The Electrical Impact of Sprite Halos on the Nighttime Lower Ionosphere

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Abstract

Significant electrostatic (ES) fields although not strong enough to produce transient luminous events (TLEs) such as elves, halos, and sprites, could be established in the lower ionosphere by underlying thunderstorms [*Salem et al.*, GRL., 42(6), 2015]. We recently found that the nighttime lower ionospheric height measured by using the VLF wave reflection technique can be increased due to the effects of the thunderstorm ES field [*Salem et al.*, GRL., 43(1), 2016]. In this study, we continue further to investigate the ionospheric effects of the quasi-electrostatic (QE) fields of cloud-to-ground (CG) lightning flashes, which can be much stronger than the thunderstorm ES field and sometimes trigger halos. Halos are relatively homogeneous glows centered on 75-85 km altitude with a horizontal extent of tens of kilometers and a vertical thickness of several kilometers. They typically appear within a few milliseconds of intense CGs. Our study is conducted by combining a one dimensional plasma discharge fluid model with a simplified ionospheric ion chemistry model described by *Liu* [JGR., 117, A03308, 2012]. The modeling results of the lower ionospheric response to the lightning-induced QE fields are analyzed to investigate the role of halos in early VLF perturbations (early VLF events). Early VLF events have been observed coincidentally in time with a variety of TLEs [e.g., *Moore et al.*, JGR, 108, 1363, 2003; *Marshall et al.*, JGR, 111, D19108, 2006; *Cotts and Inan*, GRL, 34, L14809, 2007; *Haldoupis et al.*, JGR, 14, A00E04, 2009; *Haldoupis et al.*, GRL, 39, L16801, 2012]. However, the physical processes responsible for their production have not yet been conclusively identified. Finally, we compare the modeling results with recent studies on the recovery timescales of early VLF events [e.g., *Kotovsky and Moore*, GRL 43(3), 2016].

The Nighttime Ion Chemistry Model of the Lower Ionosphere

The simplified ion chemistry used in this study is described by *Liu* [2012]. The charged and neutral species are shown in Figure 1. The ion reactions taken into account are listed in Table 1.

Reaction No.	Reactants	→	Products	Rate constant ($m^{3(n-1)}s^{-1}$)
Ionization:				
R1	$Q + M$	→	$e + M^+ + Q$	1×10^{-25}
Electron Impact Reactions:				
R2	$e + M$	→	$e + e + M^+$	$f(\bar{\epsilon}) \equiv f(E/N)$
R3	$e + M(O_2)$	→	$M^-(O_2^-) + M_{ac}(O)$	$f(\bar{\epsilon}) \equiv f(E/N)$
R4	$e + M + M$	→	$M^- + M$	$f(\bar{\epsilon}) \equiv f(E/N)$
Recombination (electron-ion):				
R5	$e + M^+$	→	$M_{ac} + M_{ac}$	3×10^{-13}
R6	$e + M_x^+$	→	$M + M$	1×10^{-12}
Recombination (ion-ion):				
R7	$M^- + M^+$	→	$M + M$	5×10^{-13}
R8	$M^- + M_x^+$	→	$M + M_x$	5×10^{-13}
R9	$O^- + M^+$	→	$M_{ac}(O) + M$	5×10^{-13}
R10	$O^- + M_x^+$	→	$M_{ac}(O) + M_x$	5×10^{-13}
R11	$M_x^- + M^+$	→	$M_x + M$	5×10^{-13}
R12	$M_x^- + M_x^+$	→	$M_x + M_x$	5×10^{-13}
R13	$M^- + M^+ + M$	→	$M + M + M$	5×10^{-37}
R14	$M^- + M_x^+ + M$	→	$M + M_x + M$	5×10^{-37}
R15	$O^- + M^+ + M$	→	$M_{ac}(O) + M + M$	5×10^{-37}
R16	$O^- + M_x^+ + M$	→	$M_{ac}(O) + M_x + M$	5×10^{-37}
R17	$M_x^- + M^+ + M$	→	$M_x + M + M$	5×10^{-37}
R18	$M_x^- + M_x^+ + M$	→	$M_x + M_x + M$	5×10^{-37}
Ion Conversion:				
R19	$M^+ + M + M$	→	$M_x^+ + M$	2×10^{-42}
R20	$M_x^+ + M$	→	$M^+ + M + M$	2×10^{-22}
R21	$M_x^+ + M_{ac}$	→	$M^+ + M$	1×10^{-16}
R22	$M^- + M + M$	→	$M_x^- + M$	1×10^{-43}
R23	$O^- + M + M$	→	$M_x^- + M_{ac}(O)$	3×10^{-43}
R24	$M_x^- + M_{ac}$	→	$M^- + M$	2×10^{-16}
Electron Detachment:				
R25	$M^- + M$	→	$e + M + M$	2×10^{-29}
R26	$M^- + M_{ac}$	→	$e + M + M_{ac}$	2.5×10^{-16}
R27	$O^- + M$	→	$e + M_x$	$f(\bar{\epsilon}) \equiv f(E/N)$
R28	$O^- + M$	→	$e + M_x$	1×10^{-21}
R29	$O^- + M_{ac}$	→	$e + M$	4×10^{-16}

Table 1. The set of reactions. The rate constants are obtained from the work of *Liu* [2012]. The value of n is 2 and 3 for two-body and three-body reactions, respectively.

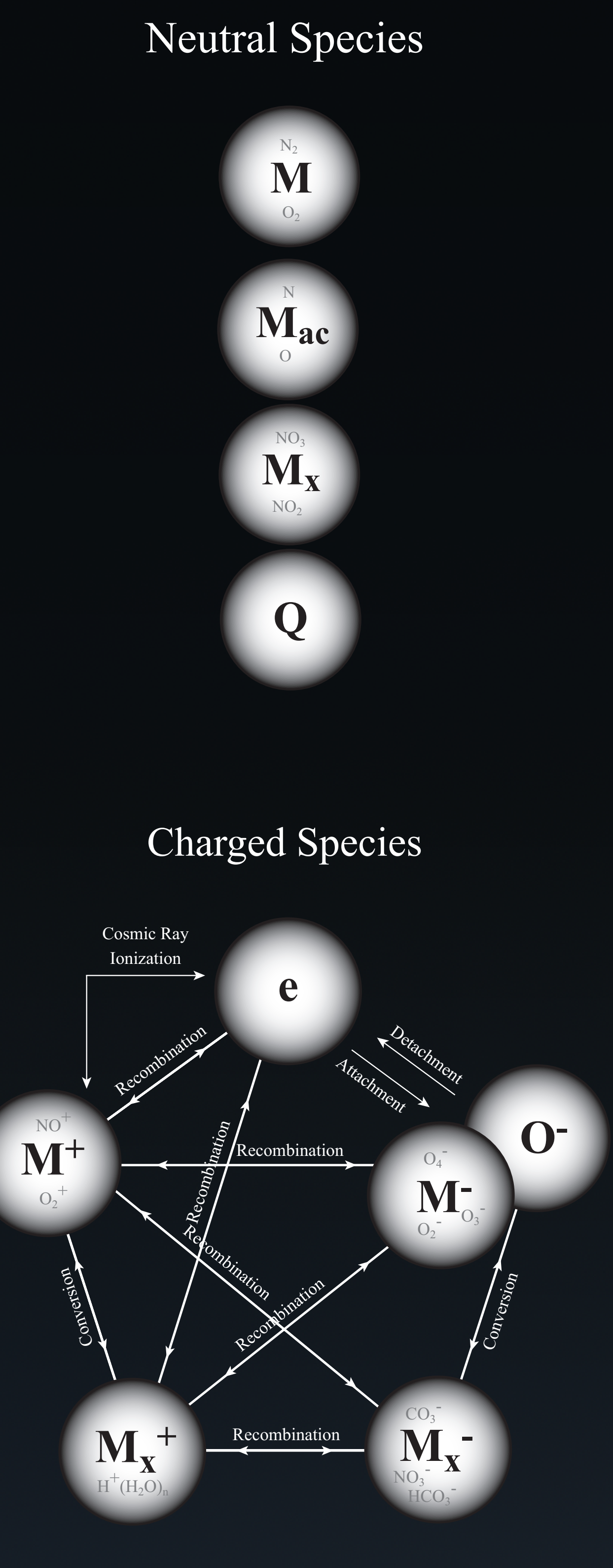

Figure 1. Model Species

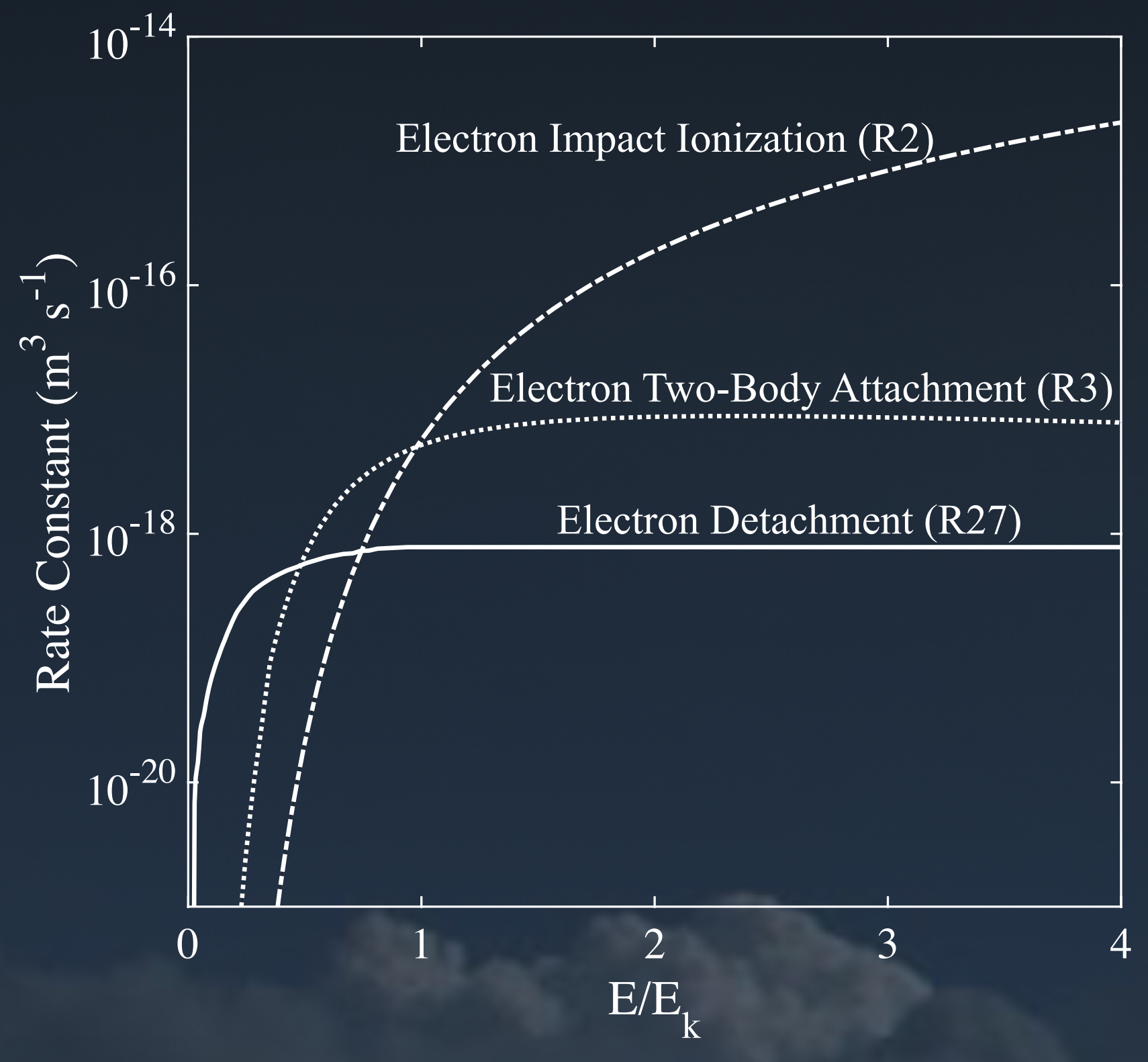

Figure 2. The rate constants for R2, R3, and R27.

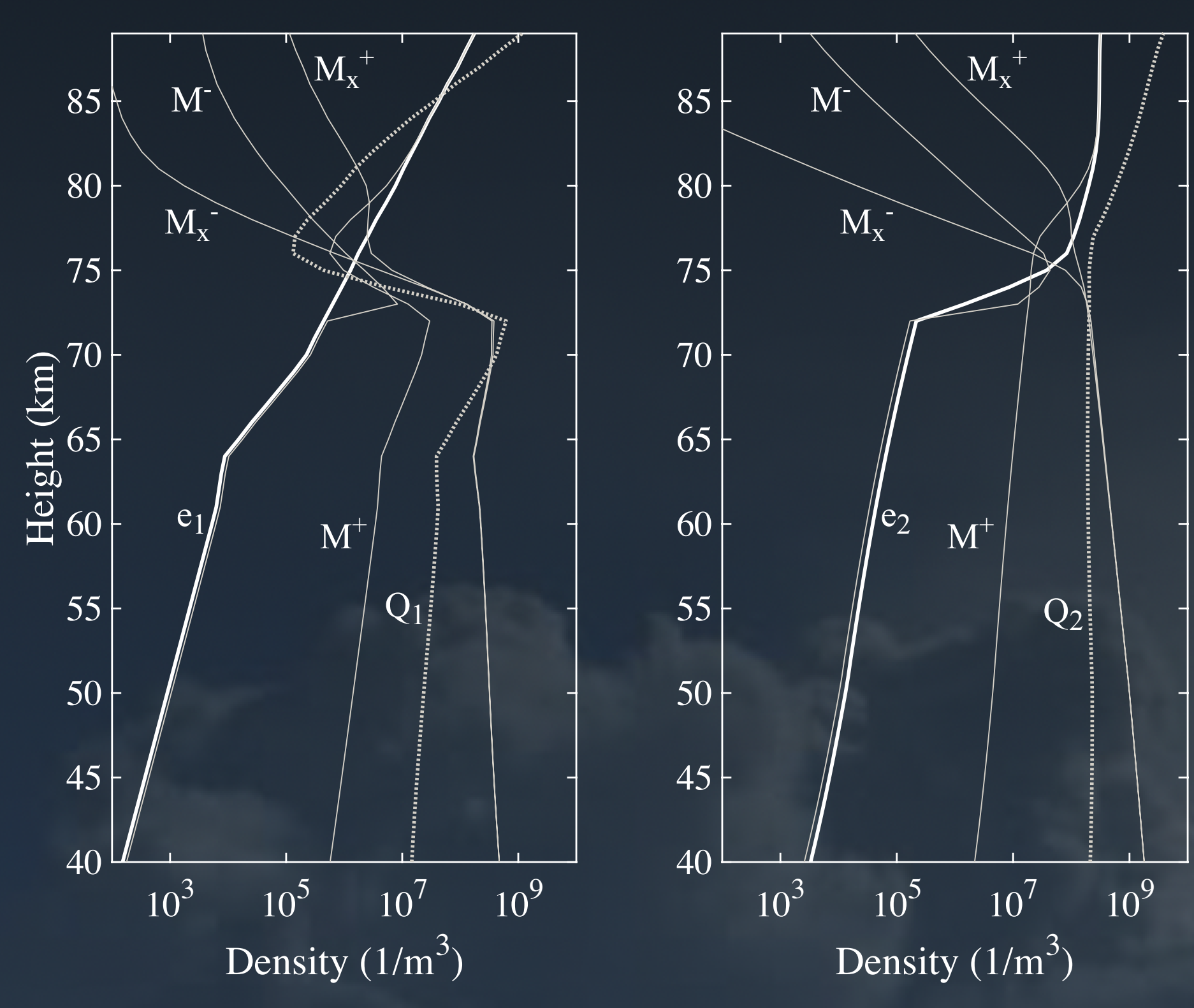

Figure 3. The ambient density profiles with the sources of ionization (Q_1, Q_2) used in this study [*Salem et al.*, 2015, 2016].

1-D Sprite Halo Model

The ionospheric response to the QE fields produced by CG flashes is modeled by solving the continuity equation coupled with Poisson's equation:

$$\frac{\partial n_i}{\partial t} + \nabla \cdot \vec{J} = S_i - L_i \qquad (1)$$

$$\nabla^2 \phi = -\frac{\rho}{\varepsilon_0} \qquad (2)$$

Modeling Results

The charge transfer (CMC) by CGs as a function of time (t) and and the time scale (τ) of the CG flash is described by [*Liu et al.*, 2016]:

$$\mathrm{CMC}(t) = \frac{\mathrm{CMC}_0}{2}\left[1 + \tanh\left(\frac{t - t_0}{\tau}\right)\right]$$

The reflection of ELF/VLF waves in the lower ionosphere is assumed to occur at the altitude where $\omega = \omega_p/\upsilon$ [*Salem et al.*, 2016].

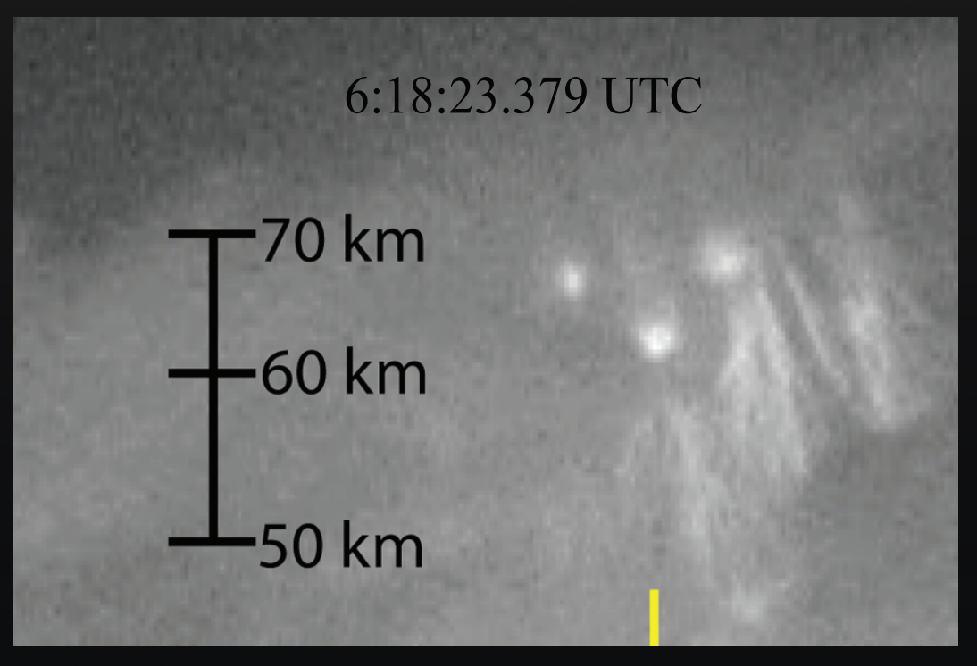

Figure 4. (Above) A negative sprite observed on 12 September 2012 above a Florida thunderstorm. It was produced by an impulsive -CG with CMC_0 as large as 1302 C km and a time scale of 0.145 ms [*Liu et al.*, 2016; *Boggs et al.*, 2016].

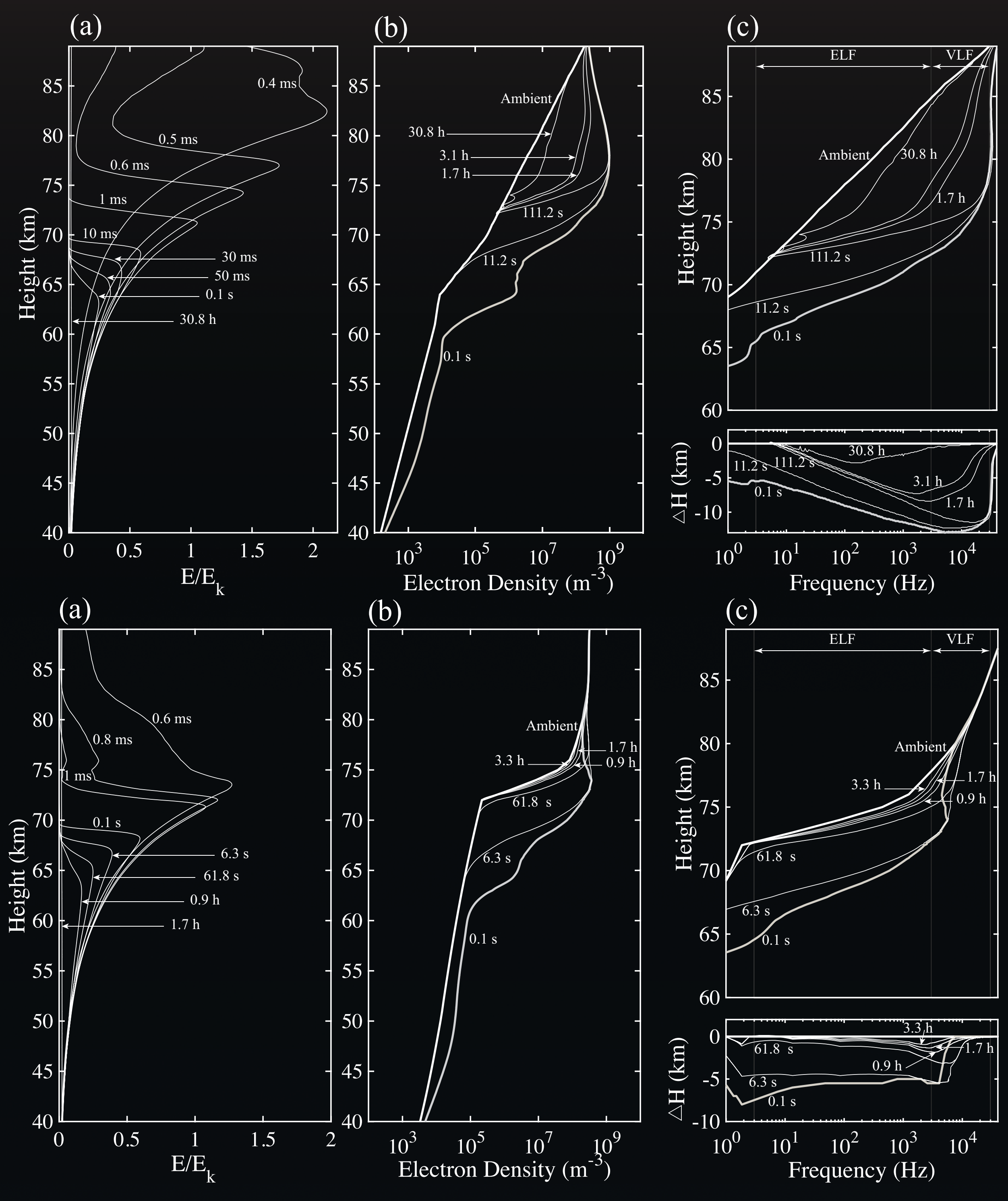

Figure 5. (Right) Modeling results of a halo caused by an impulsive -CG stroke causing the sprite shown in Figure 4. Top and bottom panels show the results obtained with the two ambient profiles given in Figure 3, respectively. (a) Normalized electric field, (b) electron density, and (c) the nighttime ionospheric reference height and its change for various moments of time.

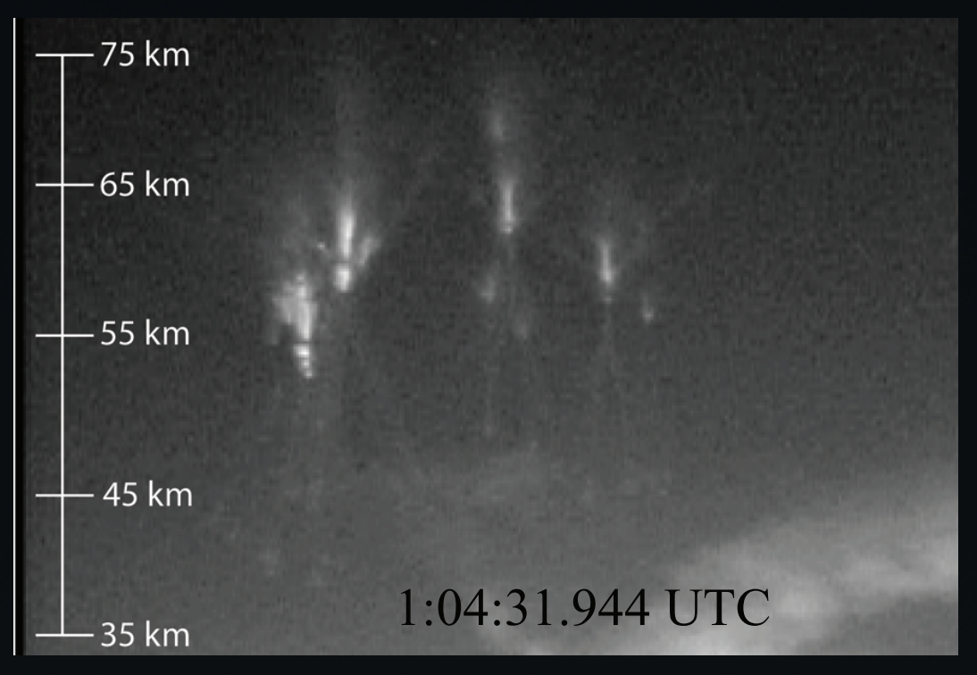

Figure 6. (Above) Another negative sprite observed on 12 September 2012. It was produced by an impulsive -CG with CMC_0 as large as 532 C km and a time scale of 0.175 ms [*Liu et al.*, 2016; *Boggs et al.*, 2016].

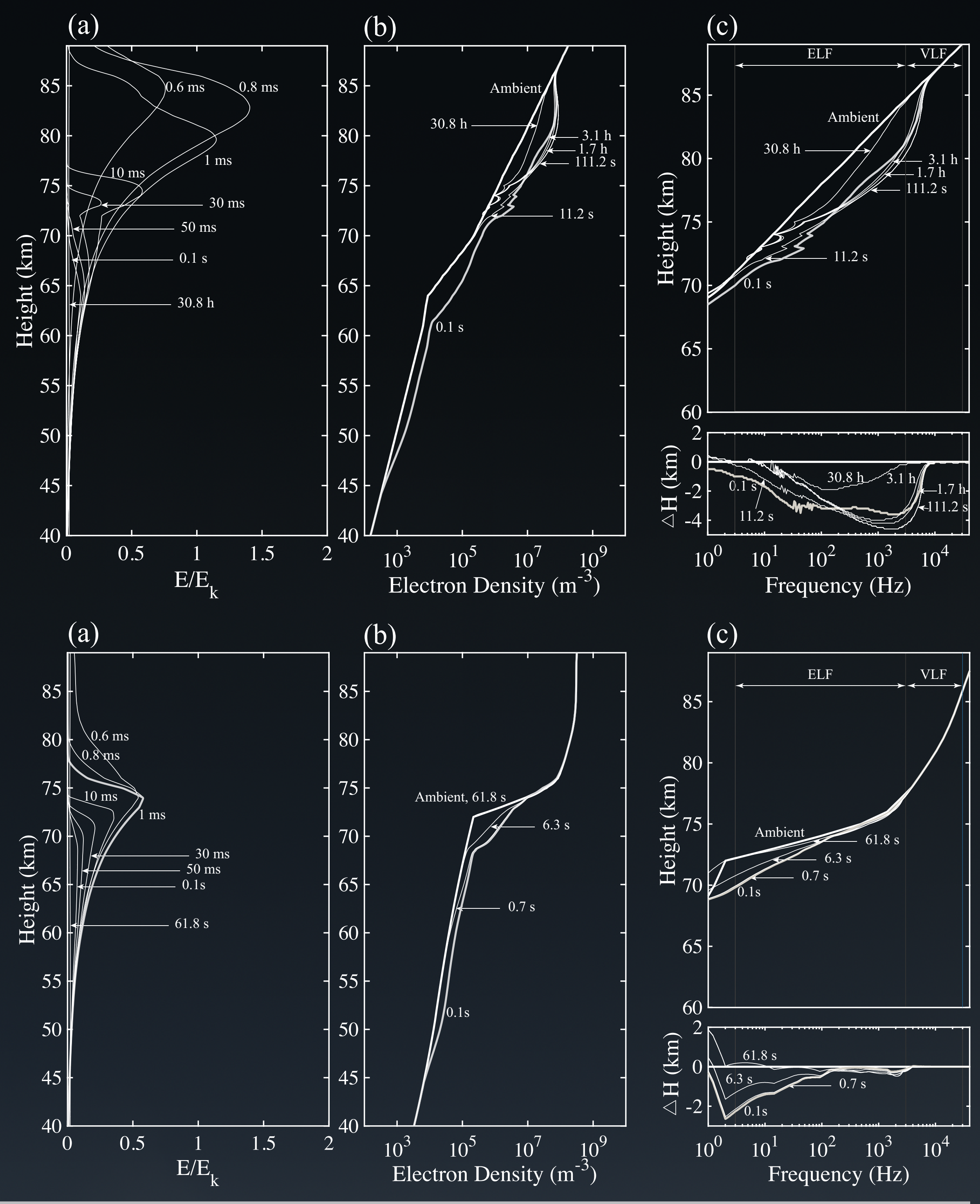

Figure 7. (Right) Modeling results of a halo caused by an impulsive -CG stroke causing the sprite shown in Figure 6. The quantities shown are the same as those in Figure 5.

Summary and Conclusions

1. A one-dimensional plasma discharge fluid model with multiple ion species is developed to model the ionospheric responses to lightning QE fields.
2. Different ambient electron density profiles can lead to significantly different impact on the lower ionosphere due to halos. Steeper ambient profile results in less enhancment in the ionospheric electron density.
3. More impulsive CGs result in greater enhancement in the ionospheric electron density.
4. The electron density enhancement due to impulsive CGs reachs its maximum in 0.1 s. Below ~75 km altitude, it recovers in a few seconds whereas the enhancement at altitude range ~75-80 km depends on the ambient density profile and can last for 10s of minutes to hours.
5. The changes in the reflection height of VLF waves due to impulsive CGs recover in 10s of minutes to hours, which can explain the long-recovery early VLF events. This time scale is in a good agreement with recent studies [e.g., *Kotovsky and Moore*, 2016] where more complex ion chemistry is used to explain the time scales of early VLF events.

Acknowledgments

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