Necessary Conditions for Initiation of Sprite Streamers

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I. Abstract

The initiation of sprite streamers remains an active topic of research to date. The two popular yet fundamentally different theories in this regard are: (i) electron density inhomogeneities in the lower ionosphere are not necessary for the inception of sprites and an artificial ionization seed does not need to be present in the model initially [*Luque* and *Ebert*, Nat. Geosci., 2, p. 757, 2009], and (ii) plasma irregularities are in fact required for sprite streamer formation [*Qin et al.*, Nat. Commun., 5, 3740, 2014; *Liu et al.*, Nat. Commun., 6, 7540, 2015; *Kosar et al.*, JGR, 117, A08328, 2012].

In this work, we will review both theories using a plasma fluid model in a two-dimensional axisymmetric cylindrical geometry and comment on numerical instabilities observed during certain simulations. In addition, we will study the effect of perturbations in the ambient atmospheric and ionospheric conditions on the halo and streamer dynamics [*Kohn et al.*, Plasma Sources Sci. Technol., 27, 015017, 2018]. We conclude with suggestions for further investigation of sprite inception.

III. Instability of Halo Front

- Sprite streamers emerge from a screening-ionization wave [*Luque* and *Ebert.* 2009].
- The collapse location is constant for various initial conditions.
- Collapse time instant depends on the spatial resolution of the grid and there is no sign of the halo collapsing into a sprite streamer at the same instant of time using the flux corrected transport (FCT) scheme.

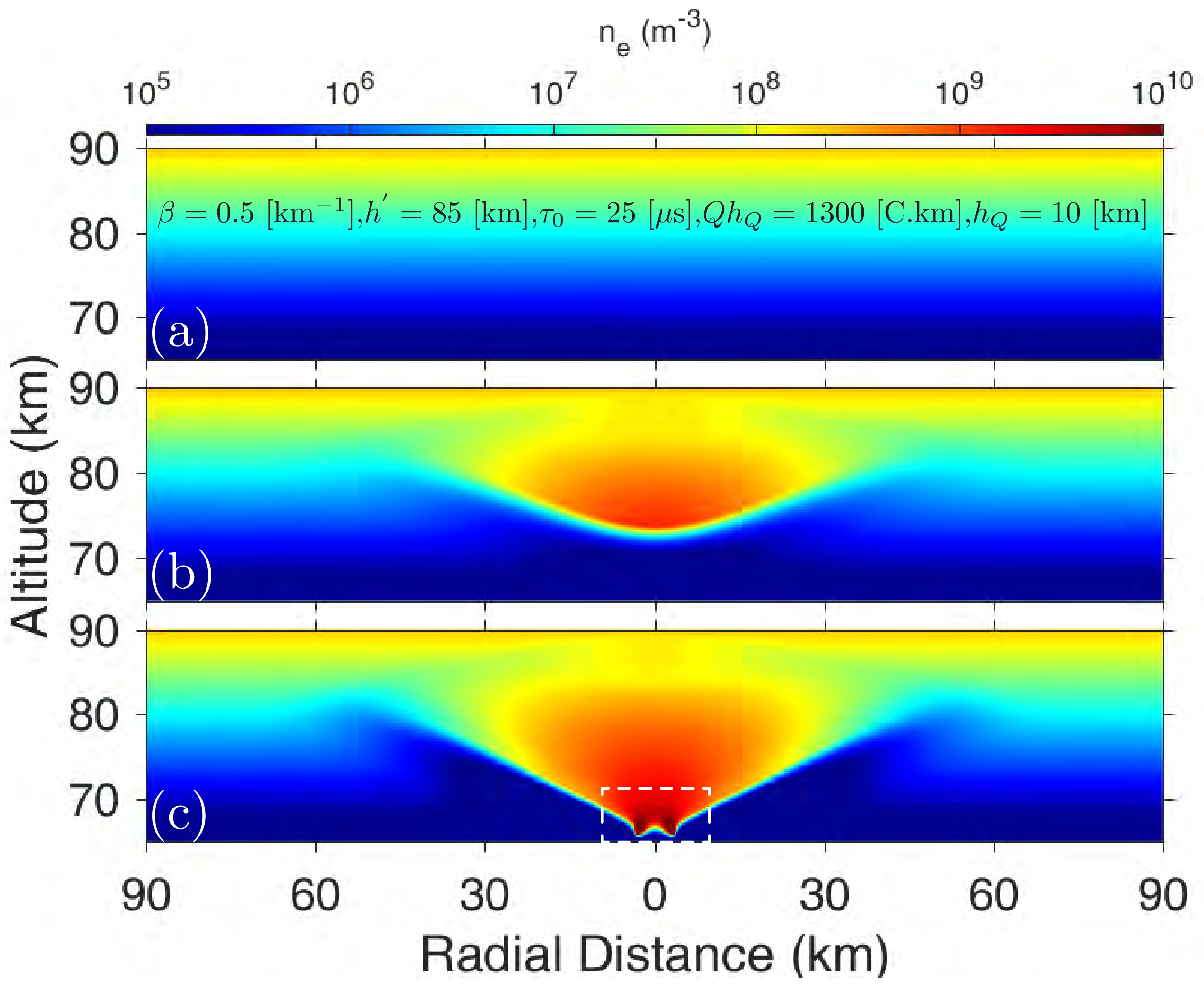


Figure 1. Electron density distribution at (a) $t = 0$ ms ,(b) $t = 0.75$ ms, and (c) $t = 1.5$ ms obtained via the donor cell scheme. The halo instability is depicted in part (c). FCT results are not shown for the sake of brevity.

V. Origin of MLT Inhomogeneities

Infrasound Sources

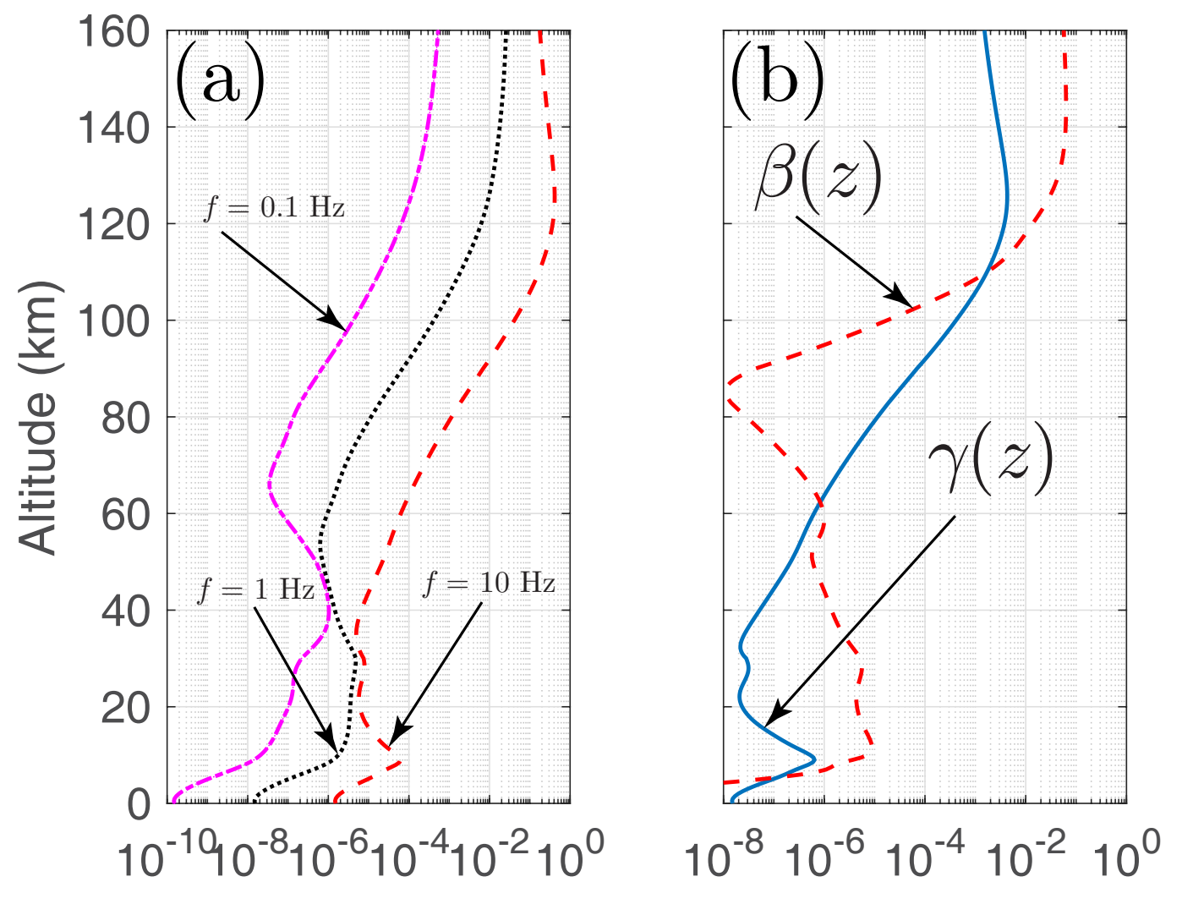


Figure 3. (a) Infrasound attenuation coefficient $\alpha(z{,}f)$ for 0.1 Hz, 1 Hz, and 10 Hz and (b) coefficients $\gamma(z)$ and $\beta(z)$ up to 160 km.

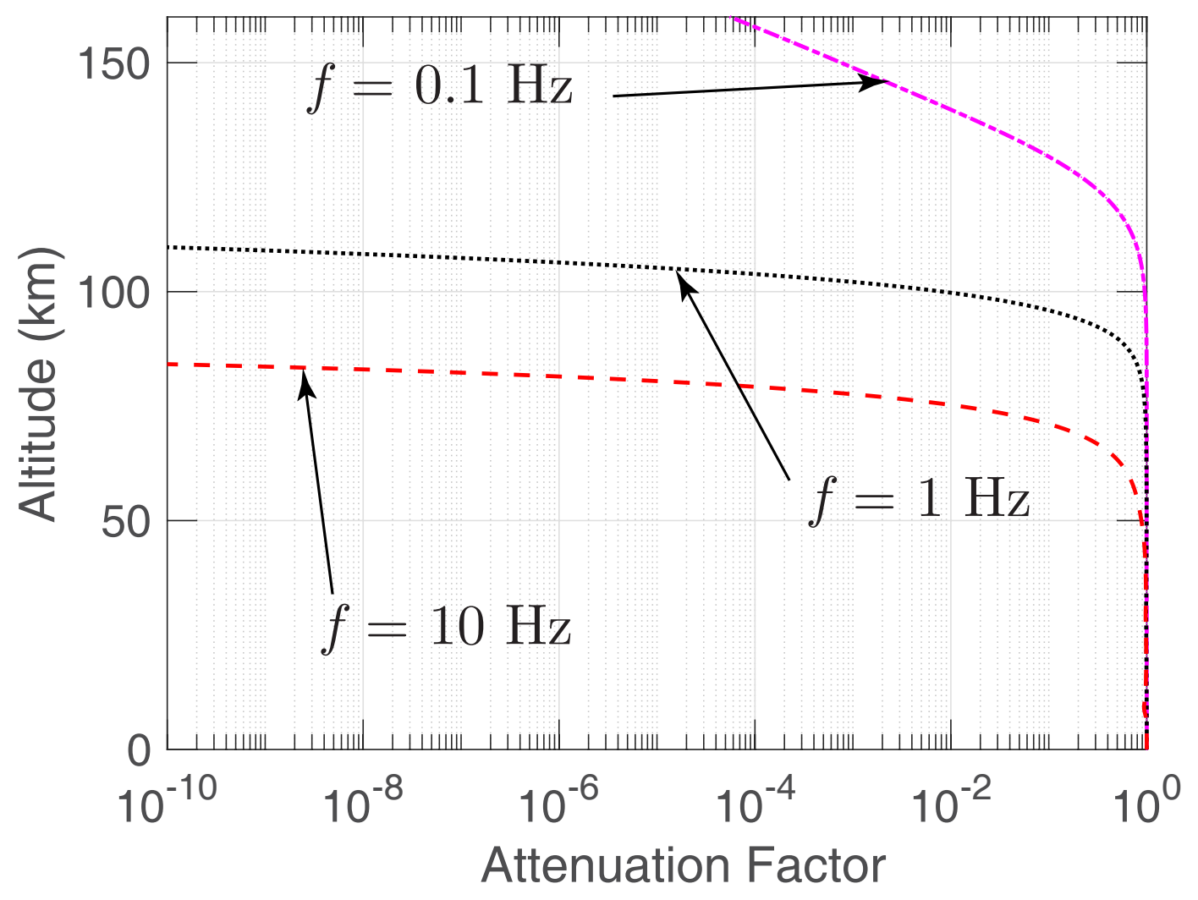


Figure 4. Infrasound attenuation factor for wave propagating up to 160 km.

- Sources of infrasound include thunderstorms, volcanic eruptions, earthquakes, etc. [*Blanc, E.*, Ann. Geophys., 3, 673, 1985].
- Atmospheric attenuation coefficient $\alpha(z{,}f)$ [*Sutherland* and *Bass*, J. Acoust. Soc. Am., 115, 1012, 2004] may be approximated as [*de Groot-Hedlin*, J. Acoust. Soc. Am., 124, 3, 2008]:

$$\alpha(z, f) = \beta(z) + \gamma(z) f^2$$

Units: $\alpha(z, f)$ $[\frac{dB}{m}]$, $\beta(z)$ $[\frac{dB}{m}]$, $\gamma(z)$ $[\frac{dB \cdot s^2}{m}]$

- Following the above approximation and in the limiting case of plane wave propagation through the atmosphere, the attenuation factor will be:

$$e^{-qz},\ q = \alpha/20\log_{10}(e)$$

- Existence of high frequency waves with spatial dimensions comparable to sprite streamers requires versy strong sources at low altitudes or an excitation at sprite altitudes.

II. Plasma Fluid Model

- The modeling approach is similar to that implemented in [*Qin et al.*, JGR, 116, A06305, 2011]:

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \vec{v}_e - D_e \nabla n_e) = (\nu_i - \nu_a) n_e + S_{ph} \quad (1)$$

$$\frac{\partial n_p}{\partial t} = \nu_i n_e + S_{ph} \quad (2)$$

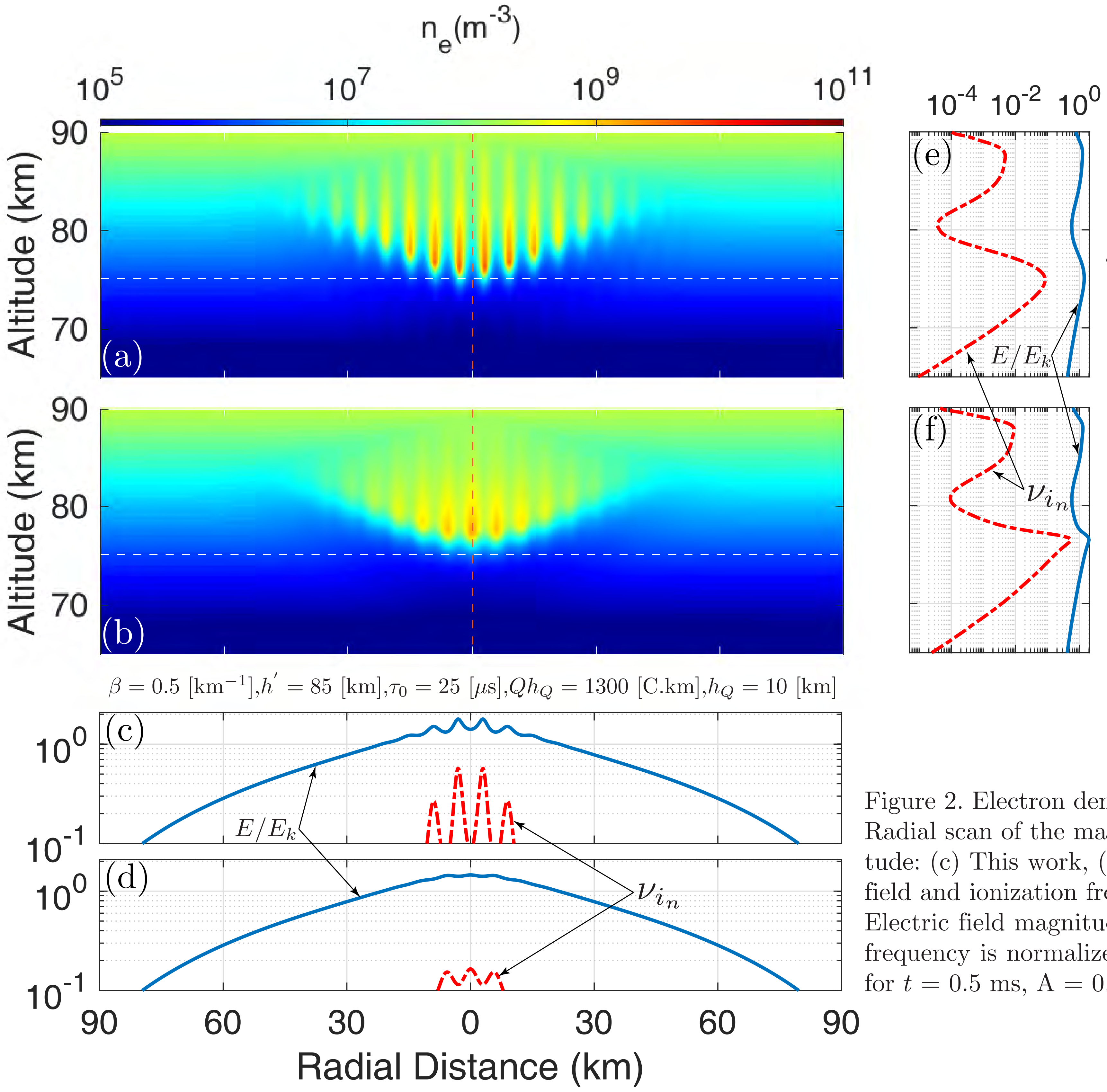
$$\frac{\partial n_n}{\partial t} = \nu_a n_e \quad (3)$$

$$\nabla^2 \phi = -\frac{q_e}{\epsilon_0}(n_p - n_e - n_n) \quad (4)$$

Symbol	Quantity
q_e	Electron charge
n_e	Electron density
n_p	Positive ion density
n_n	Negative ion density
ϕ	Electric potential
D_e	Electron diffusion coefficient
$\vec{v}_e$	Electron drift velocity
ν_i	Ionization frequency
ν_a	Attachment frequency
S_{ph}	Photoionization rate

- The model is driven by the discharge current moment $ih_Q(t) = Qh_Q \frac{1}{12}\frac{1}{\tau_0}\frac{t}{\tau_0}\exp[-(\frac{t}{\tau_0})^{\frac{1}{2}}]$ where Qh_Q is the charge moment [*Cho* and *Rycroft*, J. Atmos. Sol. Terr. Phys. 60, pp. 871-888, 1998].
- $n_e(z, t = 0) = n_{e_0} e^{-0.15h'} e^{(\beta - 0.15)(z - h')}$ [*Wait* and *Spies*, Tech Note 300, Natl. Bur. of Stand., Boulder, CO, 1964]. z denotes altitude and β and h' describe sharpness and reference altitude, respectively.
- $n_p(z, t = 0) = n_e(z, t = 0)$ at high altitudes where $n_e(z, t = 0) > 10^8$ m^{-3} and $n_p(z, t = 0) = 10^8$ m^{-3} otherwise.
- $n_n(z, t = 0)$ is determined via charge neutrality condition.

IV. Ionospheric Perturbation Effect



> “Naturally-existing, small-scale mesospheric structures such as those created by gravity waves are viable sources for mesospheric inhomogeneities.”
>
> —[*Liu et al.*, 2015]

- *Liu et al.*, [2015] directly and only modulate the ionization frequency. In our model, all fluid model coefficients are consistently computed as a function of modulated atmospheric density.

Liu et al., [2015]	$N_0 \rightarrow \nu_{i_0}, \nu_a, \ldots \rightarrow \nu_i = \nu_{i_0}[1 + A\cos(kr)]$
This work	$N_0 \rightarrow N = N_0[1 + A\cos(kr)] \rightarrow \nu_i, \nu_a, \ldots$

Symbol	Quantity
A	Modulation amplitude
k	$\frac{2\pi}{\lambda}$
λ	Modulation wavelength
r	Radial distance from the axis

Figure 2. Electron density in the entire domain: (a) This work, (b) *Liu et al.*, [2015]. Radial scan of the magnitude of electric field and ionization frequency at 75 km altitude: (c) This work, (d) *Liu et al.*, [2015]. Vertical scan of the magnitude of electric field and ionization frequency on the axis: (e) This work, (f) *Liu et al.*, [2015]. Electric field magnitude is normalized to the breakdown electric field and ionization frequency is normalized to the maximum value of both methods. Results are shown for $t = 0.5$ ms, A = 0.1, $\lambda = 6$ km.

VI. Conclusions

- Inhomogeneities are necessary for sprite streamer initiation.
- Ionospheric perturbations have been consistently included in the plasma fluid model.
- Arrival of infrasound with wavelengths comparable to spatial dimensions of sprite streamers from low altitude sources seems unlikely.

VII. Future Work

- Including the effects of infrasound radiation from sprites on ionospheric conditions and dynamically modeling consequent stages of sprite streamers' propagation.
- Investigating the effect of MLT metal layers on plasma dynamics e.g., ionization frequency. In particular, including ionization of metallic species in the current plasma fluid model.

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