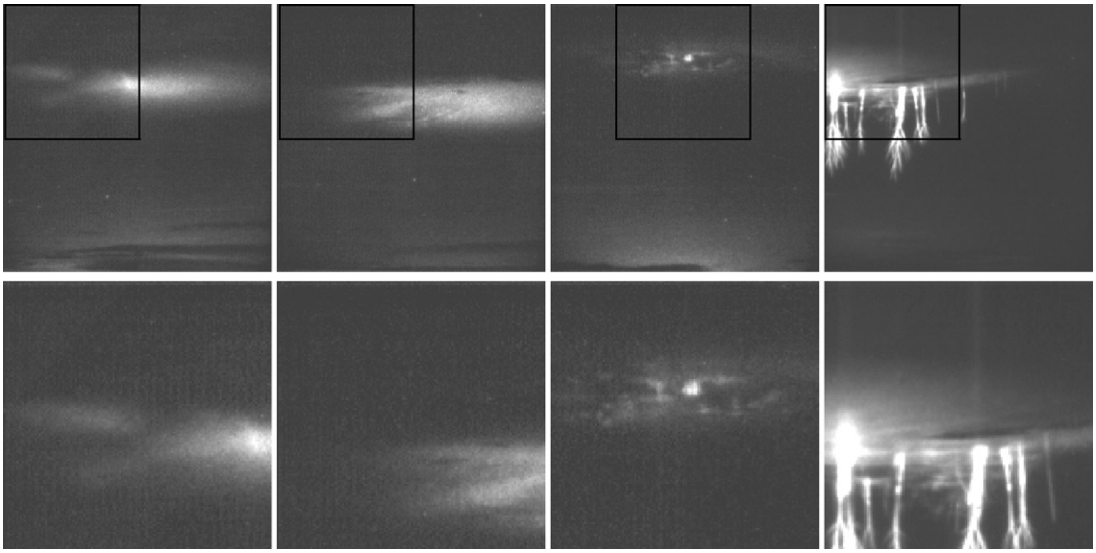

Fig. 3. Examples of structured halos. From left to right, events occurred at 04:36:09, 04:41:10, 05:24:22 and 06:32:07 UT on August 18, 1999. Top row shows the entire image of the four halos. The region indicated by a square in each field is expanded directly below it, in the bottom row.

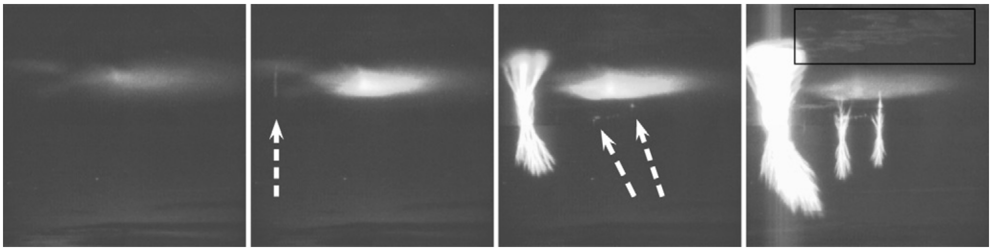

Fig. 4. An example of a sprite initiating outside of a main halo. The sprite group occurred at 04:36:09 UT, and four consecutive fields 1 ms apart are shown. Arrows indicate the initiation sites of the three sprites. Multiple small clouds close to the observer are visible at the top of the last field (in box). The vertical streak above and below the left sprite are readout artifacts of the CCD.

4.3. Analysis of halo observations

The same spatial Fourier analysis as was performed on elves (Section 3.3) was performed on four "unstructured" halos to search for evidence of periodic structure. Several horizontal image rows were chosen intersecting the halo. These were summed into a single horizontal profile, which was Fourier transformed. As with elves, no periodic structure was detected at the 95% confidence level. The other half of halos were structured, most with large scale non-periodic variations (Fig. 3 images 1,2), and a few with small-scale variation (Fig. 3 image 3). Summarizing, we found that half of the halos have no detectable small-scale spatial structure, and most of the structured ones possess large scale variations.

5. Sprite initiation

Fig. 4 shows the moment of initiation of several sprites occurring at 04:36:09 UT on August 18, 1999. The sequence shows 4 ms of data. The first image of a halo is the same image shown in Fig. 3 (first halo). One ms later, a thin sprite column appears by the side lobe of the halo (indicated by an arrow), while the main part of the halo becomes brighter. On the third field, the sprite by the side lobe has developed both extensive downward tendrils and upward branches. The main halo has brightened slightly from the previous field. Also, small, barely visible beads appear "below" the main halo (indicated by arrows in the third field). These beads are separated from the halo, but we cannot tell whether they are in front, behind or below the halo. In the 4th field, the leftmost sprite has developed into an even larger form, saturating the imager. Downward tendrils and small upward branches have developed from the two beads. By the next ms, not shown, both of the sprites on the right form large "carrot" sprites.

Fig. 5 shows a sprite initiating in field 1 with a very dim tendril (indicated by an arrow). In fields 2–8, the tendril brightens a stationary bead while propagating downward. By field 9, the tendril is visible as a thin line, and the stationary

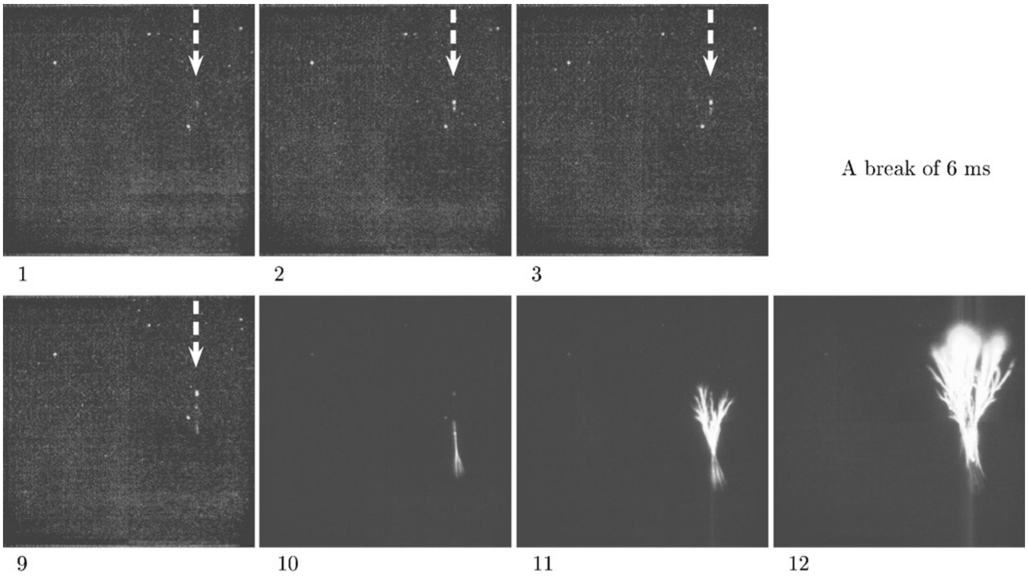

Fig. 5. Examples of sprite initiating without a sprite halo. This event occurred at 04:58:14 UT on August 18, 1999. Arrows indicate the initially very dim tendril location. Fields 1–3, 9 have greyscale enhanced with respect to 10–12 in order to show detail. As before, the vertical lines below and above the sprite on field 12 are instrumental.

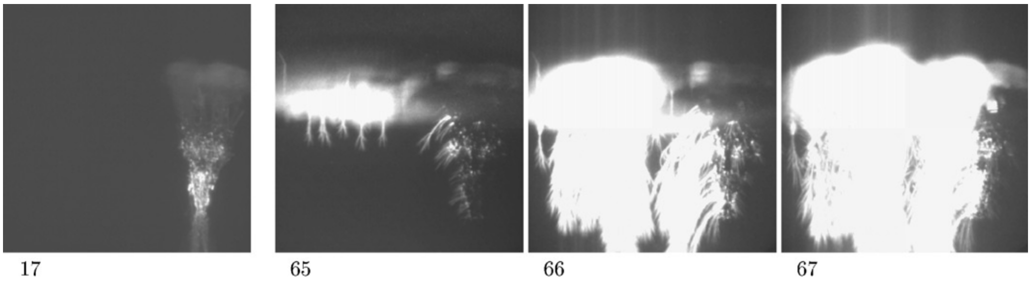

Fig. 6. Examples of sprite initiation from beads left over from a previous sprite, at 05:45:05 UT. This event was discussed by Stenbaek-Nielsen et al., 2000.

bead continues to glow. The speed of the tendril remains nearly constant throughout the first 9 fields, on the order of 1×10^6 m/s.

In the following ms (field 10), with neither Rayleigh-scattered light near the horizon nor a visible halo, the tendril brightens and speeds up, then forms upward branches (field 11) and becomes a well developed “classic carrot” sprite (field 12). This large sprite forms without any associated halo. The average downward speed of the tendrils between fields 9 and 10 is on the order of 1×10^7 m/s. From the August 18, 1999 dataset of 26 sprite/halo events imaged by the high speed imager and often consisting of multiple sprites, a total of seven sprites develop in similar manner. Many (>10) sprites follow development similar to fields 1–9 of Fig. 5 but then disappear instead of forming a large sprite.

Finally, we present in Fig. 6 an example of a complex event exhibiting a variety of effects. The series in Fig. 6 consists of two groups of sprites. In the first group, a single sprite initiates with a very slow and dim tendril, like the sprite in Fig. 5. After 13 ms, the tendril suddenly brightens, and forms a large carrot in the 14th ms. This sprite saturates the imager. In order to show the details of the sprite structure, Fig. 6 shows field 17 (17 ms after sprite onset, or 3 ms after largest extent of the sprite) by which time the brightness has started to decay. The sprite body includes many beads and remains the brightest portion of the sprite. The tendrils are not very large below the body, and extensive branches lead to a diffuse glow above. It is the beads in the body that persist the longest, but even they disappear below the detector threshold by field 30. Starting with approximately field 50, some of the original beads seen in field 17 brighten again. On field 64 (not shown), an elve appears on the top of the image. One ms later, on field 65 the beads brighten extensively (field 65, right side). In addition to brightening, some of these beads also initiate tendrils to the side. At the same time, a halo brightens to the left of the beads, and small tendrils are visible emanating downward from the halo.

All of the tendrils visible in field 65 continue their development over the next two fields, creating an immense sprite group that saturates more than half the CCD. This example shows both sprites initiating from beads left over from a previous sprite and those starting "within" halos.

6. Discussion

In the mesosphere and lower ionosphere, elves and halos appear as diffuse glows, while sprites appear as structured discharges. By examining the elves, halos and sprites as observed by the high speed imager, we can form some conclusions about sprite initiation. In particular, the spatial structure, or lack thereof, of elves and halos may indicate the structure of the causative electric field.

The emissions making up elves and halos have been proposed to be due to the interaction of electric fields from return strokes—either electromagnetic pulse or the quasi-electrostatic field—with the mesosphere and lower ionosphere (Inan et al., 1997; Barrington-Leigh et al., 2001). The structure of the emission thus depends on both the structure of the electric field (the field coming from the lightning and interactions with its own reflections from the ionosphere), and the structure of the local atmosphere due to pressure or compositional perturbations. Sprites have been proposed to be due to the interaction of quasi-electrostatic fields from the return stroke with the mesosphere, launching streamers (Pasko et al., 1998; Barrington-Leigh et al., 2001), and also to the electromagnetic pulse from the subsequent intracloud portion of the lightning discharge (Valdivia et al., 1997), also possibly launching streamers (Raizer et al., 1998).

6.1. Elves discussion

Starting with the elves, (Barrington-Leigh et al. (2001) modeled a homogeneous electromagnetic pulse from the return stroke/vertical portion of the lightning interacting with a homogeneous atmosphere, which resulted in unstructured emissions when averaged over 1 ms. The modified theory of Valdivia et al. (1997) described in Section 3.1, where the electromagnetic pulse comes from the intracloud portion of the lightning discharge very close to the return stroke channel, would result in structured optical emissions with only a small delay (<1 ms) from the unstructured emissions due to the EMP from the return stroke. These emissions would be at the same altitude as the unstructured emissions. Since a horizontal current is a better radiator into the mesosphere than a vertical current (Valdivia et al., 1997), these structured emissions, if present, should be brighter and readily visible. The lack of any obvious structure in our observations of elves (Section 3.3) implies that the electromagnetic pulses creating elves are relatively unstructured.

6.2. Halos discussion

An argument similar to that of elves can be applied to halos. Halos have been modeled to be due to a quasi-electrostatic field interacting with the mesosphere (Barrington-Leigh et al., 2001). Those results appear to match observations of unstructured halos. The emissions making up structured halos are governed by the interaction of a quasi-electrostatic field with the atmosphere, and again, either of those two could be structured. So far, no model for a structured field has been published, but Pasko et al. (1997) have explored the influence of neutral density depletions, yielding stronger emissions in the depleted regions.

There are two possibilities for QE field creating spatially structured emissions: a structured field from the underlying lightning or a structured background in the ambient atmospheric composition/density. A structured QE field of a small scale-size may be difficult to create in the mesosphere. Consider a lightning strike which drains multiple charge regions within a thundercloud (which is known to occur for sprite-producing lightning, Stanley, 2000). In an elementary approach, each of the charge regions can be treated separately to set up a QE field, and contributions from each summed to obtain the total field. In the simplest case, in the far-field approximation, the quasi-electrostatic field at a distance r from a charge Q residing at a height h above the ground is proportional to M/r^3 where $M=hQ$ is charge moment (see for example Eqs. (12), (13) of Rowland, 1998). This $1/r^3$ dependence makes it difficult to create structured fields in the mesosphere. Adding the contributions of multiple charge structures will yield only a large-scale variation in the field. Another way of possibly creating structured emissions is for there to be a structure in the mesospheric composition/pressure.

Recall that most of our halos are unstructured or with large-scale structures. We argue that if there are small scale variations in the halos, we should be able to see them. Let us assume that the halo model of Barrington-Leigh (2000) is a good approximation for the general shape of halos (as it appears to be), and also that there are small-scale (0.5–10 km) large-amplitude (for example, three times brighter than the surrounding region) variations superimposed on top of this general shape. Consider the case that this variation is superimposed on the brightest part of a halo, which is perhaps $\frac{1}{4}$ the size of the entire halo (Barrington-Leigh, 2000, Figs. 5–6), and the halo does not saturate the imager. In this case, the fainter contributions from the dimmer outer edges of the halo along the line of sight can be ignored, and the variation should be discernable in the image. If, on the other hand, the variation is in the dimmer edges instead of the bright core of the halo, we would expect to be able to see this variation on the side of the halo in some of the cases (depending on the viewing geometry). We do not detect small-scale variations in either the core or the sides of the 20 halos we examined. The remaining three halos from a dataset of 23 from the night of August 18, 1999 have small-scale structure.

The EMP from fractal intracloud lightning model (Valdivia et al., 1997) or from the intracloud portion of CG lightning, since most of our halos had a parent CG flash, could also be potentially interpreted as causing structured halos. However, zero-to-peak risetime of electric fields from +CGs range from 4 to 25 μs (Uman, 1987, p. 197). Any change in the mesosphere due to these fields will have a peak variation at these time scales (plus time-of-flight), i.e. would occur at the same time as EMP from vertical dipole when observed with a 1 ms temporal resolution instrument, and decrease in magnitude thereafter. In the high speed imager, there is a definite delay between elves and halos, suggesting halos and their variations are not due to EMP.

We found that most (20 of 23) of the halos have no detectable small-scale spatial structure, and most of the ones with some structure possess large-scale variations. The unstructured halos can be explained well by the model proposed by Barrington-Leigh et al. (2001). In the case of halos with large-scale spatial structure in their emissions, we cannot say whether they are due to QE field variations, large-scale background atmospheric composition/pressure variations, or both. In the case of structured halos with small-scale variations, we propose that these are due predominantly to compositional/pressure effects. In particular, examples showing small scale variations (Fig. 3, image 3), would be very hard to create with quasi-electrostatic fields due to their $1/r^3$ dependence.

Our observations thus indicate that both the incident electromagnetic pulses (EMPs) from lightning causing elves and the quasi-electrostatic (QE) fields causing halos tend to be uniform on 10 to 0.5 km length scale and 1 ms time scale. These observations thus appear to favor the vertical stroke model (both electromagnetic/radiation field and quasi-electrostatic field) of Barrington-Leigh et al. (2001) over the fractal radiation model of Valdivia et al. (1997) for both elves and halos.

6.3. Sprites discussion

Sprite nucleation has been proposed to be either due to the quasi-electrostatic fields that also create the halo (Pasko et al., 1998), or due to the EMP from the intracloud portion of a cloud to ground lightning discharge (Valdivia et al., 1997). Valdivia et al. (1997) proposed that since the intracloud part of lightning can continue for 10's, if not 100's of ms, their model easily explains the often-observed (Lyons, 1996) delay between sprites and the parent lightning. In addition, a horizontal discharge radiates stronger EMP in the vertical direction than a vertical discharge. This horizontal fractal lightning results in very structured emissions, of about 10 km scale size for the values used by the authors (with an adjustment of the model parameters, the scale of these patches can presumably be increased or decreased). Patches at those length scales are not visible in our data. Raizer et al. (1998) used the Valdivia model as a pre-conditioning of the atmosphere, assuming that under the application of an quasi-electrostatic field these patches of enhanced ionization formed streamers. Cho and Rycroft (2001) suggest that EMP from horizontal (intracloud) discharge forms localized peaks of electron density in the altitude range 75–85 km, from which streamers could develop under QE. Their model included inhomogeneous EMP on large length scales, ~100 km, which we were not able to observe at the distance of the storm due to our smaller (6.4 × 6.4°) field of view.

Raizer et al. (1998) proposed sprites to be streamers propagating downward in the mesosphere. Their theory predicts streamers developing under QE from packets of enhanced ionization, such as predicted by the Valdivia et al. (1997) model. As we have shown, we do not see the strong structure in emissions predicted by the Valdivia et al. (1997) model, either immediately after elves or at later times. The Raizer et al. (1998) streamer model predicts a range of velocities from 10^6 m/s at the beginning of the streamer to a maximum of 10^7 m/s near time = 4 ms for the charge used. The sprite in Fig. 5 shows a slowly developing sprite moving with nearly constant speed (10^6 m/s) which suddenly speeds up after 10 ms to 10^7 m/s. This speedup could be caused either by the streamer moving into an atmosphere with a different composition, or by an increase in electric field strength since streamer velocity increases with external field (Raizer, 1997, p. 336).

The question of whether EMP from intracloud portion of a cloud-to-ground lightning is important in sprites merits further discussion. As is presented in Valdivia et al. (1997), a horizontal antenna radiates efficiently upward. The theory predicts bright patches of emissions, with some unspecified delay from the return stroke. Such patches are not visible in our data. However, the idea of accounting for the time delay from a return stroke to a sprite by using the intracloud portion of lightning may be appealing. It is possible that the structured EMP fields from the intracloud discharge help heat the structured regions of the mesosphere, albeit not to the level of optical emissions visible by our instrument, and in turn facilitate the initiation of streamers. Combining the Lightning Mapping Array (LMA) system of New Mexico's Institute of Mining and Technology with high speed observations of upper atmospheric flashes would help answer this question.

We now turn to streamers initiated by the QE field. Pasko et al. (1998) write that under an applied quasi-electrostatic field, "... a streamer can develop from an avalanche initiated by a single electron". This electron is one of many freed by the QE fields interacting with the mesosphere to form a halo. Under an appreciable field, most of the electrons attach dissociatively to O_2 to form O^- and O. The maximum rate for this attachment is 1 kHz at 80 km and 10 kHz at 60 km

(Barrington-Leigh, 2000, Fig. 1-1 and p. 9). The attachment rate is slow enough that there would be many free electrons left after 1 ms, and within any halo the streamers should initiate in abundance. Our observation of sprites initiating outside of halos (Fig. 4) would seem contradictory to this theory, at least in its simplest form. Applying the theory to a height structured atmosphere with density fluctuations may prove more promising.

Barrington-Leigh (2000) has further suggested that the bottom of a halo, where the electric field is the strongest, could launch a streamer (a sprite tendril). This theory is contradicted by the images in Fig. 4 where a sprite is initiated well to the side of the main halo. However, we note that with these exceptions, the halo theory appears to predict halos and halo characteristics in the high speed images very well.

There have been a number of suggestions for an external trigger of sprites. Suszcynsky et al. (1999) have presented possible evidence for a sprite initiated by a meteor and a model using the meteor trail for pre-conditioning of the atmosphere was presented by Symbalisty et al. (2000). Based on the spatial separation of triangulated locations of sprites and their parent lightning Wescott et al. (2001) have likewise suggested meteors to be the possible trigger of sprites. Similarly, Zabotin and Wright (2001) have suggested micrometeors to be responsible. None of these suggestions can be discounted by our image data. In fact, the idea of a random trigger is especially appealing for events like that in Fig. 5, where a large sprite forms without any associated halo. However, the image data also suggest that there may be other types of sprite "seeds". In Fig. 6, sprites are clearly initiated from beads persisting from a previous sprite. These beads are at altitudes up to 80 km, where the electric field relaxes in less than 1 ms, according to the relaxation time scales published by Pasko et al. (1997) and (Barrington-Leigh, 2000, Fig. 1-1). The long duration of the beads (10's ms) suggest that factors other than simple electrical relaxation, such as chemical processes or ambipolar diffusion, may be responsible for determining their relatively long lifetime. Either way, the beads, being luminous, are obviously different in some aspect from the background atmosphere, and can provide initiation sites for subsequent sprites.

Overall, elves and halos can be thought of as mappings of the EMP and QE fields, respectively, from the return stroke and associated charge distribution within a thundercloud into the upper atmosphere. The mainly relatively spatially unstructured character of both phenomena suggests the underlying electric fields associated with them similarly lack significant small-scale spatial structure. The observations of sprites triggering outside of a main halo (Fig. 4), without a halo (Fig. 5) and from small scale features left over from a previous sprite (Fig. 6), respectively, when considered together with the unstructured fields discussed above, suggests sprites are triggered at sites of localized inhomogeneities in the mesospheric medium. These could be inhomogeneities persisting from a previous sprite, as proposed by Stenbaek-Nielsen et al. (2000), or could be the effects from any other pressure or composition perturbations, including but not limited to the previously suggested meteors and/or micrometeors, or gravity wave turbulence such as described by Yamada et al. (2001).

7. Summary and conclusions

We have analyzed images of elves and halos obtained with a 1 ms high speed imager. Our conclusions are: (1) Most of these events are relatively featureless on 0.5–10 km length and 1 ms time scales. (2) We conclude that the EMP and QE fields from return stroke of lightning reach the mesosphere and lower ionosphere to form elves and halos, respectively, similarly lack small-scale large-amplitude structure. Any structure in the emissions is interpreted to be due to background inhomogeneities in atmospheric composition or pressure. (3) Sprites are most likely not initiated in patches of strongly enhanced electron density created by electromagnetic pulses from either vertical or horizontal lightning channels, nor exclusively by the enhanced quasi-electrostatic field on the bottom side of halos, as evidenced by sprites that appear outside of halos, or without accompanying halos. Sprites are most likely initiated principally in regions of localized pressure or chemical perturbation of the background atmosphere at sites most conducive to streamer formation. Such perturbations include beads left over from a previous sprite, or other sources such as gravity wave turbulence. Meteors or micrometeors could also act as triggers in some circumstances.

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