Understanding the Dynamics of Upward Propagating Sprite Streamers

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Introduction

Sprites occur in the 40-90 km altitude range and manifest an electrodynamic coupling between the troposphere and mesosphere/lower ionosphere. They are driven by the electrostatic field induced by an intense lightning stroke. Figure 1 shows a typical sprite, with positive streamers, toward the bottom of the image, as the thinner, less optically-intense, tree-like structures and negative streamers, toward the top of the image, as the diffuse, bright structures [1]. Streamers are highly non-linear space charge waves that ionize the medium through which they propagate, forming filamentary, cold-plasma channels.

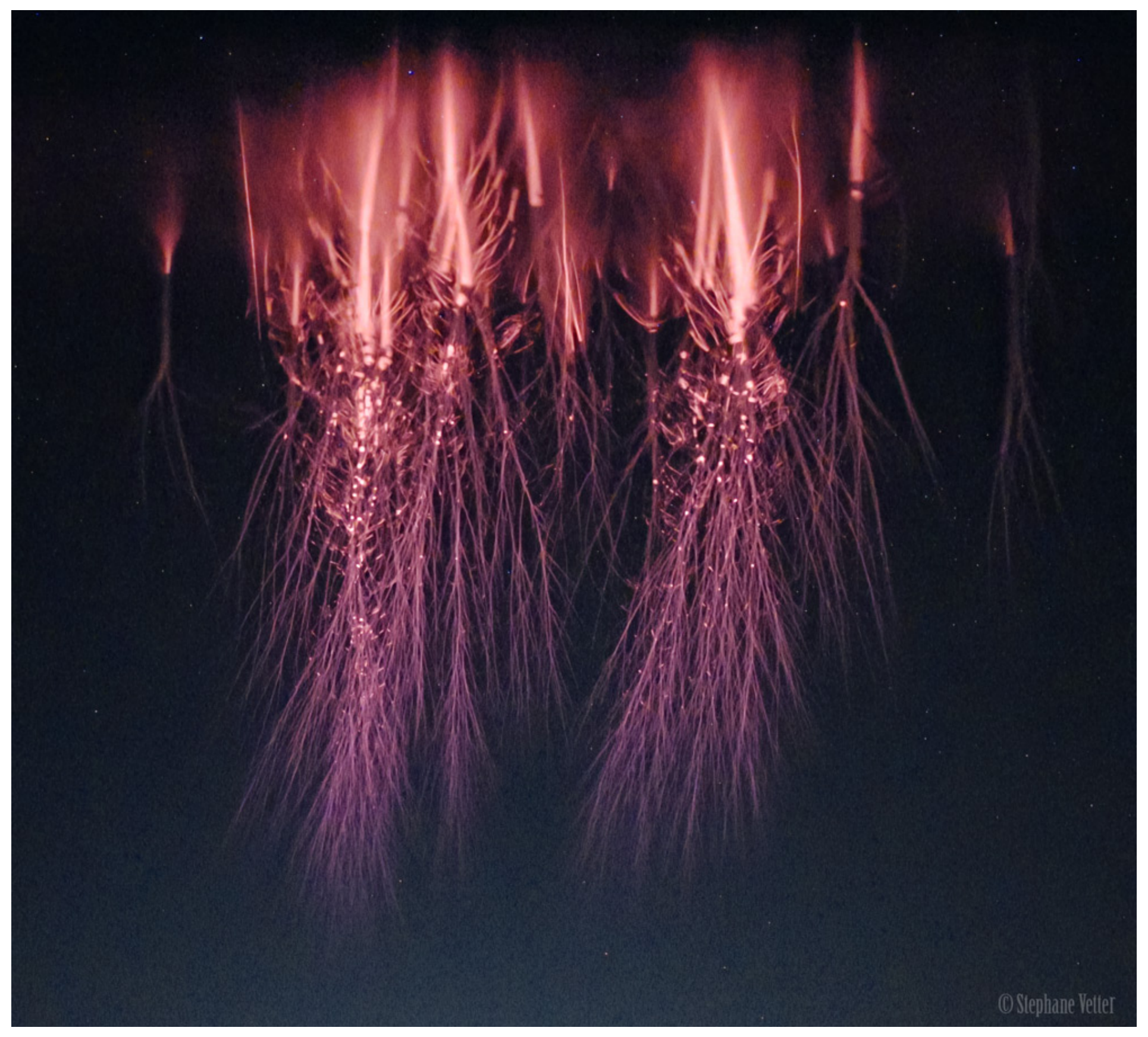

Figure 1: High resolution image of a sprite. *Vetter, Stephane. "Sprite Lightning." https://science.nasa.gov/sprite-lightning-hd*

Motivation

Figure 2 shows recently published optical observations of upward sprite streamers interacting with the D-region of the ionosphere [2].

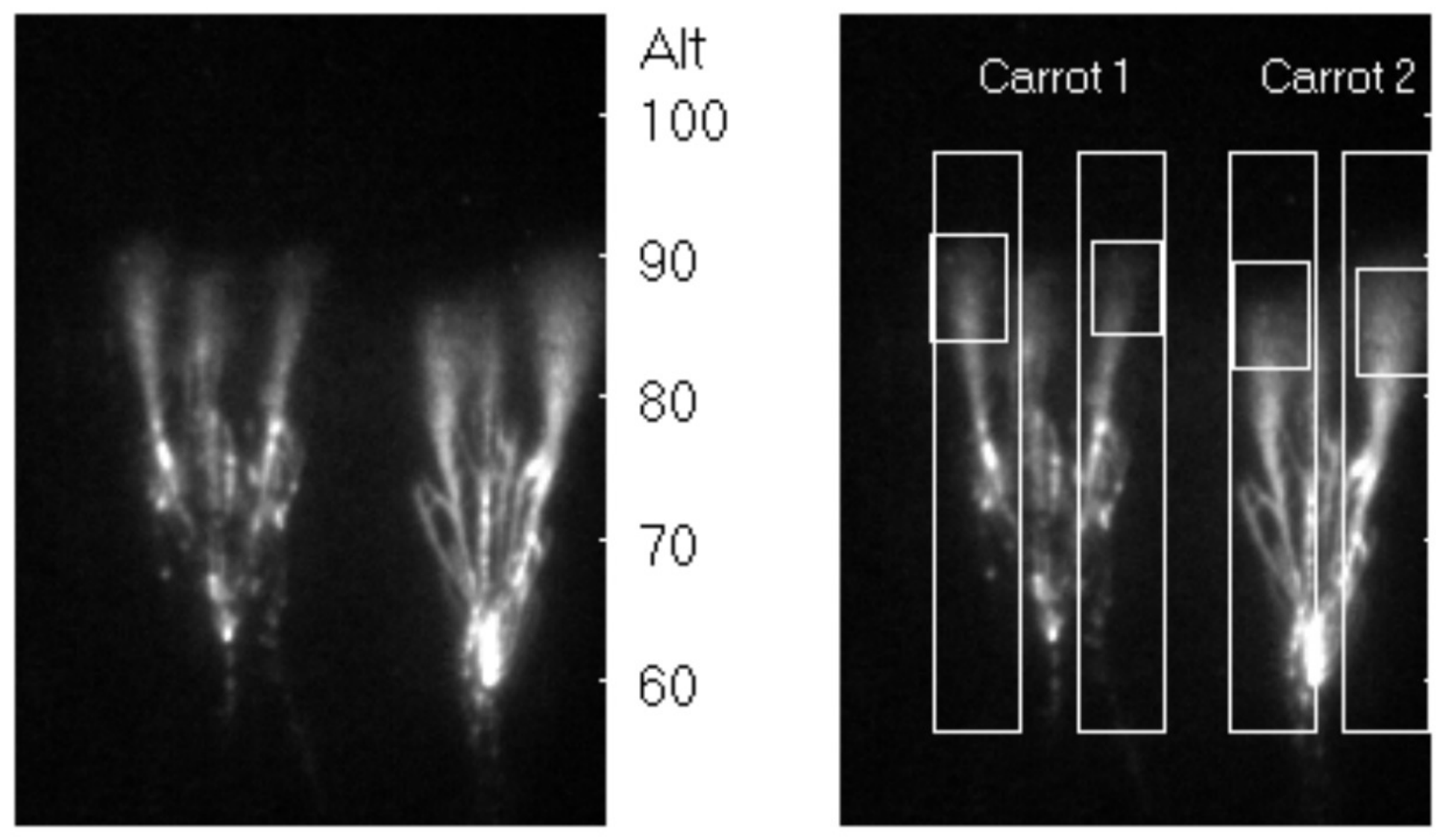

Figure 2: Upward sprite streamers interacting with the ionosphere. *Image taken from* [2].

The top row of strip images in Figure 3, shows the rightmost streamer head from Figure 2, growing and brightening as it propagates upward, transforming from a compact, bright structure to a diffuse, dimmer structure. Using the time constant of optical decay, inferred from the observations, *Stenbaek-Nielsen et al., 2023* was able to estimate the approximate electron density of the ionosphere's D-region. These types of observations, therefore, allow for a method to better understand the dynamics of the ionosphere above a thunderstorm.

Objectives

With the estimated characteristics deduced from recent optical observations of streamer-ionosphere interaction events [2], we use a numerical model to answer the following:

- How can we exploit the observations to infer information about the ionosphere?
- What causes the streamer head optical decay?
- What causes the streamer head field to decay?

Numerical Model

We use a three-dimensional, axisymmetric fluid model to simulate a negative streamer at an altitude consistent with observations and inside an electric field of a strength and geometry similar to that caused by a typical parent lightning discharge. As the negative streamer propagates upward, it grows and interacts with an electron number density distribution formulated using the estimated values of the ionospheric region in [2].

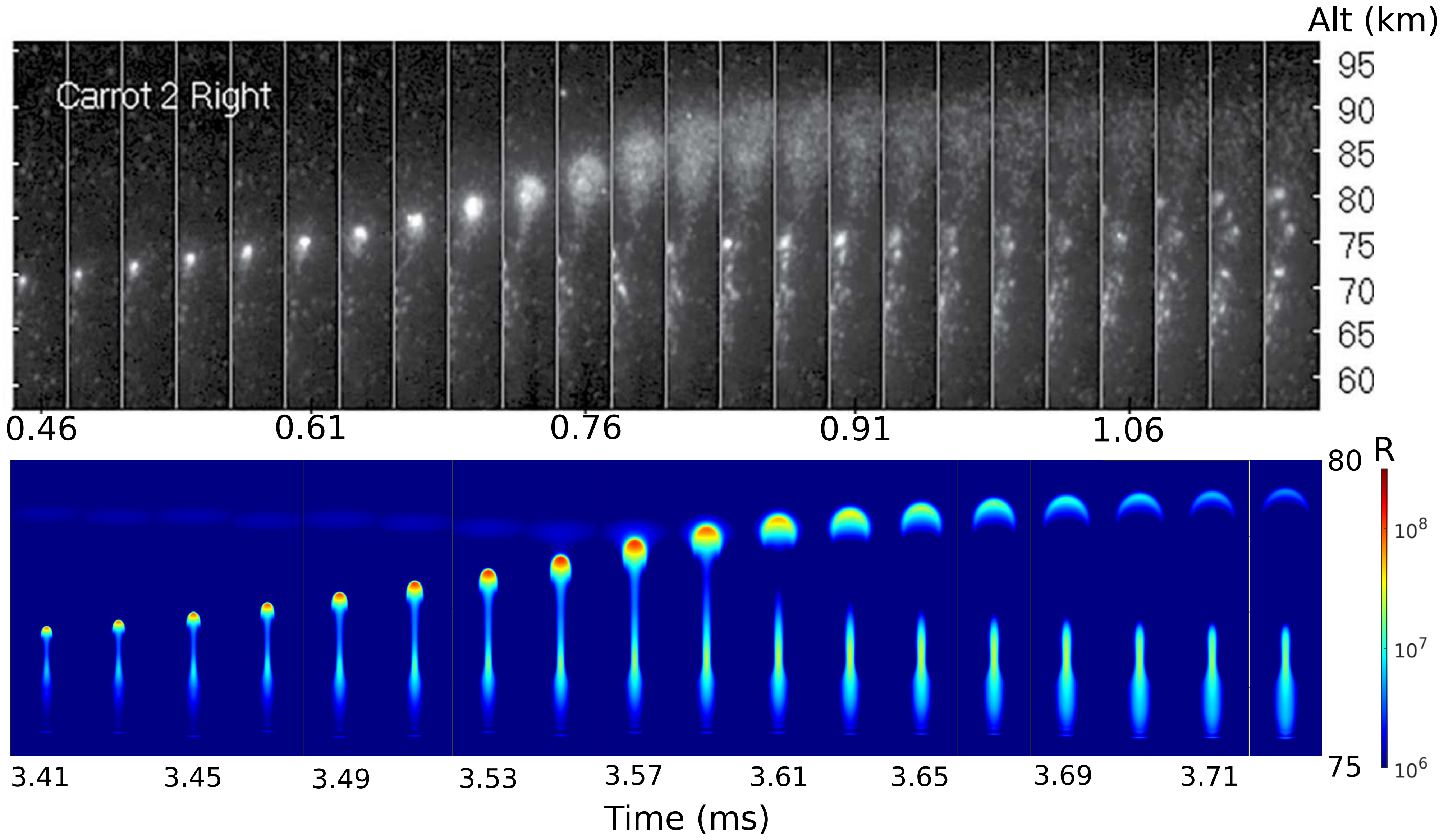

Figure 3: Top row: Strip images of optical observations from [2]. Bottom row: Strip images of $1PN_2$ from simulation results.

Result 1

The time constant of optical decay found in [2], was between 80-100 μs. Applying

$$\frac{dn}{dt} + \frac{n}{\tau} = \nu n_e, \qquad (1)$$

which describes evolution of the number density of the excited species in the $1PN_2$ emission band system, we analyze the optical decay found in the simulation results, shown in Figure 3. Because of negligible quenching effects, the natural lifetime τ of the excited state is 5.9 μs, therefore, we analyze the source term to understand the optical decay.

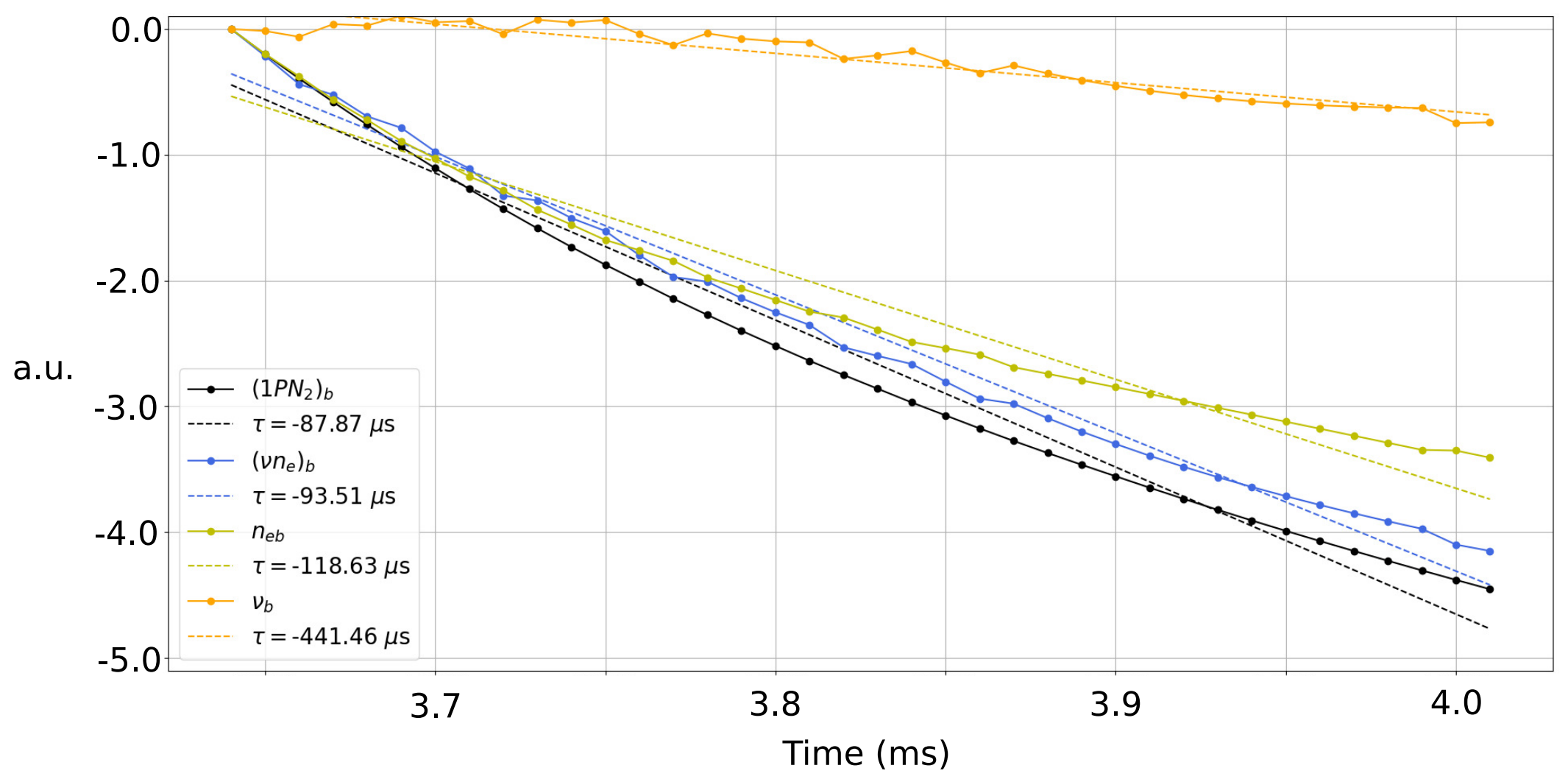

Figure 4: Optical intensity from $1PN_2$, source term from equation (1), ν, and n_e at location of maximum brightness plotted over the approximate time of decay.

Result 2

From Figure 4, we see that n_e decrease is the dominant process causing the optical decay. To understand the rate of n_e decrease, we apply to it the exponentiated ionization integral,

$$n_e = n_0 \exp\left[\int_{z_h}^{z_p} \frac{\nu_i - \nu_a}{v_{st} \pm v_{dr}} dz\right], \qquad (2)$$

with each variable from the simulation results, except n_e (on the left hand side). Figure 5 shows that, after the time of maximum brightness t ≈ 3.57 ms, the equation describes well, in 1D, the rate of n_e decrease.

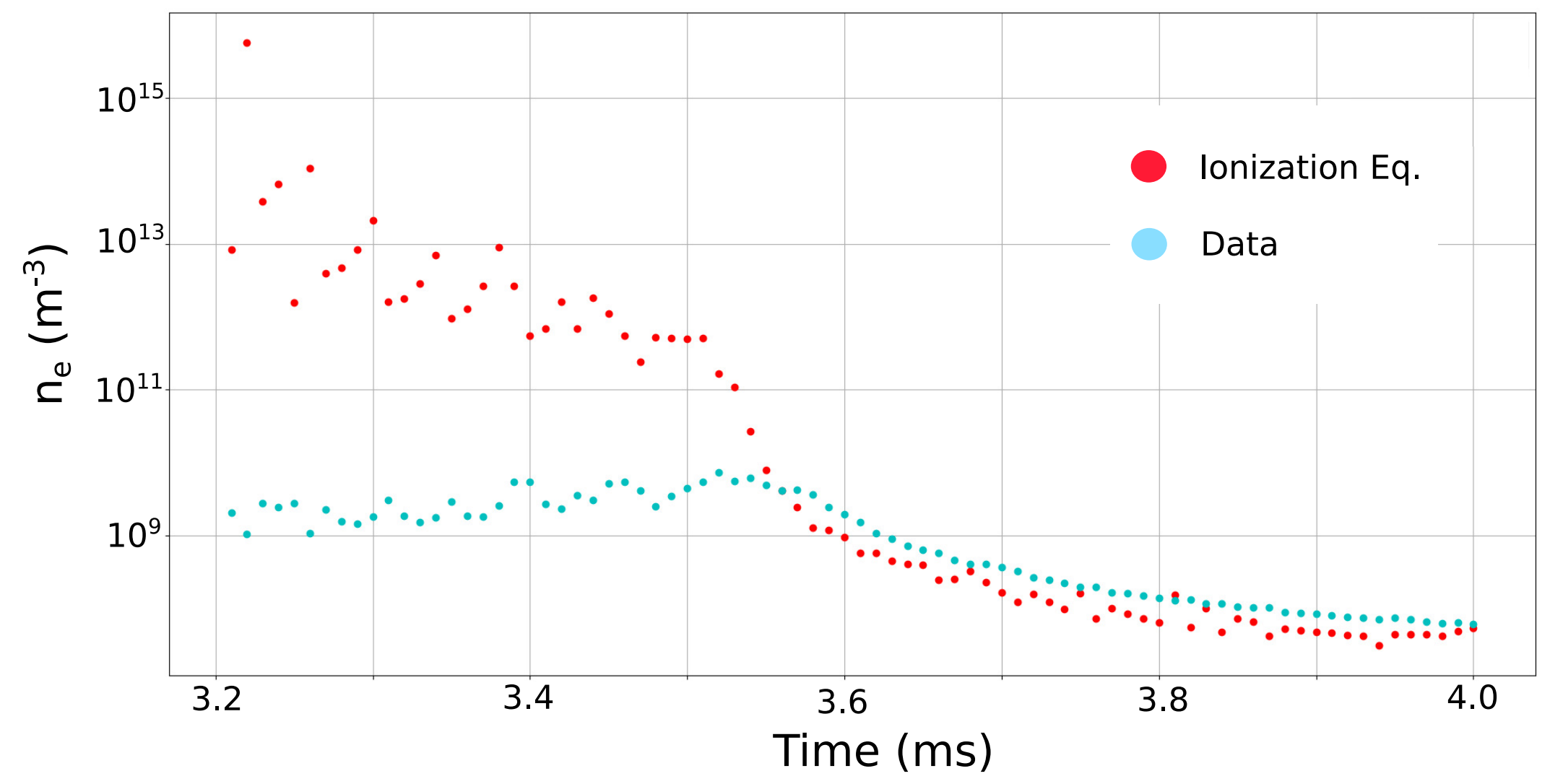

Figure 5: Plotting the result, n_e, from equation (2) above.

Result 3

The n_e is driven by the strong electric field region ahead of the streamer. We use two approximations to understand the strong field region dynamics. The maximum electric field of the streamer head, E_h, can be related by multiplying the maximum space charge density, ρ_{max}, and space charge width, R_ρ [3],

$$E_h \sim \rho_{max} R_\rho. \qquad (3)$$

Since a streamer is a conductive body, it tends to carry a high potential at its head. The potential drop, ΔU_h over R_ρ, can be used to determine E_h by [4],

$$E_h \sim \Delta U_h R_\rho^{-1}. \qquad (4)$$

Taking these two arguments into account we compare in Figure 6 how each, alongside their constituents, changes over the time of optical decay. We determine that the broadening R_ρ and decreasing ρ_{max} weaken the field at the greatest rate.

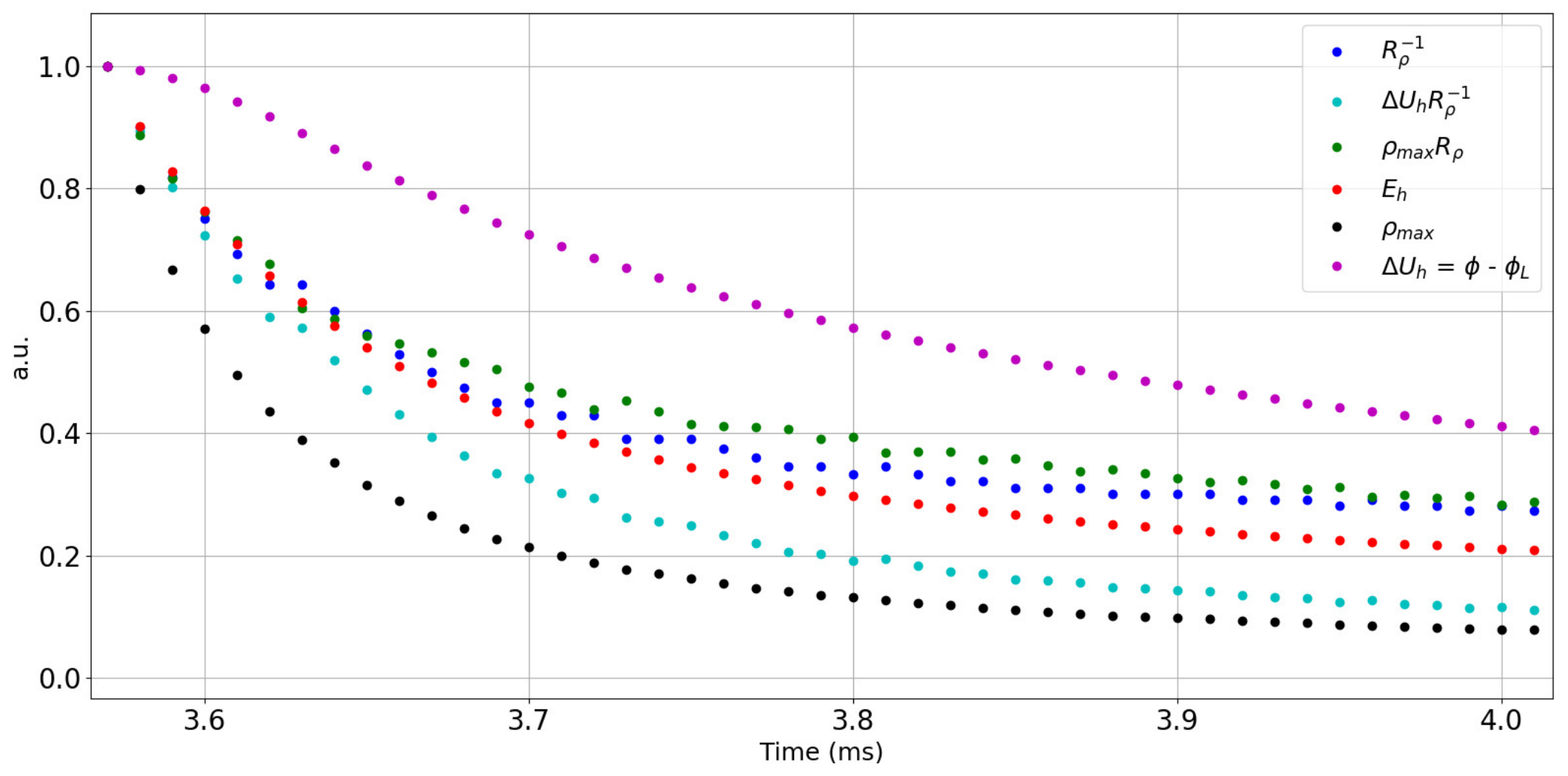

Figure 6: Different values pertaining to the streamer head electric field plotted over time. All are normalized to their value at t = 3.57 ms.

Conclusions

- Electron number density dynamics, driven by the strong field region, has the greatest affect on optical decay.
- The strong electric field decays due to the widening space charge region and decreasing space charge density.

Implications

Through the analysis of the simulated streamer-ionosphere interaction, we further the understanding of the electron number density distribution and dynamics of the lower D-region above a thunderstorm, near a sprite. With fine temporal-resolution optical observations of sprites, the presented research allows for a method of ionospheric remote-sensing.

References/Acknowledgements

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