Elves as the Optical Signature of Lightning Precursor Discharges in the Lower Ionosphere

Zaid Pervez, Reza Janalizadeh, and Victor P. Pasko
School of Electrical Engineering and Computer Science, Penn State University, University Park, PA 16802, USA
(zpervez@psu.edu; reza.j@psu.edu; vpasko@psu.edu)

PennState

1. Introduction

Narrow bipolar events (NBEs) are compact intracloud discharges, with spatial extent of 100s of meters, that usually precede lightning flashes. There is growing evidence that these discharges are associated with elves [Neubert et al, Science, 367, 183, 2020; Nature, 589, 371, 2021; Østgaard et al., JGR, 126, e2020-JD033921, 2021]; a type of transient luminous event observed at ~80-95 km altitude as laterally expanding rings of light. Elves are produced when electromagnetic pulses from high peak current lightning discharges interact with the lower ionosphere [Fukunishi et al., GRL, 23, 2157,1996; Inan et al., GRL, 24, 583, 1997].

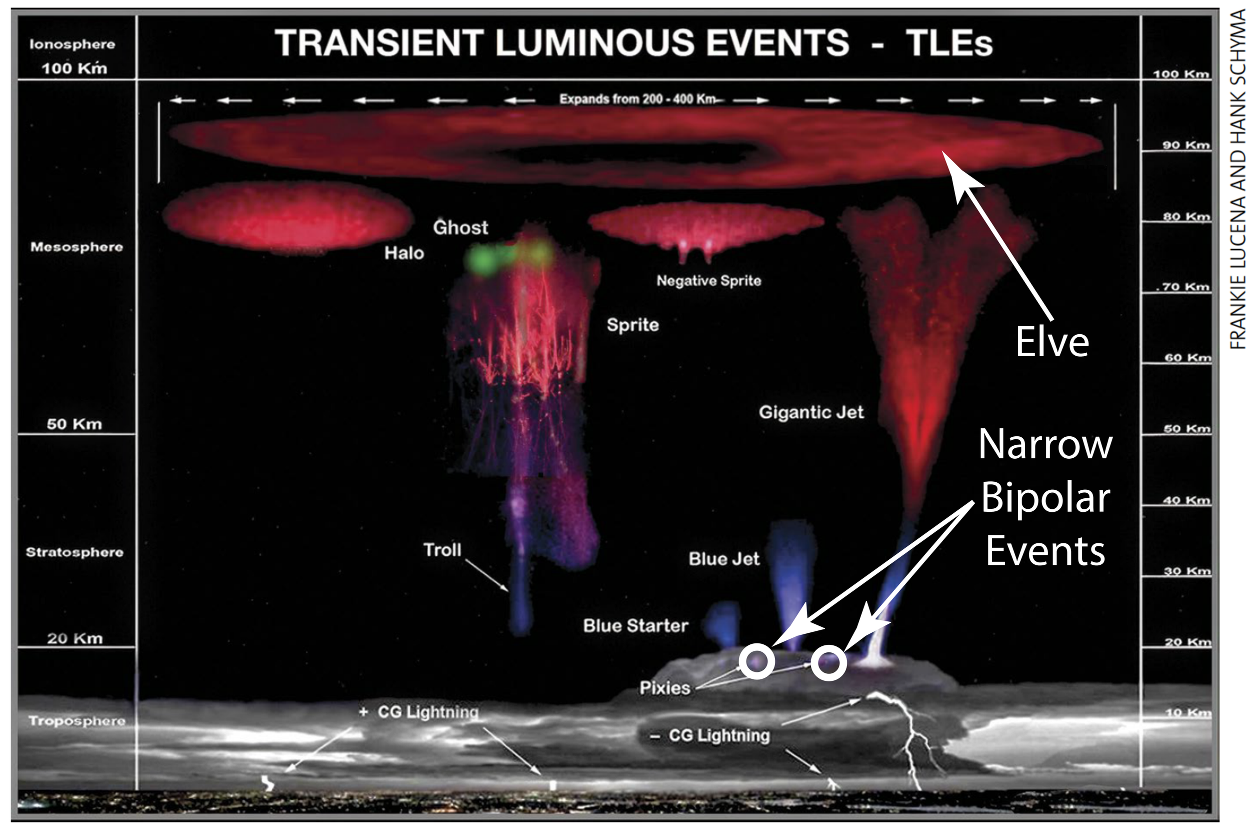

Figure 1. Schematic illustration of the known Transient Luminous Events by citizen scientists Frankie Lucena and Hank Schyma [Lyons, Weatherwise, 75, 14, 2022]. Emphasis to NBEs and elve added.

In this work we study the association of NBEs and elves by:

1. Using electric field measurements of an observed NBE to recover its source current using the method given in [Pervez et al., GRL, e2023GL107789, 2024].
2. Using the recovered source current to estimate optical emissions at elve altitudes.

2. Model Geometry

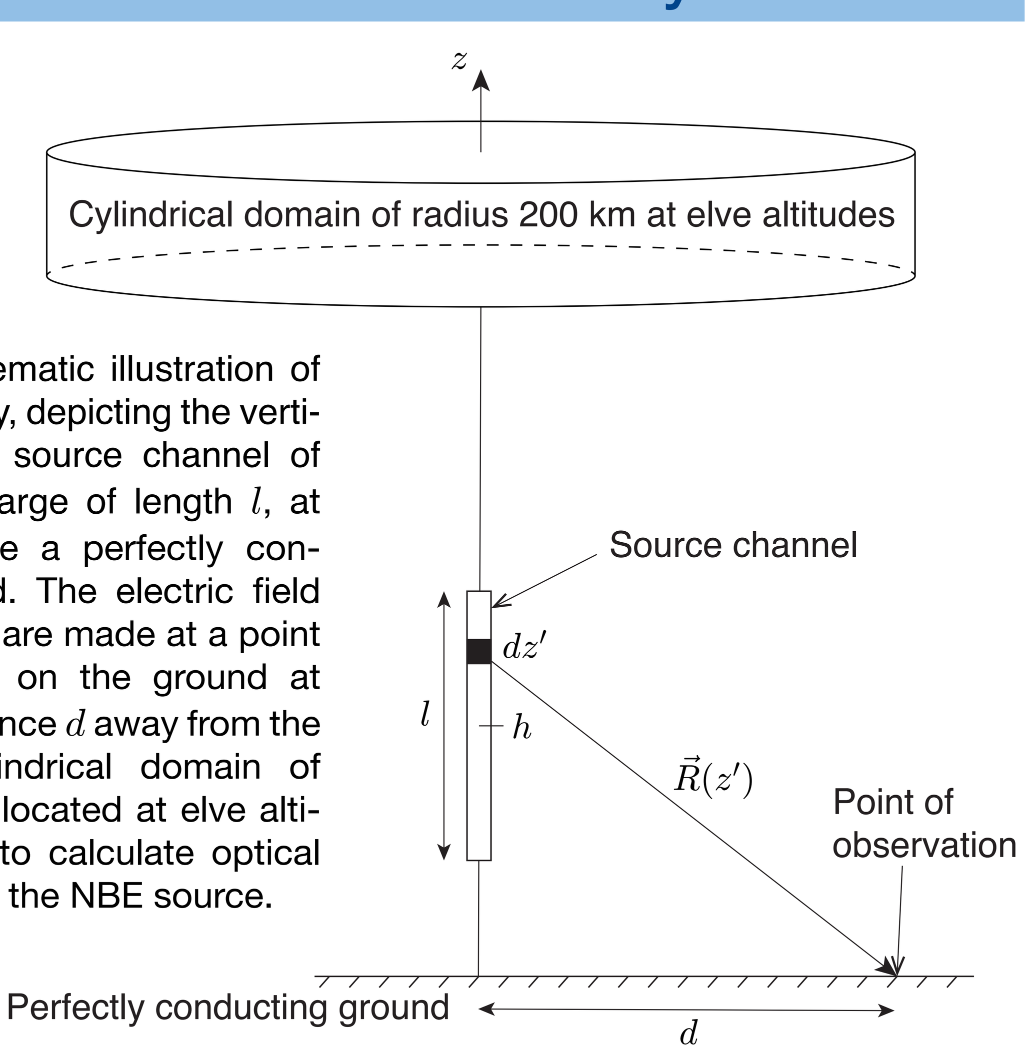

Figure 2. Schematic illustration of model geometry, depicting the vertical conducting source channel of the NBE discharge of length l, at height h above a perfectly conducting ground. The electric field measurements are made at a point of observation on the ground at horizontal distance d away from the source. A cylindrical domain of radius 200 km located at elve altitudes is used to calculate optical emissions from the NBE source.

3. Source Current Extraction

We use an NBE observed by Eack [GRL, 31, L20102, 2004], for which electric fields were measured both in the near field (d = 2.8 km) and the far field (d = 200 km). The waveforms used here (shown in Figure 3) come from the model of Watson and Marshall [GRL, 34, L04816, 2007].

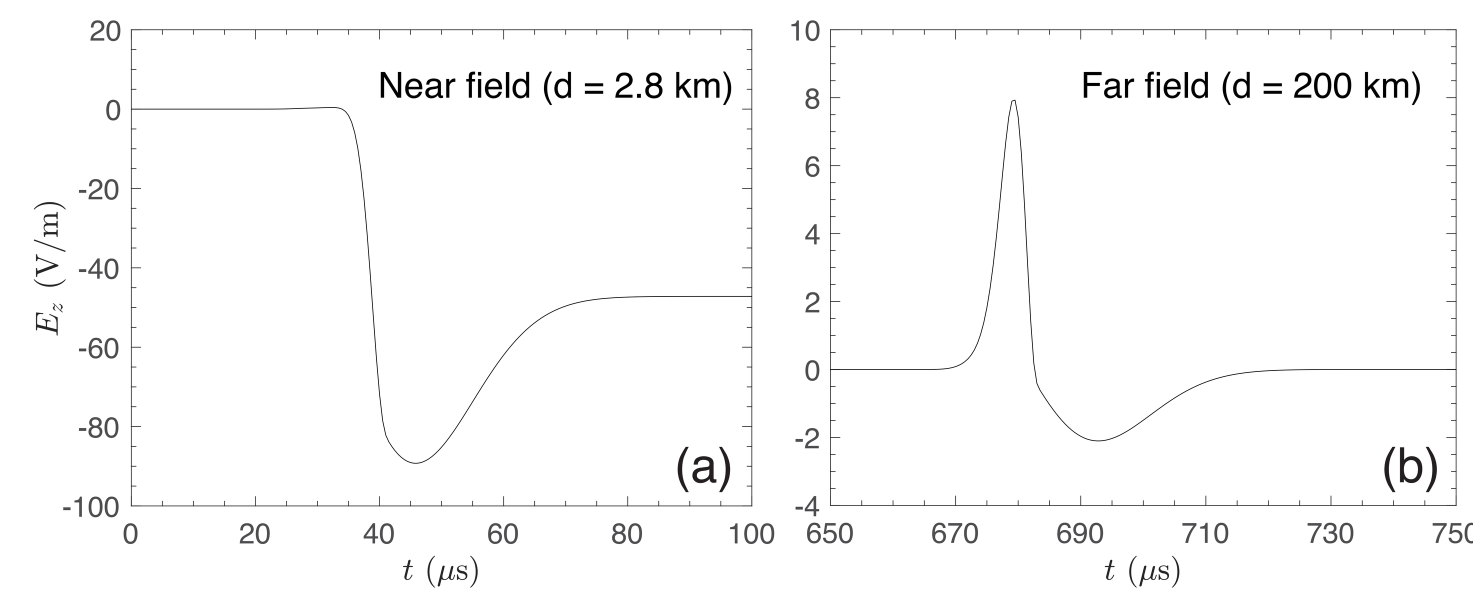

Figure 3. NBE electric field waveforms observed in (a) the near field (d = 2.8 km), and (b) the far field (d = 200 km).

The electric field spectrum observed at a point on the ground from a linear vertical conducting source is given by

$$E_z(\omega) = -\frac{j\eta}{2\pi\beta}\int_{h-l/2}^{h+l/2} I(z',\omega)\left[G_1 + {z'}^2 G_2\right] e^{-j\beta R} dz',$$

where η is the characteristic impedance of free space, $\beta = \omega/c$ is the phase constant, $I(z,\omega)$ is the spectrum of source current $I(z,t)$ in the frequency domain, that is, $I(z,\omega) = \mathcal{F}[I(z,t)]$, where $\mathcal{F}$ denotes Fourier transform, and

$$G_1 = \frac{-1 - j\beta R + \beta^2 R^2}{R^3}, \quad \text{and} \quad G_2 = \frac{3 + j3\beta R - \beta^2 R^2}{R^5}.$$

The current is modeled in the following manner

$$I(z,t) = g(z)i(t), \quad g(z) = \cos\left(\pi(z-h)/l\right), \quad z \in [h - l/2, h + l/2].$$

This current polarizes the channel similar to a dipole, with one half of the channel being positively charged, and the other half negatively charged. The source-propagation-observer system forms a linear time-invariant system, and the current $i(t)$ can be recovered using the field impulse response E_z^{IR} as

$$i(t) = \mathcal{F}^{-1}\left[\frac{\mathcal{F}[E_z(t)]}{E_z^{\mathrm{IR}}(\omega)}\right].$$

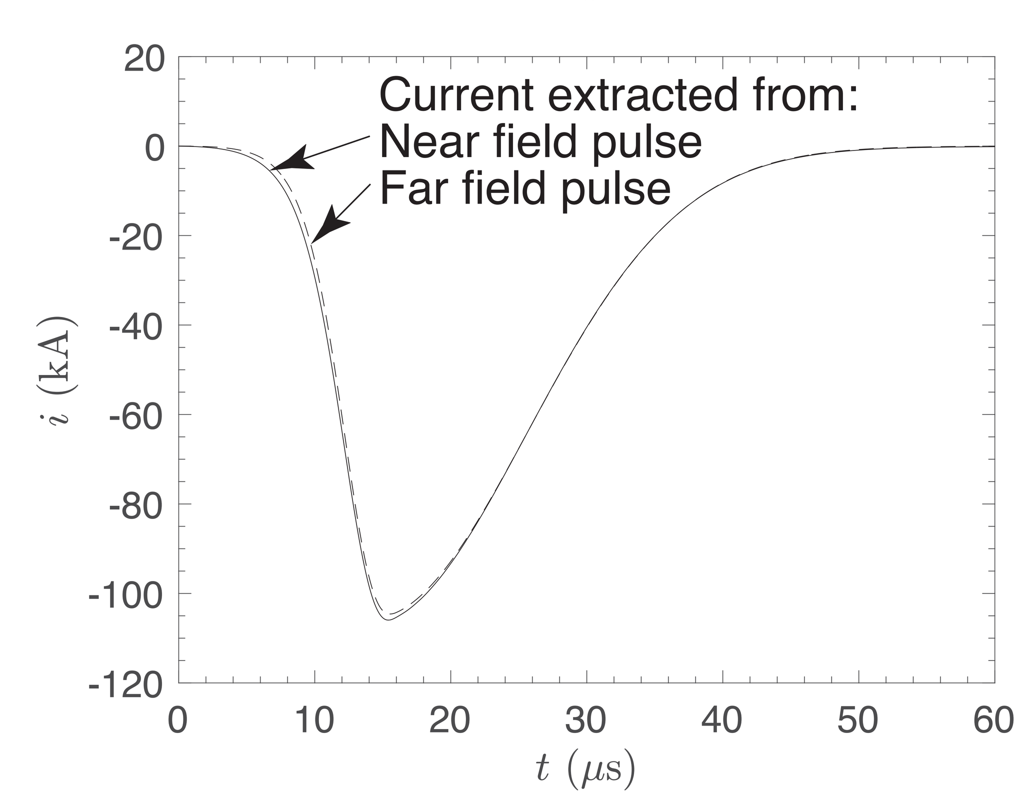

Figure 4. The current $i(t)$ recovered from the NBE waveforms of Figure 3 using the methodology described, with parameters $h = 7$ km, and $l = 600$ m.

4. Optical Emissions at Elve Altitudes

Using the NBE source current from Figure 4, we can calculate the radiated electric field in the cylindrical domain at elve altitudes, and consequently the optical emissions. The chemical reactions considered here are given in Table 1. The intensity of each optical emission in Rayleighs is given by:

$$I_m = 10^{-6}\int_\Gamma A_m n_m \, d\Gamma$$

where n_m [1/cm³] is the number density of excited particles in state m, A_m [1/s] is the radiative transition frequency, and the integral is taken along the horizontal line of sight Γ [cm]. We calculate optical emissions from the first $(B^3\Pi_g \rightarrow A^3\Sigma_u^+)$ and second $(C^3\Pi_u \rightarrow B^3\Pi_g)$ positive band systems of N_2. Assuming steady-state, i.e., $\partial n_m/\partial t = 0$, the densities of the $N_2(B)$ and $N_2(C)$ states, n_1 and n_2, respectively, are given by

$$n_2 = \tau_2 \nu_2 n_e, \quad \text{and} \quad n_1 = \tau_1\left[n_2 A_2 + (k^2_{N_2}/2) N_{N_2} n_2 + \nu_1 n_e\right],$$

where $\tau_m = (A_m + k^m_{N_2} N_{N_2} + k^m_{O_2} N_{O_2})^{-1}$ is the total lifetime of state m.

We use the following vertical profile for the electron number density n_e [Marshall et al., GRL, 42, 6112, 2015]:

$$n_e = n_{e0} e^{-0.15h'} e^{(\alpha - 0.15)(z - h')}$$

where,

$$n_{e0} = 1.43 \times 10^7 \ \mathrm{cm}^{-3}$$
$$\alpha = 0.8 \ \mathrm{km}^{-1}$$
$$h' = 87 \ \mathrm{km}$$

Table 1. List of chemical reactions considered [da Silva and Pasko, JGR, 118, 13,561, 2013, and references therein]

Reactions	Frequency (1/s) or Rate Constant (cm³/s)
$N_2 + e \longrightarrow N_2(B) + e$	υ_1 (1/s) (from BOLSIG+)
$N_2 + e \longrightarrow N_2(C) + e$	υ_2 (1/s) (from BOLSIG+)
$N_2(B) \longrightarrow N_2(A) + h\upsilon$ (1PN$_2$)	$A_1 = 1.7 \times 10^5$ 1/s
$N_2(C) \longrightarrow N_2(B) + h\upsilon$ (2PN$_2$)	$A_2 = 2.0 \times 10^7$ 1/s
$N_2(B) + O_2 \longrightarrow N_2 + O + O$	$k^1_{O_2} = 3 \times 10^{-10}$ cm³/s
$N_2(B) + N_2 \longrightarrow N_2(A) + N_2$	$k^1_{N_2} = 10^{-11}$ cm³/s
$N_2(C) + O_2 \longrightarrow N_2 + O + O(^1D)$	$k^2_{O_2} = 2.5 \times 10^{-10}$ cm³/s
$N_2(C) + N_2 \longrightarrow N_2(B) + N_2$	$k^2_{N_2}/2 = 10^{-11}$ cm³/s
$N_2(C) + N_2 \longrightarrow N_2(a') + N_2$	$k^2_{N_2}/2 = 10^{-11}$ cm³/s

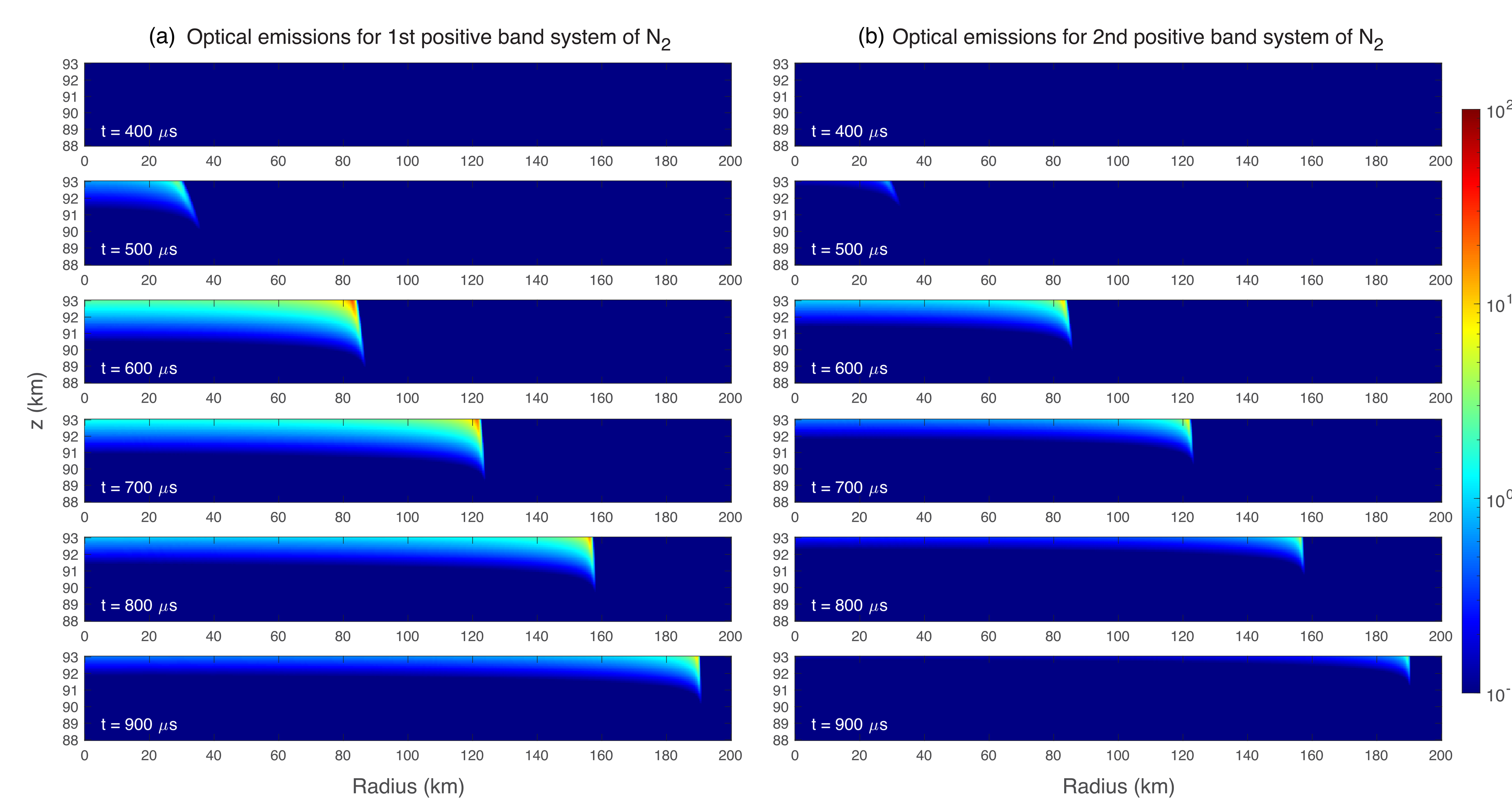

Figure 5. Snapshots of optical emissions in units of mega-Rayleighs (MR) at several instances of time for the (a) 1st and (b) 2nd positive band systems of N_2 in the cylindrical domain at elve altitudes.

5. Conclusion

The source current recovered for the NBE results in observable first-order estimates of optical emissions at elve altitudes, providing further support to the association between NBEs and elves.

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