Identification of Sprites and Elves with Intensified Video and Broadband Array Photometry

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Abstract.
Confusion in the interpretation of standard-speed video observations of optical flashes above intense cloud-to-ground lightning discharges has persisted for a number of years. New high speed (3000 frames per second) image-intensified video recordings are used along with theoretical modeling to elucidate the optical signatures of elves and sprites. In particular, a brief diffuse flash sometimes observed to accompany or precede more structured sprites in standard-rate video is shown to be a normal component of sprite electrical breakdown and to be due entirely to the quasi-electrostatic thundercloud field (sprites), rather than the lightning electromagnetic pulse (elves). These "sprite halos" are expected to be produced by large charge moment changes occurring over relatively short time scales (∼1 ms), in accordance with their altitude extent of ∼70 to 85 km. The relatively short duration of this upper, diffuse component of sprites makes it difficult to detect and to discriminate from elves and Rayleigh-scattered light using normal-speed video systems. Modeled photometric array signatures of elves and sprites are contrasted and shown to be consistent with observations. The diffuse portion of sprites may be a cause VLF scattering phenomena known as early/fast VLF events.

1. Introduction

Classification of high-altitude optical flashes caused by tropospheric lightning as "sprites" and "elves" has been guided as much by theorized physical causes as it has by distinct sets of observed phenomena. The electric field which causes heating, ionization, and optical emissions in sprites is caused by the charge moment changes (e.g., 250 to 3250 C·km in *Cummer and Inan* [1997]) associated with the movement of large thundercloud charges, usually in association with intense positive cloud-to-ground lightning. In contrast, the electric field causing heating, ionization, and optical emissions in elves is that of an electromagnetic wave which is launched by, and occurs in proportion to, changing current moments associated with very impulsive (>60 kA) return stroke currents [e.g., *Barrington-Leigh and Inan*, 1999]. As a result, elves last no longer than ∼1 ms, while the durations of sprites vary greatly, ranging from a few to many tens of milliseconds.

1.1. High speed array photometry

Due to their fleeting (<1 ms) existence, elves have been somewhat harder to study optically than have sprites, whose lifetime is more on par with the exposure time of standard video fields (∼17 ms). Nevertheless, a predicted telltale signature of elves was discovered using a horizontal array of high speed (∼30 μs resolution) photometers, the "Fly's Eye" [*Inan et al.*, 1997]. By aiming well above the ionospheric D-region overlying a strong CG, this array is used to unambiguously identify optical emissions (elves) due to a lightning-launched electromagnetic pulse (EMP). An example is shown in Figure 1; based on the short (∼150 μs) delay between reception of the return stroke's radio pulse, or 'sferic'

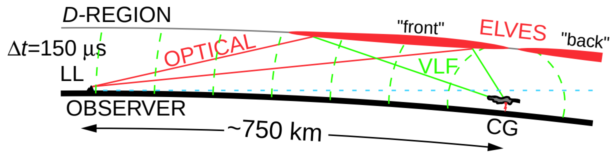

Figure 1. Geometry for photometric observations of elves at 500-900 km range. Of the two VLF/optical paths shown, the one seen by the observer at a higher elevation angle is shorter. Light from this path arrives ~150 μs after the radio sferic but before light from the longer, lower elevation path. The lightning storm is beyond the observer's horizon, which is indicated by the straight dashed line.

(dashed curves), and reception of the first photometric signature from the ionosphere, the optical emission can be located to be hundreds of km from the lightning. This timing constrains the physical mechanism to be one involving speed-of-light propagation only [*Inan et al.*, 1997].

All elves events as identified by the Fly's Eye have been found in direct association with the sferic signature of a CG. Furthermore, the timing always indicates that the elve is caused by the CG rather than by any associated sprite.

Timing considerations also enable a photometer array to distinguish between elves and scattered light. Figure 2 shows examples of the signatures of these two phenomena for a horizontal array. The VLF/optical path lengths involved in photometric measurements at different azimuths result in a horizontal dispersion among the signal onsets in the photometers. In contrast, light from the cloud-to-ground lightning return stroke can be Rayleigh-scattered in the lower atmosphere, but produces neither the characteristic delay nor the dispersion in photometry.

Although the small total optical output of elves (on the order of 0.1-1 MR lasting 0.1 ms, or an integrated energy of ~0.2-2 pJ/cm^2/str between 650 and 750 nm wavelength) makes spectroscopic studies exceedingly difficult, two-color photometric observations have been made. For instance, the ratio between emissions from the first positive and second positive bands of N_2 is much higher for elves (and sprites) than for the broadband emissions of lightning. Such spectral ratios have been used by *Armstrong et al.* [1998], *Barrington-Leigh and Inan* [1999], and *Uchida et al.* [1999] as another criterion for discriminating between elves and scattered light from lightning.

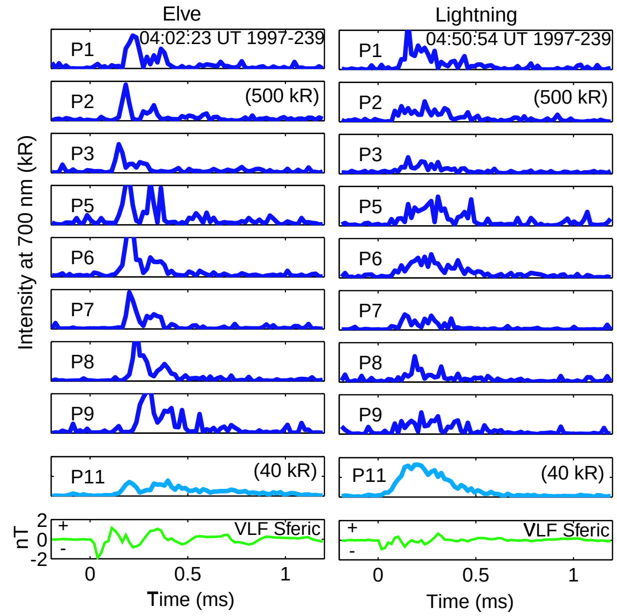

Figure 2. Distinctive signatures of elves (with onset delay and dispersion) and scattered light (with neither) as seen in the Fly's Eye. The relative fields of view of the narrow (P1-P9) and broad (P11) photometers are shown in Figure 4.

With knowledge of lightning location, supplied by the National Lightning Detection Network (NLDN, *Cummins et al.* [1998]), the onset delay of an optical pulse after a sferic can be used to locate the source of the flash [*Inan et al.*, 1997]. *Barrington-Leigh and Inan* [1999] used this technique to place minimum bounds on the horizontal extents of 38 elves from one storm (Figure 3).

1.2. Normal video rate observations

In recent years ostensible "elves" have also routinely been identified based on the existence of diffuse glows, often preceding or accompanying more filamentary "sprites," in intensified video recordings. While we have not claimed to identify elves without the photometric evidence described above, these diffuse glows seemed generally to occur when the photometric signature of elves also existed. For instance, Figure 4 shows a (dim) diffuse optical emission which was associated with a negative cloud-to-ground lightning return stroke and with the photometric signature of elves, but without any subsequent streamer-type sprites. These optical flashes are very rarely observed on more than one successive video field, indicating that the luminosity per-

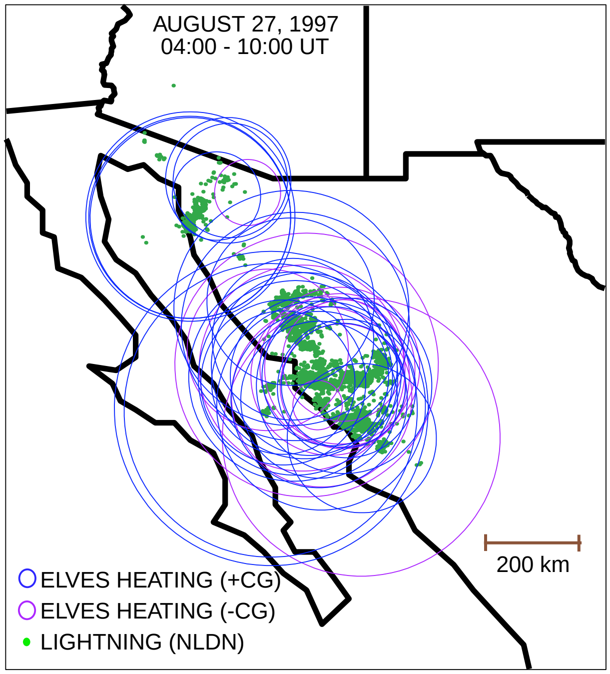

Figure 3. Horizontal extents of optical emissions in 38 elves from one mesoscale convective system observed over northwestern Mexico.

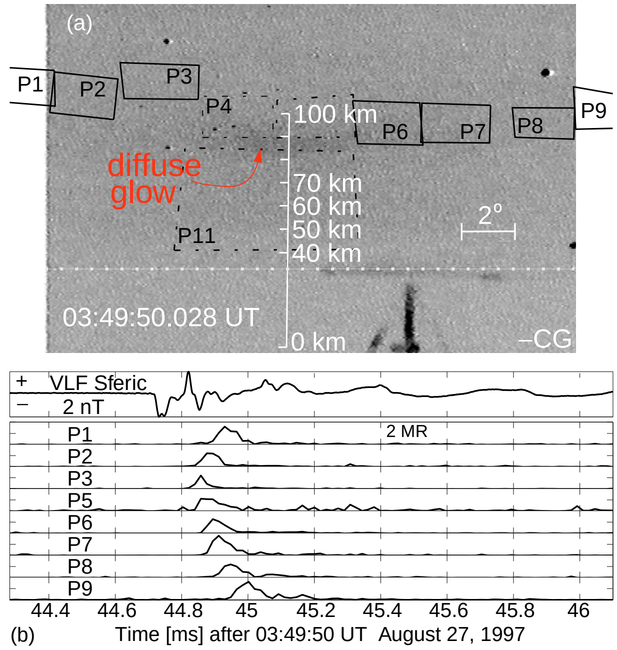

Figure 4. (a) Figure from *Barrington-Leigh and Inan* [1999], showing what was at the time thought to be the video signature of a (−CG) elve. In retrospect, and based on the discussion in the present paper, this diffuse glow is not an elve but is instead the "sprite halo" produced entirely by QE heating. (b) The photometric signature of elves, not apparent in the video, was also seen for this event.

sists for much less than 17 ms.

However, upon critical inspection, these closely localized ($\sim$40 km horizontally) flashes do not bear a strong resemblance to the expected form of an elve, which is predicted to be relatively uniform in brightness over a horizontal scale of >150 km [*Inan et al.*, 1997].

In this paper we demonstrate that the diffuse glows previously misidentified as elves are well described by models of electrical breakdown in sprites due to the thundercloud quasi-electrostatic (QE) field. The recent analysis of the temporal and spatial scales which characterize the electrical breakdown at different altitudes above sprite producing thunderstorms has demonstrated that the upper extremities of sprites are expected to appear as amorphous diffuse glows, while the lower portions exhibit a complex streamer structure [*Pasko et al.*, 1998]. We refer to the diffuse region of sprite breakdown, especially as observed optically, as a "sprite halo," and to the lower portion as the streamer region of sprites.

In Figure 4 the intensified video shows the signature of a sprite halo while the photometric array shows primarily that of an elve for the same lightning event. This reflects the capabilities of each instrument. It should be noted that in especially rare (i.e., bright) cases elves are detectable in a 17 ms video field. Figure 5 shows the video record of such an event, which was due to an unusually impulsive −CG. Note the large ($\gtrsim$250 km) spatial extent of the luminosity. Without the accompanying photometry, however, one could not tell whether this was an elve or scattered light from lightning [*Inan et al.*, 1997].

As shown below in Section 5, the optical signature of an elve caused by the EMP from a strictly vertical lightning current is expected to exhibit a central "hole" corresponding to the minimum in the radiation pattern of a vertical dipole. Such a central dimmed region may be perceptible in Figure 5, but it is ambiguous, given the existence of intervening cloud bands.

The vertical scales in Figures 4 and 5, as well as in subsequent video images for which the NLDN located an associated CG stroke, show the azimuth of the parent CG and indicate altitudes directly overlying it. Because the images are taken from the ground and are not in limb view, these altitudes do not necessarily correspond to the altitude of any horizontally-extended luminosity in the image. Moreover, sprites are known not always to lie over their parent CG [*Lyons*, 1996]; for a horizontal range uncertainty of ∼50 km, the uncertainty in the altitude scales is approximately 10 km.

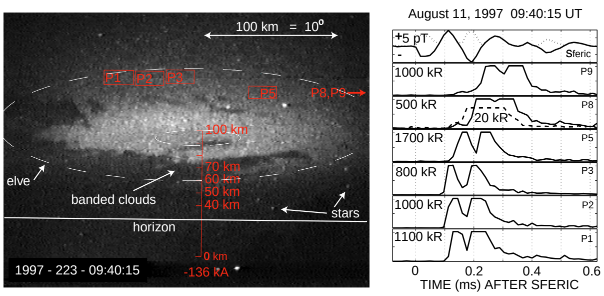

Figure 5. A 17 ms field from image-intensified video shows a broad flash, deduced to be an elve from the accompanying photometry. The photometers each saturated, but show the signature of an elve. The image shows altitudes overlying a strong −CG discharge reported by NLDN. P8 and P9 were pointed just to the right of the image. Dashed lines show the approximate extent of the elve and its central minimum. Some dark bands (foreground clouds) obscure part of the elve.

1.3. High speed video

Stanley et al. [1999] reported the use of a high-speed triggered image-intensified video system for sprite observations which included recordings of several cases of diffuse flashes preceding streamer formation in sprites. The recordings reported here were acquired at 3000 frames/second on on October 6, 1997 from Langmuir Laboratory, NM (33.98°N × 107.19°W) while observing the atmosphere above a storm ∼875 km to the south. These data provide an opportunity to compare in more detail the appearance of diffuse video flashes with the predictions from a numerical model.

2. Model description

The effect of vertical tropospheric lightning currents on the electron population at altitudes up to 100 km is modeled with a finite-difference time domain calculation in cylindrical coordinates, adapted from that used by *Veronis et al.* [1999]. The model solves Maxwell's equations around a vertical symmetry axis, solving for the vertical and radial electric field, azimuthal magnetic field, electron density, and conduction current. Optical emissions in the N_2 first positive band are calculated from the electron density and net electric field, and instrumental response is predicted for a given geometry and field of view. Ionization, attachment, electron mobility, and optical excitation coefficients used by *Pasko et al.* [1999] were implemented in the updated model, which is available from the authors.

A cloud-to-ground lightning return stroke (CG) is modeled by imposing a current between the ground and a spherical gaussian charge distribution at 10 km altitude. For lightning currents of ∼30 μs duration, mesospheric electric fields are dominated by those of the lightning electromagnetic pulse (EMP), while for ∼500 μs currents, the quasielectrostatic (QE) field dominates. Both EMP and QE fields are inherently accounted for in the fully electromagnetic model [*Veronis et al.*, 1999].

3. Time resolved imagery of sprite halos

Figure 6a shows VLF sferic, wide field of view photometer, and high speed video recordings from Langmuir Laboratory for an event at 05:00:04.716 UT on October 6, 1997. The data are time-tagged and coaligned to <50 μs accuracy. Less than 0.5 ms after the arrival of the sferic, a photometric enhancement corresponds to a diffuse, descending glow in the imagery. Following this by ∼1 ms, a group of sprite columns develops and subsequently brightens in a manner similar to that described by *Cummer and Stanley* [1999].

Figure 6b shows the two hypothetical lightning currents used to model emissions resulting predominantly from the EMP and QE fields. While all fields are encompassed within the full electromagnetic model, the slow and fast input currents will be referred to as the "QE case" and the "EMP case," respectively. The EMP case has a 30 μs current rise time and thus radiates ∼10 times as intensely as the QE case which has a 300 μs rise time. However, on time scales >0.2 ms the QE case brings about a much larger charge moment change.

The three sequences shown in Figure 6c compare observations of the diffuse flash with video signatures predicted by the model, given the lightning currents shown in (b) and the precise video frame timing (with respect to the lightning return stroke) and viewing geometry in effect during the observations. Scales show altitude above the source lightning discharge. The optical signature for the EMP case is that of elves, but the field of view shown reveals only a small part of the elve around its center. A wider field of view would reveal that the elve extends over hundreds of km horizontally and begins before the luminosity recorded in high speed video and well above the recorded field of view.

A more realistic lightning current profile may have a fast rise time, like that of our EMP case, but a slow relaxation, like the QE case. For the parameters used in the model, the elve (EMP case) is less than one sixth as bright as the diffuse flash of the QE case. Thus, even if both optical emissions were produced in the observed event, the elve may not have been bright enough to be detected by the high speed imager. Nevertheless, the timing, altitude, shape (including upward concavity), and development of the observed luminosity match closely those of the modeled response to a slow lightning current producing a charge moment change of ∼900 C·km in ∼1 ms.

By comparison with the model, it can be inferred that this luminosity occurs at altitudes of 70 to 85 km, localized (∼70 km wide) over the source currents, and descends in altitude in rough accordance with the local electrical relaxation time $\tau = \epsilon_o/\sigma$, where ϵ_o is the permittivity of free space and σ is the local conductivity [*Pasko et al.*, 1997]. In contrast, the luminosity in elves is confined to higher (80 to 95 km) altitudes and its time dynamics are dominated by an outward expansion in accordance with the speed of light propagation of the lightning EMP.

Modeling also indicates that the upward curvature apparent in the luminosity (Figure 6c) after its first appearance is due to the 'expulsion' of the electric field by the enhanced ionization. This ionization enhancement is presented in Figure 7. While optical luminosity, especially at the higher altitudes (>80 km) of the diffuse upper portion of a sprite, can occur without extra ionization, the upwardly-curved shape of the observed event indicates that significant ionization did occur.

Figure 7 compares the ionization changes produced in elves and in the diffuse upper portion of sprites. The central minimum in the EMP case is due to the radiation pattern of a vertical dipole, and it suggests that even when elves and sprites occur together, the extra ionization in elves is not likely to affect the breakdown processes in sprites occuring overhead the causative CG. On the other hand, it would not be surprising for the large ionization enhancements evident in the QE case to affect the formation of subsequent streamer breakdown. Indeed, there is an apparent correlation between the tops of the columnar features and the curved lower boundary of the diffuse region seen in Figure 6c. This correlation is seen also in other events.

Two other similar events were observed in high-speed video recordings from October 6, 1997. The three events showed varying delays between the beginning of

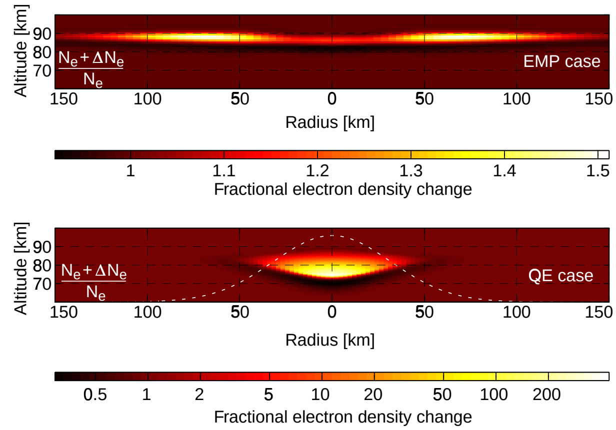

Figure 7. Model cross sections of ionization enhancement for elves (EMP case) and the diffuse portion of sprites (QE case) 2 ms after the lightning stroke. The line shows the shape of the disturbed region deduced by *Johnson et al.* [1999]. The effect of dissociative attachment is evident in the dark band below each bright region.

the sprite halo and the first development of streamer structure. In particular, in the two events not shown in Figure 6, the streamers initiated ∼0.3 ms and ∼3.6 ms after the halo onsets, based on the high speed video. Altogether 42 sprite clusters were recorded at video frame rates of 1000-4000/s during observations on October 3,6, and 7. Halos were recorded by the high speed video for only four of these events. All four of the lightning events which did produce sprite halos exhibited unusually large vertical charge moment changes during the initial ≤1 ms of the return stroke, as inferred from sferics measured at Langmuir Laboratory. This time scale is fast enough for the electric field to penetrate to lower ionospheric altitudes (see Section 8).

4. Sprite halos in normal-rate video

When averaged over 2 ms, the observed sprite of Figure 6 appears as a diffuse halo capping a cluster of columnar features. Figure 8 compares this to a commonly observed form for sprites in normal-speed video, and suggests that broad upper halos occasionally seen in video of sprites are also sprite halos preceding the onset of streamer formation. When the frames of this high speed video sequence are averaged over the entire duration of the sprite (∼4 ms, still much less than a normal video frame) the sprite halo is mostly washed out and becomes hard to perceive. It is likely that only in exceptionally bright cases are the diffuse upper por-

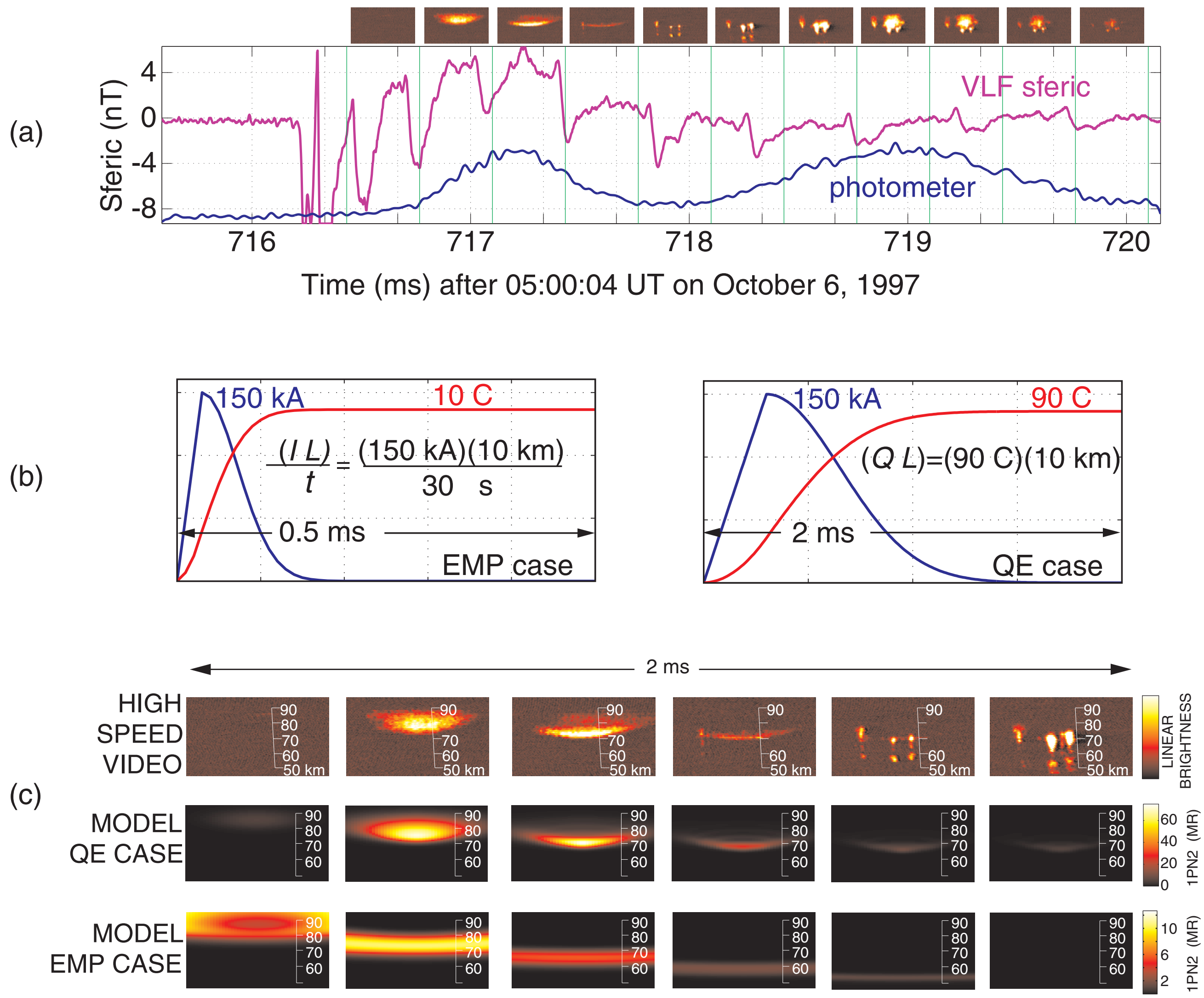

Figure 6. (a) A time-resolved sprite halo, with VLF sferic and photometer data; (b) theoretical lightning currents used as input to the model; and (c) comparison of observations (false color) and the modeled QE and EMP cases.

tions of sprites visible in a normal video field as sprite halos.

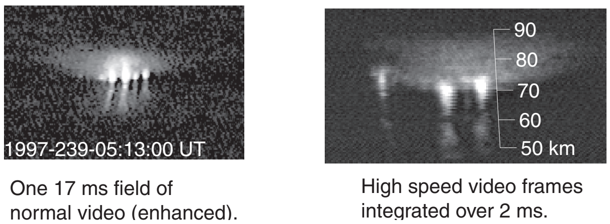

Figure 8. Comparison of two sprite halos observed in normal speed and high speed video.

5. Photometry

No elves were recorded by the high speed video system in three nights of observation in 1997. With much higher temporal resolution than that afforded by even this system, one may be able to resolve in two dimensions the temporal evolution of an elve. These dynamics are dominated by the propagation time between the source of optical emissions and the observer. As shown in Figure 1, this results in later emissions being observed before earlier ones, and in an apparent downward and outward development of the flash, consistent with the predictions of *Inan et al.* [1996b].

Figure 9a shows the same model events as in Figure 6 but as seen from 745 km away with a broader field of view and with a higher time resolution. Both sequences show a flash which descends over the course of about 1 ms and exhibits an upwardly concave curvature. While the descent and curvature of the sprite halo represent true descent and curvature of the optical source, these features in elves are instead a result of the propagation geometry between the highly extended source and the observer.

Figure 9b shows 28° × 8° images of the predicted emissions from the QE and EMP cases, as would be observed from 745 km away by an instrument integrating over 2 ms. Modeled optical intensities shown here and in Figure 6 correspond to the total output of the first positive band of N_2 over its entire spectrum from 570 to 2310 nm. About 15% of this intensity would reach the Fly's Eye photometers in their passband of 650 to ~780 nm. For the lightning parameters used here, the elve is only 8% as bright as the sprite halo when integrated over 2 ms. This example illustrates the fact that sprite halos are much easier to image with a 17 ms video field than are elves. However, the intensity of each phenomenon varies strongly with electric field strength, so either emission could be much brighter or dimmer than the cases modeled here, depending on the characteristics of the causative lightning current.

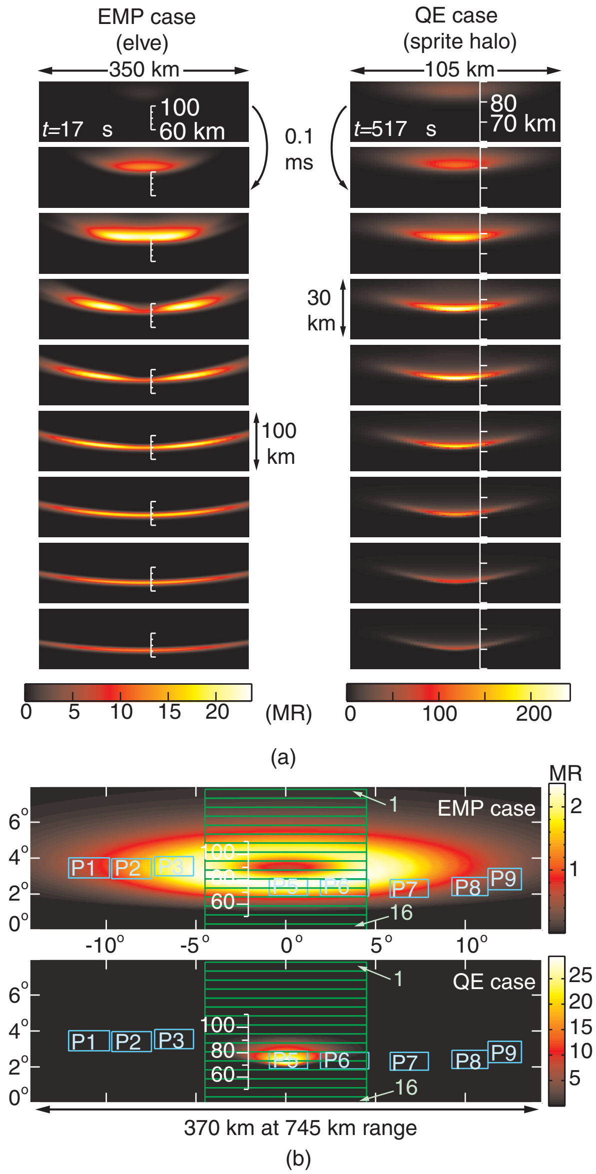

Figure 9. (a) Modeled temporal development of elves and sprite halos as seen in 10 μs-long snapshots every 100 μs, viewed from ground level 745 km from the causative CG. The QE and EMP sequences begin 17 μs and 517 μs after the lightning sferic would be received by the observer. (b) The flashes integrated over 2 ms. Superimposed are the fields of view of two typical photometer arrays.

It has previously been established (see Section 1.1)

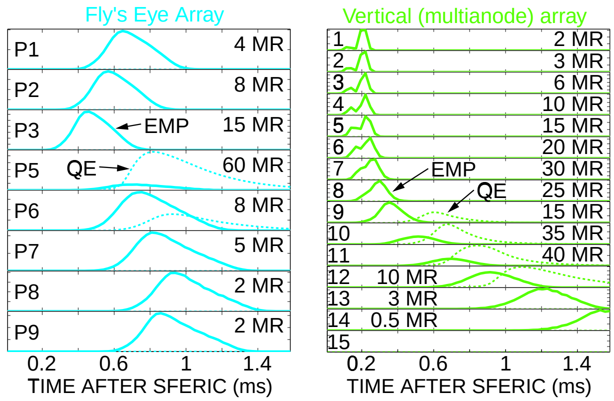

Figure 10. Predicted signatures from the two photometric arrays shown in Figure 9b, showing contributions from both EMP and QE emissions.

that a horizontal photometer array with time resolution ≪1 ms is well suited for identifying elves. We now show how the photometric signatures of sprite halos compare to those of elves. Overlaid on the model images in Figure 9b are the fields of view of the Fly's Eye array (in blue) and of a $16\times(0.5^\circ \times 9^\circ)$ multianode photometer (in green) similar to that used by *Fukunishi et al.* [1998].

Predicted photometric signatures are shown in Figure 10 in corresponding colors for EMP (solid lines) and QE (dashed lines) emissions. In both the vertical and horizontal photometer arrays, the initial signature of the "front" of the elve (i.e., luminosity produced at a point nearer than the CG to the observer) is unambiguous. However, at later times, the "back" of the elve (i.e., luminosity produced beyond the CG, as seen by the observer) may be confused with that due to the upper part of the sprite. This feature could make it somewhat difficult to measure the downward propagation of the sprite halo in the vertical array, and also makes the horizontal array (Fly's Eye) configuration very sensitive to its viewing elevation angle. The modeled response of the Fly's Eye array takes into account the imperfect array alignment. This imperfection is reflected in the fact that photometers P1, P2, and P3 are viewing the "front" of the elve in Figures 9b and 10a, while P5 through P9 view the "back."

Figure 11 shows normal-speed video and photometric responses for three events recorded with the Fly's Eye using slightly different pointing elevations with respect to the observed flash. All three events produced elves and sprite halos. The event in Figure 11a includes an elve and sprites with a halo, but all the photometers are pointing high enough to observe the front of the elve. In Figure 11b the sprite halo, which occurred without any further sprite development, may be contributing to the enhanced brightness in P5 and P6. In Figure 11c the response of P5 and P6 is clearly dominated by that of the sprite halo, which again occurred without any apparent streamer breakdown.

In the most energetic sprites, any sprite halo is often followed very closely (<1 ms) by the much brighter filamentary sprite breakdown, so that all these emissions may not appear as distinct peaks in the photometric record.

6. Dependence on the ambient electron density

The distinctive shape, motion, and altitude range of the sprite halo of Figure 6 represents the first instance of an observed large-scale feature of sprites which can be accurately modeled in detail. These detailed features can potentially serve as a diagnostic tool for the ambient electron density profile at the time of the discharge. Figure 12 shows the modeled luminosity for three initial electron density profiles, using the lightning parameters and timing of the QE case in Figure 6. The ambient electron density N_e at altitude h follows the form [*Wait and Spies*, 1964]

$$N_e(h) = 1.43 \times 10^7 \text{ cm}^{-3} \exp[(-0.15/\text{km})h'] \exp[(\beta - 0.15/\text{km})(h - h')]$$

with $\beta = 0.5$ km^{-1} for each h' shown in Figure 12. For numerical efficiency, the ambient profiles were capped at 5×10^3 cm^{-3}. Both the intensity and shape of optical emissions vary with the D-region height. Following well characterized lightning discharges, these optical emissions could reveal information about the local electron density profile over a thunderstorm. The case of $h' = 85$ km was chosen as a best match for the observed sprite halo development in Figure 6c.

7. Early/fast VLF perturbations

Johnson et al. [1999] determined that the lateral extent of the ionospheric disturbance responsible for the so-called "early/fast" VLF perturbations was 90±30 km, suggesting that clusters of ionization columns in sprites were not the cause. Instead, the authors suggest that a quiescent (rather than transient) heating (rather than ionization) mechanism [*Inan et al.*, 1996a] could explain the observations. However, as shown in Figure 7, the diffuse upper region of sprites may produce significant ionization enhancements with a horizontal scale

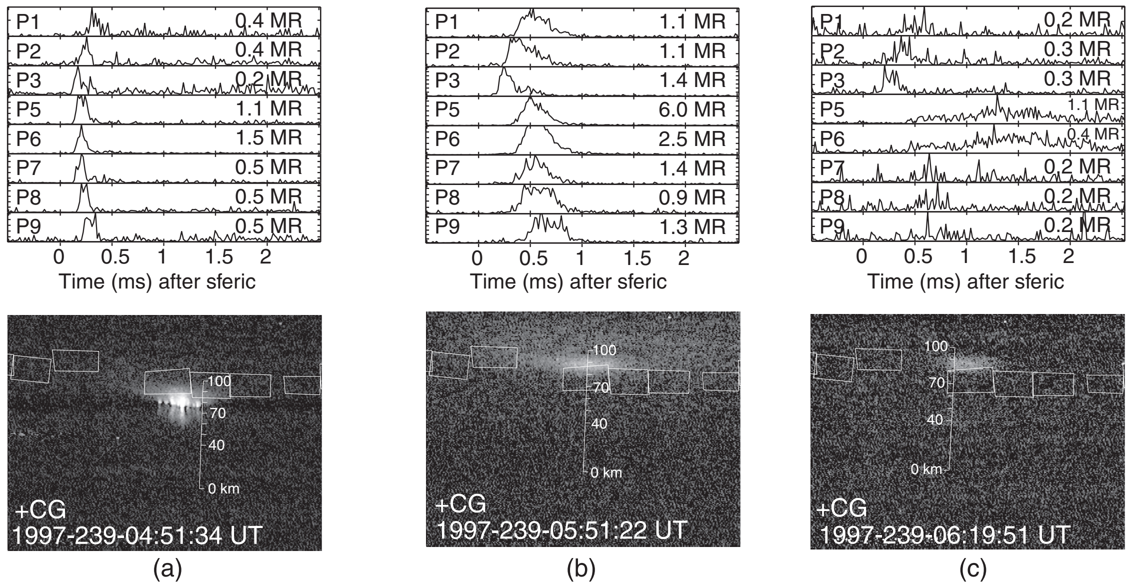

Figure 11. Photometry and enhanced video images from the Fly's Eye for three events exhibiting sprite halos. A sprite halo caused by a −CG is shown in Figure 4.

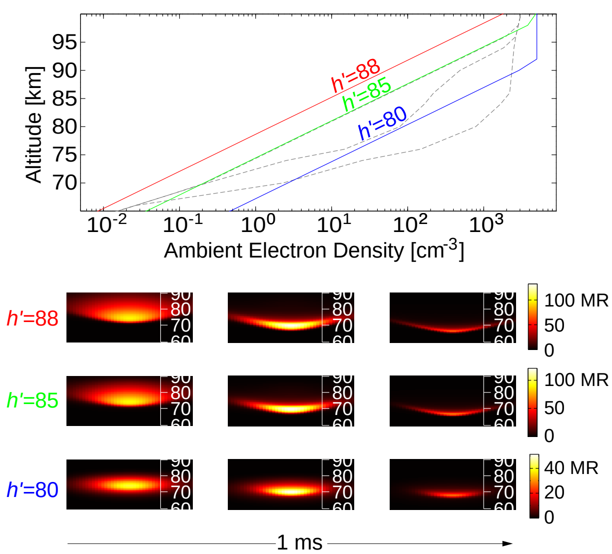

Figure 12. Ambient electron density profiles for three values of h', and the resulting modeled sprite halos. The $h' = 85$ km case corresponds to Figure 6c. Each image shows a region 30 km high by 105 km wide at a range of 875 km. Dashed lines show profiles used by *Pasko et al.* [1997].

of ∼80 km and at an altitude of 70 to 85 km, below the nighttime VLF reflection height and where the time scale for relaxation of electron density enhancements is 10 to 100 s [*Glukhov et al.*, 1992]. These characteristics qualify the diffuse sprite region as a candidate for a cause of VLF scattering as resolved by *Johnson et al.* [1999].

In addition, "post-onset peaks" lasting ∼1 s may speculatively be ascribed [*Inan et al.*, 1996c] to the heating and ionization change evident in Figure 7 at lower altitude (down to 70 km), where the three-body electron attachment time scale is <10 s [*Glukhov et al.*, 1992]. However, this would predict a broader VLF scattering pattern for the post-onset peak portion of the event, and may also require a temporary lowering of the VLF reflection height [*Wait and Spies*, 1964].

VLF early/fast events are observed with both +CG and −CG's, and do not correlate well with lightning return stroke peak current, as reported by NLDN. This, in part, led *Inan et al.* [1996a] to propose a less exotic cause than electrical breakdown. However, many lightning discharges of both polarities may produce significant charge moment changes on 0.5 ms time scale and may produce sprite halos but no further sprite breakdown, for which additional charge moment changes, possibly accumulating over some ms, may be necessary. Many of these events may be invisible when integrated on a 17 ms video field. As mentioned by *Inan et al.* [1996a], a combination of quiescent, EMP, and QE effects is likely necessary to explain all observed VLF early/fast events.

8. Discussion

The diffuse region of sprites has been previously described in the context of a QE model [*Pasko et al.*, 1995, 1997] with the shape, size, and dynamics of optical emissions closely resembling those observed in the high speed video presented here, and is modeled with a more general fully electromagnetic model and more realistic viewing geometry in this paper. The direct large scale (∼100 km) modeling of the lower portion of sprites dominated by streamers using the QE or the electromagnetic model utilized in this study is computationally not possible at present due to the extremely fine spatial resolution which is required to resolve individual streamer channels [*Pasko et al.*, 2000].

Ionization and optical emissions in the diffuse region and in the lower streamer region of sprites is observed to occur both as fairly separate events and as closely-coupled processes. The upper diffuse region of sprites [*Pasko et al.*, 1998] is characterized by very fast relaxation of the driving electric field due to the high ambient conductivity associated with electrons at the lower edge of the ionosphere. The ionization process in this region of high electron concentration is theorized to be simple collective multiplication of electrons. In the lower streamer region of sprites, formation of streamer channels follows strong dissociative attachment of electrons (e.g., Figure 7). The upwardly concave shape sometimes evident in sprite halos is due to enhanced ionization in the descending space-charge region. This extra ionization will enhance the electric field outside (below) the region and may affect the formation of streamers.

However, because the time scale for electrical relaxation varies strongly with altitude, breakdown in the two regions can occur somewhat independently. A lightning discharge with a fast (<1 ms) charge moment change may be sufficient to cause diffuse emssions at higher altitudes, where the threshold for ionization and optical excitation is lower, but if lightning currents do not continue to flow, there may not be sufficient electric field to initiate streamers below ∼75 km. Conversely, slow continuing currents may cause a (delayed) sprite without a significant initial flash in the diffuse region.

Although sprite halos in high speed video can be compared in detail with modeled luminosity, single-site recordings are not a robust method to experimentally determine sprite halos' altitude distribution. Two-site triangulation of sprite halos was accomplished for the first time by *Wescott et al.* [1999], and further measurements using triangulation and high-speed imagers may be necessary to statistically characterize the initial development of either the halo or streamer regions of sprites.

9. Conclusions

Following distant, strong CG lightning, at least three classes of optical emissions are observed to have characteristic durations of ∼1 ms. These are scattered lightning flashes, elves, and the diffuse upper portion of sprites, observed as sprite halos. In addition, further sprite development (streamer breakdown) may be observed to occur for several to many milliseconds.

We provide a one-to-one comparison between high speed video observations of sprites and a fully electromagnetic model of sprite driving fields and optical emissions. This comparison for the first time identifies observed sprite halos as being produced by quasi-electrostatic thundercloud fields. Sprite halos are observed in high speed video as a transient descending glow with lateral extent on the order of 40 to 70 km preceding the development of streamer structures at lower altitudes. Our results agree well with recent theoretical analysis of electrical breakdown properties at different altitudes [*Pasko et al.*, 1998] and previous sprite modeling using the quasi-electrostatic (QE) model [*Pasko et al.*, 1997].

A class of upper mesospheric flashes observed in normal speed (30 frames per second) image-intensified video (e.g., Figure 4) over strong cloud-to-ground lightning is not the same phenomenon as that originally identified in photometry as elves by *Fukunishi et al.* [1996]. This video feature is likely also due to observations of the diffuse upper portion of sprites caused by a quasi-electrostatic field, although it is likely that the especially impulsive lightning discharges causing such events usually produce elves as well.

The introductory comment of *Barrington-Leigh and Inan* [1999] that "video recordings at standard frame rate are an inefficient and sometimes confusing method for identifying elves in comparison with a photometric array" seems even more compelling given this misidentification. In addition, high temporal resolution is needed for both horizontal and vertical arrays to discriminate between elves and sprite halos. Photometry with the Fly's Eye array remains a robust method for identifying elves and determining their horizontal extent and bottom height.

Sprites exhibiting bright vertical columnar structure and close association with −CG discharges ("negative sprites") were reported as a rare event by *Barrington-Leigh et al.* [1999]. On the other hand, occurrence of the sprite halos reported here is not unusual in association with −CG's, based on Fly's Eye and normal-rate video observations (e.g., Figure 4). Due to the exponential reduction with altitude of the fields required for ionization and optical excitation, the diffuse region is easier to excite with lower driving fields (i.e., lower thundercloud charge moment changes). However, this excitation is also very transient and is likely often undetectable in 17 ms video fields.

Acknowledgments. We are grateful to Victor Pasko for helpful discussions at every stage. We thank Ken Cummins of Global Atmospherics Inc. for provision of NLDN data, the Astronomical Data Center for their stellar database which was used for interpreting star fields, Rick Rairden of Lockheed Palo Alto Research Lab for the use of an intensified video camera and light source, Bill Abrahams of Speed Vision Technologies and Bill Kline of Eastman-KODAK Company for the high-speed camera, and Langmuir Laboratory for the use of their facilities. This work was supported by the Office of Naval Research under grant N00014-94-1-0100 and AASERT grant N00014-95-1-1095 and by the National Science Foundation under grant ATM-9731170.

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This preprint was prepared with AGU's LaTeX macros v5.01, with the extension package 'AGU^{++}' by P. W. Daly, version 1.6b from 1999/08/19.