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Rapid lateral expansion of optical luminosity in lightning-induced ionospheric flashes referred to as 'elves'

U. S. Inan, C. Barrington-Leigh, S. Hansen, V. S. Glukhov, and T. F. Bell

STAR Laboratory, Stanford University, Stanford, CA 94305

R. Rairden

Lockheed-Martin Palo Alto Research Laboratory, Palo Alto, CA 94309

Abstract. Data acquired by a new array of horizontally spaced photometers boresighted with a low-light-level camera provide the first measurement of the rapid lateral expansion of optical luminosity in lightning-induced ionospheric flashes referred to as 'elves', occurring over time scales substantially less than 1 ms. The narrow individual fields-of-view of (2.2°×1.1°) provide a spatial resolution of ~20-km at a range of 500 km, enabling the documentation of expansion occurring over a horizontal range of 200 km with a time resolution of ~30μs. The observed dynamic features of elves are consistent with a model in which the optical output is produced as a result of heating by the electromagnetic pulse (EMP) from a lightning discharge.

Introduction

Recent two-dimensional modeling of the interaction with the lower ionosphere of intense electromagnetic pulses (EMPs) from lightning discharges has indicated [*Inan et al.*, 1996a] that optical luminosities (produced at 85-95 km altitudes as a result of heating by the EMP fields) as observed from a distance would appear to expand laterally at speeds faster than the speed of light. This apparent spatial expansion was predicted to occur during the few-hundred-microsecond temporal duration of the optical flashes, often referred to as elves [*Fukunishi et al.*, 1996]. Noting that the measurement of the sub-millisecond dynamics of the phenomenon would constitute an excellent test of the EMP-heating mechanism, a novel high speed photometric array (named the 'Fly's Eye') was designed and built at Stanford University and was operated at the Yucca Ridge field station in Colorado during July 1996. In this paper, we present the observed features of two different cases which clearly demonstrate the rapid lateral expansion of the optical luminosity. Most aspects of the data from the two events uncovered so far are consistent with the EMP-heating mechanism as the root cause of elves.

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Instrumentation

The 'Fly's Eye' instrument consists of an array of Hamamatsu HC124-01 integrated photomultiplier assemblies, sensitive in the range 185 nm to 800 nm, with light shields, lenses, and precision-cut focal-plane screens arranged to provide the sky-view depicted in Figure 1a. Each numbered box in the top row corresponds to the 2.2° wide by 1.1° high sensitive region ('pixel') of one photometer. Inset in Figure 1a shows the horizontal angular dependence of the sensitivity of one of the nine pixels. Photometer 11 (P11) has a 6.6° by 3.3° field of view. Figure 1 shows the observation

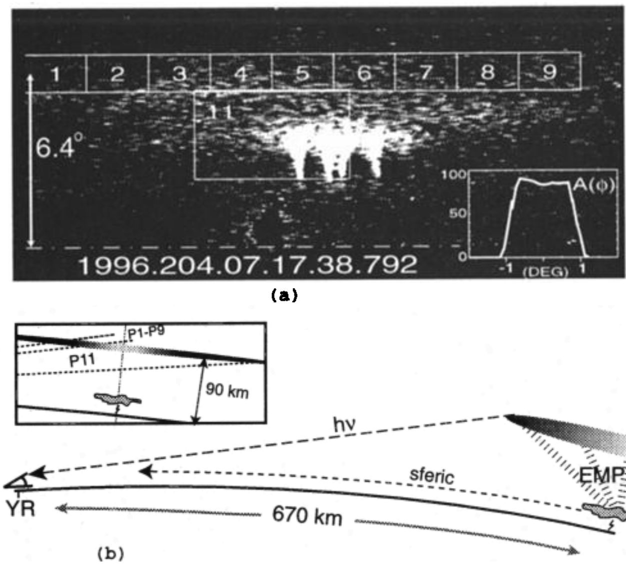

Figure 1. (a) The video camera and photometer array views of the sky during the 07:17:38 UT event on July 22, 1996. The cluster of sprites with columnar structure is at the center. The single video field (33 ms long, ending at 07:17:38.792 UT) has been enhanced (by subtracting a previous field and by thresholding its intensity) to highlight the diffuse emissions constituting the elves. The dashed line indicates the horizon. The inset shows the measured horizontal angular response function A(ϕ) for one of the top-row photometers. (b) The observation geometry for the two cases reported here. The inset shows the viewing altitudes of P1 through P9 and P11.

geometry for the case of the examples presented in this paper, with the inset showing the viewing altitudes of P1 through P9 and P11.

The photometer array was boresighted with an image intensified (Varo Noctron V) black and white Pulnix video system with a field of view of ~20° x 14°. The video frames were time coded with a GPS-based timing system and recorded on standard VHS videotape. A clinometer was used to automatically record the viewing elevation. Signals from all the photometers, the clinometer, another GPS receiver, and a broadband (300 Hz to 20 kHz) very low frequency (VLF) receiver were sampled and recorded with ~30μs resolution. The absolute sensitivity of one photometer was calibrated for white light at one gain level, and dealer-supplied relative sensitivities of the photomultiplier tubes and data for wavelength and gain level dependence were used to calibrate the other photometers for other wavelengths and gain levels. Many nearby lightning flashes were recorded nearly simultaneously on all channels, providing a calibration of system timing.

Observations

On July 22, 1996, a large mesoscale convective system ~650 km southeast of the Yucca Ridge (YR) Field Site (40°40'N, 104°56'W) produced many sprites and was observed at YR unimpeded by any intervening clouds. At this distance the ground under the storm was ~35 km below the horizon from YR so that neither the cloud-to-ground (CG) nor intracloud (IC) flashes produced by the storm, nor their cloud-scattered light, were visible from YR. Figure 1 shows the first video frame of a sprite event observed coincident in time (within ~30 ms) with a positive CG discharge of estimated peak-current +150 kA occurring at 669 km from YR at 07:17:38.767 UT, as recorded by the National Lightning Detection Network (NLDN).

At 07:17:38.769 UT the onset of an intense VLF radio atmospheric ('sferic' for short) was observed (Fig. 2 top panel) followed in ~150μs (in agreement with path length difference as discussed below) by a bright pulse in the center of the top row of photometers (Fig. 2, middle panel). Photometer 11 detected the same event (Fig. 2, lower panel) but also showed a less intense but longer lasting luminous event starting ~7 ms after the sferic onset. This second event is interpreted as the sprite itself, occurring over a time scale of tens of ms [*Pasko et al.*, 1996] and filling part of the field of view of photometer 11 (Figure 1a), consistent with past observations [*Fukunishi et al.*, 1996].

Although intense, the initial pulse observed on the top row of photometers lasting for <1 ms is only visible in the video image as a diffuse glow due to the 33 ms integration time of the video camera. Simultaneous observation of the temporal signatures on all nine pixels resolves the rapid lateral expansion as shown in Figure 3.

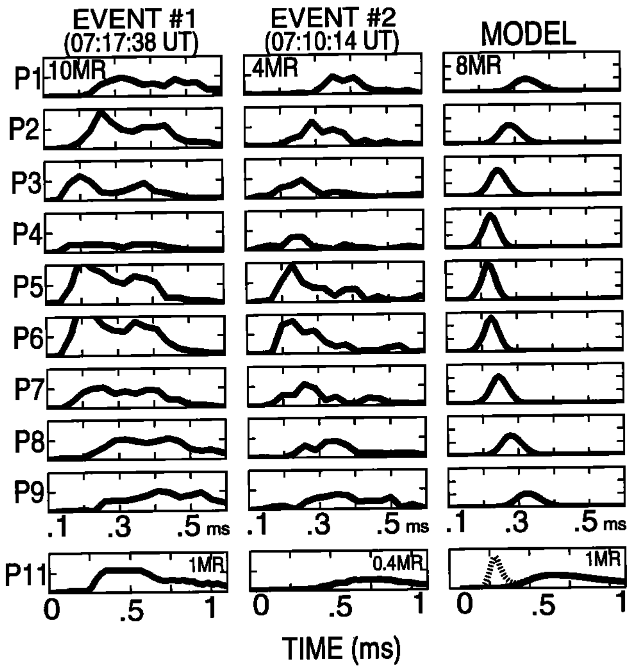

Figure 3. The two left columns show photometer recordings from two events on July 22, 1996. The responses recorded in the nine top-row pixels as well as P11 are shown. The vertical axes range from 0 to the inset values (in MR) in each column; P1–P9 share a common intensity scale. The time axes for P1–P9 are also identical and show ms after the onset of the associated VLF sferic. The time axes for P11 are compressed (×2) to show the later part of the pulse. The righthand column shows the predicted photometer responses using a two dimensional lightning EMP-ionosphere interaction model [*Inan et al.*, 1996a].

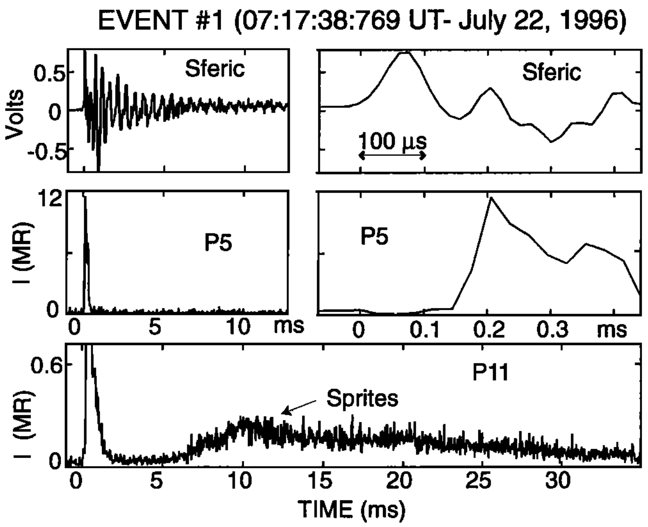

Figure 2. The relative timing of the VLF sferic (top row), intensity in P5 (middle row) and that in P11 (bottom row). The expanded sferic and P5 responses (right hand panels) clearly show the delay between the onsets. P11 detects both the fast event (i.e., elves) and the longer and dimmer sprites starting several milliseconds later.

The left column shows the first 0.6 ms of optical signals following the sferic onset ($t = 0$) for the event shown in Figures 1 and 2. The top-row pixels P1–P9, all pointed at 6.4° elevation, share time and intensity luminosity scales in Figure 3, while the less bright but longer-lived signal from P11 is plotted with separate scaling. The increasing delay of the flash onset with pixel distance from the center, ranging from $\sim 150\mu s$ for pixel 5 to $\sim 220\mu s$ for P1 and P9, is clearly apparent. The peak intensities of the pulses generally decrease with lateral distance from the center. At a distance of 670 km, the fields of view are ~25 km across for the top row of pixels. The luminosity lasts longer as observed by P11 due to its larger field of view, which includes the distant half of the expanding ring (Fig 1b).

A second event exhibiting similar lateral expansion is shown in the same format in the center column of Figure 3. This event was associated with a 120 kA +CG lightning discharge occurring at 666 km distance from YR at 07:10:14.100 UT on the same day. Analysis of less than 5% of the data from the Summer 1996 campaign has revealed several similar cases.

The luminosity scales in Figure 3 range from 0 to the MegaRayleigh (MR) value inset in each column for P1–P9 and, separately, for P11. These values represent photon intensities assuming the incident radiation is at 700 nm. Based on the predicted spectral distribution [*Taranenko et al.*, 1993] of lightning-EMP-produced optical emissions, and on the wavelength-dependence of atmospheric Rayleigh scattering, and on the spectral response of the photomultiplier tubes (which peaks at ~350 nm), the signal is expected to come primarily (95%) from the lower 1st positive band of N_2. The peak intensities for P4, and in the first event for P11, are uncertain due to saturation of the photomultipliers.

Interpretation

The features exhibited in Figures 2 and 3 are consistent with those expected to be produced by the electrodynamic interaction with the lower ionosphere of lightning EMP, as modeled by *Inan et al.* [1996a]. To illustrate, we use a modified version of the two-dimensional EMP-ionosphere interaction model to calculate the light output in the N_2 1st positive and N_2 2nd positive bands as would be measured by the Fly's Eye photometric pixels pointed at 6.4° elevation and their individual azimuths, for a source CG lightning discharge at 669 km range. These theoretical predictions, shown in the righthand column of Figure 3 (plotted with the same time scale as the data and with $t = 0$ corresponding to the time of arrival of the sferic at YR) are in good agreement with the observations. The observed onset delay, the speed of lateral expansion, the general form of the apparent vertical development as manifested in P11, and the broadening of pulse widths and reduction of peak intensities at wider angles are all represented in the model predictions. For the model calculations,

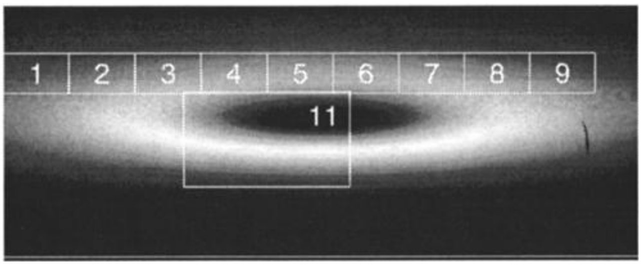

Figure 4. Calculated time-integrated spatial structure of the lightning EMP-produced optical luminosity shown in the field of view of the video camera. The Fly's Eye pixel views are superimposed.

the intensity of the lightning flash was taken to correspond to a peak electric field intensity at 100-km horizontal distance of 44 V/m, empirically consistent with an NLDN-estimated peak current of 150 kA [*Inan et al.*, 1996b]. The width and shape of the shortest (P5) modeled pulse reflects the current waveform of the modeled lightning. The actual durations of the causative lightning flashes for the observed events were not independently measured, and were thus not entered in the model. The spectral distribution of the N_2 1st positive and N_2 2nd positive bands, and the heavily wavelength-dependent effects of Rayleigh scattering and photometer response, were taken into account to predict voltage levels in the photomultipliers. These were in turn expressed in Rayleighs assuming a 700 nm source for direct comparison with the observations in Figure 3.

The calculated response of P11 shown in the solid line is for an elevation angle of 3.1°, which is ~ 1.1° lower than the actual recorded elevation of this pixel. At the recorded elevation, the computed response is very similar except for an additional initial peak (shown as a dashed line), due to the front part of the expanding ring of emission. The fact that such an initial peak is not observed in the 07:10:14 UT event data can be well explained by a small difference in the lower altitude limit of the luminosity, or by the refractive bending of the light rays travelling nearly tangential to the surface. Indeed, a slightly higher altitude for the latter event is suggested by independent estimates based on timing and geometry; these place the two light sources at 90±5 km and 92±5, respectively. As for atmospheric refraction, the bending in an ideal dry atmosphere can be ~0.3° for the elevation angle of P11 and can greatly exceed this value for a disturbed atmosphere [*Landolt-Börnstein*, 1988, p. 229] .

Based on the photometer data alone, the apparent speed of lateral expansion of each of the two luminous events in Figure 3 is ~3.1±0.8 times the speed of light, in good agreement with the original predictions [*Inan et al.*, 1996a]. Both this fact and the close agreement between theory and experiment as illustrated in Figure 3, support the predicted structure of elves as consisting of a rapidly expanding ring of luminosity in a narrow altitude range (~85-95 km). A time-integrated image of the optical luminosity predicted by our model to be observed over the entire field of view of the video camera is shown in Figure 4, together with the superimposed fields of view of the Fly's Eye pixels. The black region in the center is the center of the ring, corresponding to the minimum in the radiated EMP intensity above the source CG discharge, while the lower white region is the back part of the emission ring. The effect of Rayleigh scattering is not reflected in the image; it would attenuate slightly the lower limb with respect to the upper one. Comparing the image of Figure 4 with that of Figure 1, we note that in this case the central hole region is masked by the sprites.

Discussion

Both the high intensities (> 1 MR) of the optical signals received by the top-row Fly's Eye pixels and the fact that the luminosity is seen in the top-row photometers before P11 indicate that the observed signals are not due to Rayleigh scattering of light produced by the parent lightning flash.

The 154±30 and 164±30 μs delays respectively for the two events (07:17:38 and 07:10:14 UT) shown in Figure 3 between the onsets of the VLF sferic and the first optical pulse (P5) are in close accord with the calculated ~ 150μs delay. Note that because the outer limb of the luminous events moves considerably faster than the speed of light [*Inan et al.*, 1996a], the first signal detected by the photometers is the outermost bright region along the line of sight.

Although the fields-of-view of the Fly's Eye pixels do not extend beyond a full range of ~234 km (i.e., 117 km radius), the theoretical model (using a broader simulation region than used in [*Inan et al.*, 1996a]) indicates that, for the 44 V/m electric field intensity used here, the lateral extent of the luminous region (defined as the region in which the emission rate exceeds 1% of its peak value) is ~600 km. The extension of luminosity over such a large region is consistent with the video observations from the Space Shuttle of lightning-associated airglow enhancements (which in retrospect are most likely elves) with lateral extent ~ 500 km [*Boeck et al.*, 1992].

Summary and Conclusions

The remarkable agreement between data and theory as displayed in Figure 3 provides strong evidence that the fast lower-ionospheric optical flashes referred to as elves are manifestly distinct from later arriving red sprite events and that they exhibit clearly discernable outward expansion at apparent speeds greater than that of light. All measured aspects of this phenomenon appear to be consistent with those expected on the basis of heating by lightning-EMP as the root cause.

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U. S. Inan, C. Barrington-Leigh, S. Hansen, V. S. Glukhov, and T. F. Bell, STAR Laboratory, Stanford University, Stanford, CA 94305. (e-mail: inan@nova.stanford.edu)

R. Rairden, Lockheed-Martin Palo Alto Research Laboratory, Palo Alto, CA 94309.

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