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Elves triggered by positive and negative lightning discharges

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Abstract. Optical flashes in the lower ionosphere due to the transient heating caused by lightning electromagnetic pulses (EMP) are unambiguously identified with the Fly's Eye photometric array. Data from a thunderstorm over Mexico recorded at Langmuir Laboratory on August 27 1997 demonstrate that relatively common negative cloud-to-ground lightning is a previously unrecognized major cause of elves. The spatial extent of the transient heating is shown optically to be typically at least 200-700 km laterally, indicating the possibility for accumulation of ionization effects produced by successive flashes within large nighttime thunderstorm systems. One especially bright event suggests that temporal fine-structure in the causative very low frequency EMP can manifest itself in the photometric record of elves.

Introduction

The most rapid coupling of tropospheric electrical energy to the mesosphere and lower ionosphere was predicted [*Inan et al,* 1991; *Taranenko et al,* 1993a] to be due to the electromagnetic pulse (EMP) from lightning current, which can cause heating, ionization, and optical emissions at altitudes of 75-95 km. The resulting brief (∼1 ms) flashes, or 'elves,' were subsequently observed [*Fukunishi et al,* 1996] in association with rare, large positive cloud-to-ground (+CG) discharges during nighttime sprite observations, and their spatio-temporal development was shown to be consistent with the theorized cause [*Inan et al,* 1997].

The "Fly's Eye," an array of photomultiplier-based photometers with a high-speed (∼60 kHz on each channel) data acquisition system, is described in *Inan et al* [1997]. The fields of view of the Fly's Eye photometers are shown in Figure 1. The observations described here were made with blue interference filters (350 - 475 nm) on two photometers and red longpass filters (> 650 nm) on the rest. The photomultipliers are sensitive from the UV to 800 nm. Because their response varies significantly over the wavelengths passed by the blue and red filters, we report in Figure 2 an intensity in Rayleighs at 400 nm or 700 nm, as if the observed signal were due entirely to photons at one of those wavelengths.

The submillisecond development of elves in the Fly's Eye's horizontally-spaced photometers provides an unambiguous signature for the identification of a laterally expanding (EMP-caused) flash, and is used here as a means to differentiate it from the Rayleigh-scattered light which originates in lightning. Indeed, all events identified as 'elves' herein exhibit (1) appropriate onset delay following the parent lightning sferic (∼120 to 160 μs typical for elves 600 to 800 km away) recorded by the same data acquisition system, (2) fast lateral expansion [*Inan et al,* 1997], and (3) when recorded, much brighter red emissions than blue. These criteria were used to analyze elves recorded during August 1997.

In contrast, Rayleigh - scattered light from lightning appears in our lateral array with an onset that is simultaneous (to within one sample, ∼16μs) amongst the different photometers, and with no more than one sample delay with respect to the associated sferic [*Inan et al,* 1997]. In addition, Rayleigh - scattered light from the continuum emissions of lightning produces emissions in the blue almost as strong as those in the red (being governed only by atmospheric extinction). Not all strong lightning strokes produced a bright 'sky flash,' presumably due to the variability in cloud geometry; however, because sky flashes last 500-1000 μs, they can obscure any elves that are also present.

The identification of elves in this study does not rely either on recordings from the 30 frame-per-second video which was boresighted with the photometer array (Figure 1), nor on the microsecond timing provided by the National Lightning Detection Network (NLDN; see *Cummins et al.* [1998]). Indeed, video recordings at standard frame rate are an inefficient and sometimes confusing method for identifying elves in comparison with a photometric array.

A Sample Event

Figure 2 shows the sferic and photometric signals recorded for an event at 09:40:15 UT on August 11, 1997. The NLDN simultaneously recorded a negative CG discharge with current 155 kA, located 571 km away at a bearing of 82° east of geographic north. The central pixel (P5) of the Fly's Eye was pointed at a bearing of 86° and an elevation of 11°. The polarity of the CG lightning is unambiguously confirmed by that of the received sferic.

This event exhibits an interesting double-pulse structure and is unusually bright, showing strong emission outside the N_2 1st positive band. The delay between reception of the sferic and first optical signals, and the apparent lateral 'expansion' indicated by the non-simultaneous onset in the laterally-arrayed photometers (Figure 2), are features shared by all the elves, including those studied during the period 03:00 - 10:00 UT on August 27 (see below).

The dashed trace shown in Figure 2 is the response of P12, a blue photometer (see Figure 1) with a rectangular field of view containing that of P8, but approximately 3 times as large in each dimension. Only a handful of events during the study period were bright enough to be detected by our blue photometers.

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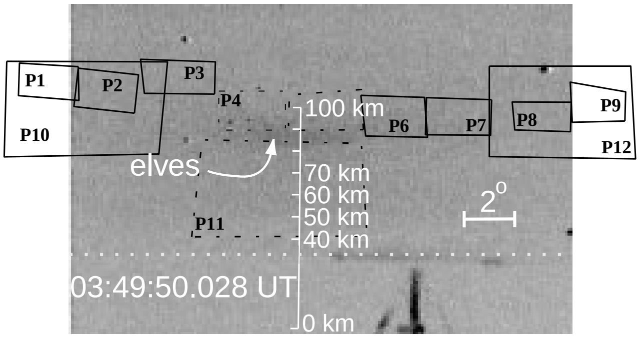

Figure 1. Fields of view of red (P1-P9; P11) and blue (P10; P12) photometers superposed over enhanced inverse-video of "elves". The vertical bars show elevations at the range and azimuth of an associated NLDN event. Even this unusually bright event is hard to distinguish in video.

The dotted trace in Figure 2 shows the absolute magnitude of the greater than 1 kHz component of the sferic, to emphasize that the optical pulses occur on the same time scale as the amplitude variations in the sferic. This suggests that the fine structure of the EMP electric field waveform may be manifested in the optical emission signature.

Elves Triggered by Negative CG Discharges

We now consider only events in the period 03:00 - 10:00 UT on August 27 1997, when a large mesoscale convective system was very active 700 - 850 km southwest of Langmuir Laboratory for Atmospheric Research (107.19° W × 33.98° N × 3200 m). Instruments deployed at Langmuir included a broadband (300 Hz to 20 kHz) VLF receiver to record sferics, an intensified video system, and the Fly's Eye photometric array. Signals from the sferic receiver and photometers were recorded in data snapshots of about 2 seconds duration by a pre-trigger buffering system, with timing synchronized to within 16 μs of GPS time through a parallel New Mexico Tech data stream.

On this night the triggering was done manually, based on observations with the bore-sighted intensified video system. Due to the much longer (5-150 ms) duration of sprites as compared with elves (< 1 ms), sprites are better suited for detection at a video frame rate than are elves; in fact, many elves are not detectable above the night sky background with our video imaging system. Consequently our manual triggering method was biased towards events associated with sprites, and thus towards large positive cloud-to-ground lightning discharges [*Boccippio et al,* 1995]. On the other hand, manual triggering was not exclusively selective of events with sprites, since occasionally bright Rayleigh scattered light from the parent flash and brighter than usual elves were also captured. Photometric signatures of sprites were never confused with the onset of elves, in part because sprites begin at least $\sim$500-2000 μs after any closely associated sferic.

During the period 03:00-10:00 UT on August 27, at least 39 flashes were identified as elves, based on the criteria described above. Figure 3(a) shows a histogram of these events sorted by the peak-to-peak intensity of their associated sferics. While most of the +CG events in Figure 3 were associated with sprites, it is remarkable that a considerable fraction (31%) of the events were associated with -CG flashes, in spite of the fact that the manual triggering method used on this day was highly biased towards sprite-associated discharges and towards the very brightest of elves.

The fact that -CG flashes also produce elves is consistent with our theoretical understanding of EMP-heating, a process which is independent of the polarity of the field. During the period 03:00 - 10:00 UT, 90% of the CG flashes recorded by NLDN from the Mexican MCS and with peak current greater than 25 kA were -CG. Based on the occurrence rate of highly energetic -CG and +CG discharges the above result indicates that EMP-induced heating and ionization of the lower ionosphere (as manifested by elves) above nighttime thunderstorm systems may well be much more prevalent than sprites.

To further assess the prevalence of elves, we surveyed all the NLDN flashes with peak current over 38 kA that were within the Fly's Eye field of view and which occurred during one of the 261 recorded data samples, each lasting about 2 seconds. Of the 86 NLDN events in this set, the photometric records for 13 events were dominated by the Rayleigh-scattered light due to the parent lightning flash. Of the remaining 73 flashes, 52% (38) exhibited the telltale signature of elves. Above 45 kA in the NLDN record, this fraction was 73% (37); above 57 kA, all (34) of the flashes had accompanying elves.

These statistics are necessarily affected by our manual triggering method. Nevertheless, Figure 3(b) shows a good correlation between the peak VLF fields produced by lightning and the maximum optical intensity seen by any of the Fly's Eye photometers, even though the photometers were not necessarily looking at the same part of the flash in different events. The scale on the top of Figure 3(b) shows NLDN peak current values based on a linear fit to the good correlation between VLF peak and NLDN peak which was

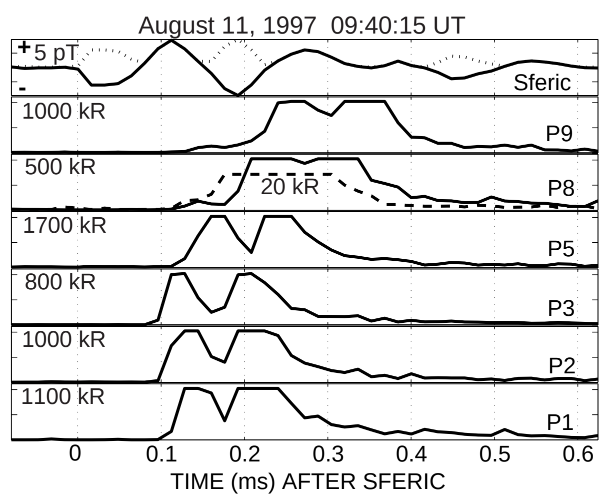

Figure 2. Photometer responses and simultaneous sferic recording for an unusually bright event, showing the photometric onset delay and the lateral 'expansion.' The unusually short onset delay for an event 571 km away is indicative of the low vertical extent of the flash. The dotted curve is the absolute value of the sferic, showing variations in optical output and causative EMP with similar time scales.

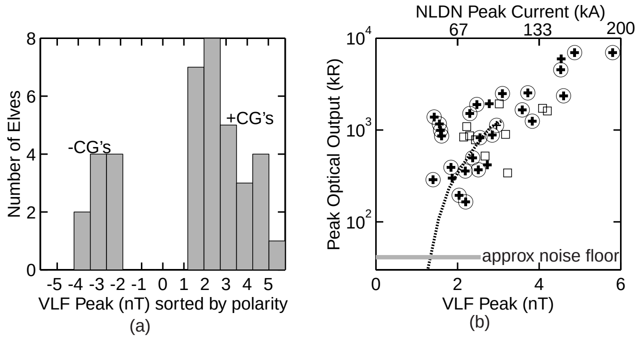

Figure 3. (a) Histogram of elves detected versus the strength of their causative VLF sferic, sorted by CG polarity. (b) Correlation between sferic strength (measured in equivalent wave magnetic field) and peak optical output. Squares and crosses show -CG and +CG events, respectively. A circle indicates that sprites were associated (within 100 ms) with the event. The dotted line shows the predicted relationship, scaled vertically to fit the observed intensities.

found for all but a few outliers among these events. Using this axis, the predicted relationship between N_2 1^{st} positive optical emissions and source lightning strength for a dense nighttime ionosphere is plotted (dotted line) from *Taranenko et al* [1993b]. A threshold in the VLF peak is evident; this results from a combination of the instrument background signal level and the well known [*Taranenko et al,* 1993b] highly nonlinear dependence of N_2 1^{st} positive optical output on the instantaneous field strength.

Spatial Extent of Elves

The field of view of each photometer was measured precisely (Figure 1), and the pointing elevation and azimuth at any time during observations were recorded by an electronic clinometer and a compass-adjusted, graduated mount. This knowledge, coupled with the lightning locations given by NLDN and the delay in each photometer between the sferic and the flash onset, constrain in three dimensions the source of the first light seen in each photometer [*Inan et al,* 1997]. The VLF sferic constitutes a ground wave propagating at very nearly the speed of light, and the observed flash is due to a VLF EMP propagating to an ionospheric point which emits the optical wavelengths received by the photometer. The onset delays in each photometer for all the events ranged from 97 μs to 620 μs, where the longer times correspond to parts of the elves located behind the source lightning or far to the side of it. However, the first appearance of each event in any photometer occurred almost exclusively between 100 μs and 200 μs after reception of the associated sferic.

Figure 4 shows the top view of source locations for a bright flash producing a considerable response in the two blue photometers. The uncertainty due to the extent of the fields of view is shown by the dotted quadrilaterals. We performed this analysis for all identified elves associated with an NLDN flash, and in a majority of cases, flashes were localized at a distance of over 100 - 200 km from the source lightning. In several cases this distance was well over 300 km, as predicted for strong discharges [*Inan et al,* 1997].

While both the altitude and the geographic location of the initial observed point of each flash are determined in this way, the altitude is not as tightly constrained for very low elevation angles (about 4° on the 27th of August). Nevertheless, the deduced lower altitudes of each flash source remained roughly consistent with the predicted 85-95 km [*Inan et al,* 1996] and served as a sanity check for discrimination of elves from Rayleigh - scattered lightning, which, due to its short onset delay, would have a deduced altitude near zero.

Discussion

Elves are optical signatures of strong energetic coupling of lightning EMP to a narrow altitude range in the D-region of the ionosphere. Detecting elves in association with negative lightning discharges implies the ubiquity of this phenomenon. Since negative CG discharges are known to be much more common than positive discharges [e.g. *Orville,* 1994], our results indicate that nearly all discharges with EMP intensity above a certain threshold may trigger elves. Our results further indicate that the spatial extent of the ionospheric disturbance from a single discharge is as large as anticipated [*Inan et al,* 1996]. While the optical emissions in elves are expected to be strongly dependent on the strength of the causative discharge, transient electron heating should occur for smaller discharges which may not produce detectable optical output.

Moreover, the possibility of the superposition of electron density changes due to subsequent CG strokes described in *Taranenko et al* [1993a] seems cogent given the large area ($\sim 3 \times 10^5$ km^2) shown here to be affected by a single EMP. Ionization changes decay over time scales on the order of 10-100 s in the D-region, so that the accumulated effect of successive strong cloud-to-ground strokes occurring at different points in a large storm system may profoundly affect the nighttime D-region. As an example, within a 770 km length of the Mexican mesoscale convective system of Au-

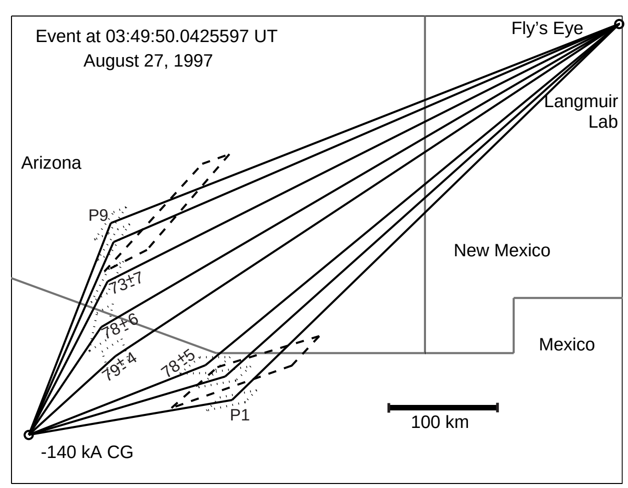

Figure 4. Flash onset locations determined by timing considerations for a single discharge 647 km from the observation site. P4 was not recording. The arc formed by these positions is due to the curvature of the ionosphere. The fields of view of P2 and P3 are slightly higher than the others. The dashed lines correspond to the two blue photometers. Lower bounds on the located altitudes are shown in km for P3-P7.

gust 27, NLDN recorded 310 CG's with peak current greater than 45 kA during the period 03:00 - 10:00 UT (an average of one per 80 s), with much more intense local clustering during some periods.

Summary

A large number of subionospheric flashes apparently caused by lightning EMP were observed with similar characteristics to those described in *Inan et al* [1997]. Two further predictions of the lightning EMP model were upheld: (1) elves seem to occur in relation to the strength of lightning EMP in the VLF frequency range, independent of field polarity; and (2) their lateral spatial extents are often on the order of at least 200 - 660 km.

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