A51B-02

Elves: Photometric and Video Observations *and misidentification of sprites*

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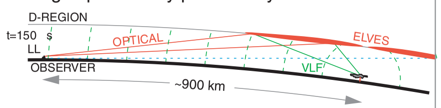
1 Introduction: Sprites and elves

Names for classes of high-altitude optical flashes caused by tropospheric lightning, "sprites" and "elves" may be used to represent as much two physical causes as they do two sets of phenomena. The electric field which causes heating, ionization, and optical emissions in sprites is caused by the charge moment changes associated with the movement of large thundercloud charges, usually during intense positive cloud-to-ground lightning [*Cummer and Inan,* 1997]. 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 return stroke currents [*Barrington-Leigh and Inan,* 1999]. As a result, elves last no longer than ~1 ms, while the durations of sprites vary greatly.

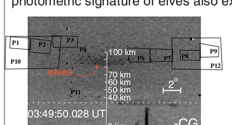
1.1 High speed array photometry



Due to their fleeting (< 1ms) 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 in a horizontal array of high speed (~17 s resolution) photometers, the "Fly's Eye" [*Inan et al.,* 1997]. By aiming well above the D-region overlying a strong CG, this array can be used to unambiguously identify optical emissions (elves) due to a lightning-launched electromagnetic pulse (EMP). This can be seen in the diagram above; based on the short (~150 s) delay between reception of the return stroke's radio pulse 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 only speed-of-light propagation [*Barrington-Leigh and Inan,* 1999].

1.2 Elves on video?

In recent years ostensible "elves" have also routinely been identified by others based on the existence of diffuse glows, often preceding or accompanying "sprites," in intensified video recordings. While we have not claimed to identify elves without the photometric evidence described above, these diffuse glows have seemed only to occur when the photometric signature of elves also exists.



(Misguided) figure from *Barrington-Leigh and Inan* [1999], showing what was thought to be the inverse video signature of a (CG) elve. The photometric signature of elves was also seen for this event.

However, upon critical inspection, these relatively compact (~40 km horizontally) optical 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 >100-200 km [*Inan et al.,* 1997].

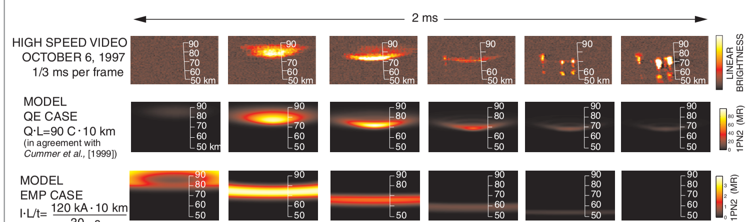
1.3 High speed video

Recently, *Stanley et al.* [1999] reported the use of a high-speed (333 s resolution) triggered image-intensified video system for sprite observations which included recordings of three apparent "elves." These data provide an opportunity to compare in more detail the appearance of diffuse video flashes with the predictions from a numerical model. The recordings were made on October 6, 1997 from Langmuir Laboratory, NM while observing the atmosphere above a storm ~875 km to the south.

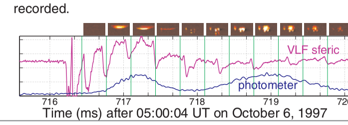
2 Description of the model

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. For lightning currents of ~30 s duration, mesospheric electric fields are dominated by those of the lightning electromagnetic pulse (EMP), while for ~500 s currents, the quasielectrostatic (QE) field dominates.

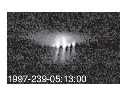
3 Model results and observations from high speed video: Discovery of diffuse sprites



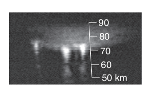
The sequences to the left compare observations of a diffuse flash preceding vertically-structured sprites (top row) to the modeled emissions from a quasielectrostatic (QE) field (middle row) and an electromagnetic field (bottom row) following two extremes (slow and fast) of lightning current. Below, high-resolution timing provides further evidence that the diffuse flash occurs much too late to be an elve. Two other similar events were recorded.



4 Are diffuse sprites common?



One 17 ms field of normal video.

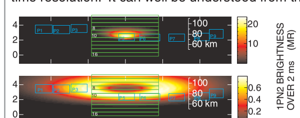


High speed video frames integrated over 2 ms.

When averaged over 2 ms, the observed sprite shown above appears as a diffuse halo capping a cluster of columnar features. Comparing this to a normal-rate video image of a commonly observed form for sprites suggests that broad upper haloes sometimes seen in sprites may be due to diffuse sprites 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 diffuse sprite is mostly washed out and is hard to perceive. It is likely that only in exceptionally bright cases are these diffuse sprites visible in a normal video field.

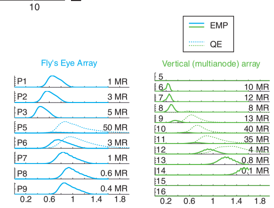
5 What do diffuse sprites look like in a photometer array?

To the right are shown 30x6 degree 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. For the reasonable lightning parameters used here, the elve is only 3% as bright as the diffuse sprite using this time resolution. It can well be understood from this example that diffuse sprites are much easier to image with a 17 ms video field than are elves.

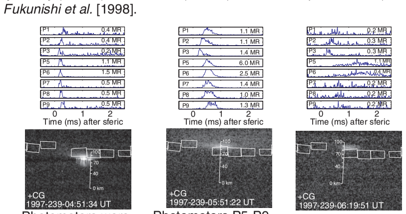


It has previously been established (see Section 1.2) that a horizontal photometer array with time resolution << 1ms is well suited for identifying elves. Here we show how the photometric signatures of diffuse sprites compare to those of elves. Overlaid on the color model images are the fields of view of the Fly's Eye array (in blue) and of a 16x(0.5°x9°) multi-anode photometer (in green) similar to that used by *Fukunishi et al.* [1998].

Predicted photometric signatures are shown at right in corresponding colors for EMP (solid lines) and QE (dashed lines) emissions.



Observed normal-speed video (enhanced) and photometric responses seen by the Fly's Eye are shown at far right for three events.



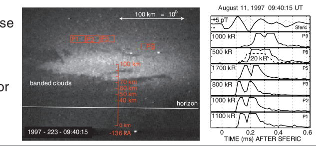
Photometers were pointed high enough to see the front of the elve.

Photometers P5-P9 see the "tail" of the elve and maybe P5 and P6 see the diffuse sprite??

P5 and P6 see the diffuse sprite.

6 Are elves *ever* actually seen on video?

Shown to the right is an extremely rare (i.e. bright) case showing an elve that is readily apparent in a 17 ms video field. Note the large 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]. See also the middle video field in Section 5.



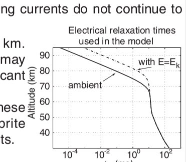
7 Why do sprites not always develop streamers?

The diffuse region of sprites [*Pasko et al.,* 1998] is characterized by very fast relaxation of the driving electric field due to 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.

The upwardly concave shape of the diffuse sprites (Section 3) 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. Notice the apparent correlation between the tops of the columnar features and the curved lower boundary of the diffuse region seen in Section 4.

However, because the time scale for electrical relaxation (shown at right) varies strongly with altitude, breakdown in the two regions can occur somewhat independently. A lightning discharge with a fast (< 1ms) charge moment change may be sufficient to cause diffuse emssions at higher altitudes but if lightning currents do not continue to flow, there may not be sufficient E field to propagate streamers below ~70 km. Conversely, slow continuing currents may cause a (delayed) sprite without a significant initial flash in the diffuse region.

Further studies are underway to relate these predicted behaviors to observed sprite morphology and lightning current moments.



8 Conclusions

- 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 for the first time documents the observed diffuse region of sprites as being produced by quasi-electrostatic thundercloud fields. The diffuse region is a transient descending glow with lateral extent on the order of 40-50 km preceding the development of streamer structures at lower altitudes. Our results agree well with recent theoretical analysis of the 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 frequently observed in image-intensified video over strong cloud-to-ground lightning may not be the same phenomenon as that originally identified as elves [*Fukunishi et al.,* 1996]. These reports are more likely due to observations of diffuse 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 widespread misidentification. In addition, high temporal resolution is needed for both horizontal and vertical arrays to discriminate between elves and diffuse sprites. Photometry with the Fly's Eye array remains a robust method for identifying elves and determining their horizontal and lower extents.
- Sprites exhibiting bright vertical columnar structure and close association with CG discharges were reported as a rare event by *Barrington-Leigh et al.* [1999]. However, occurrence of the diffuse sprites reported here is not unusual in association with CG's, based on normal video observations (e.g., see Section 1.2). However, these events are likely often undetectable in 17 ms video fields.

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Acknowledgements - to Victor Pasko for helpful discussions at every stage.