Photoionization and Electron Impact Ionization of Metallic Species at Sprite Altitudes as a Mechanism of Initiation of Sprite Streamers

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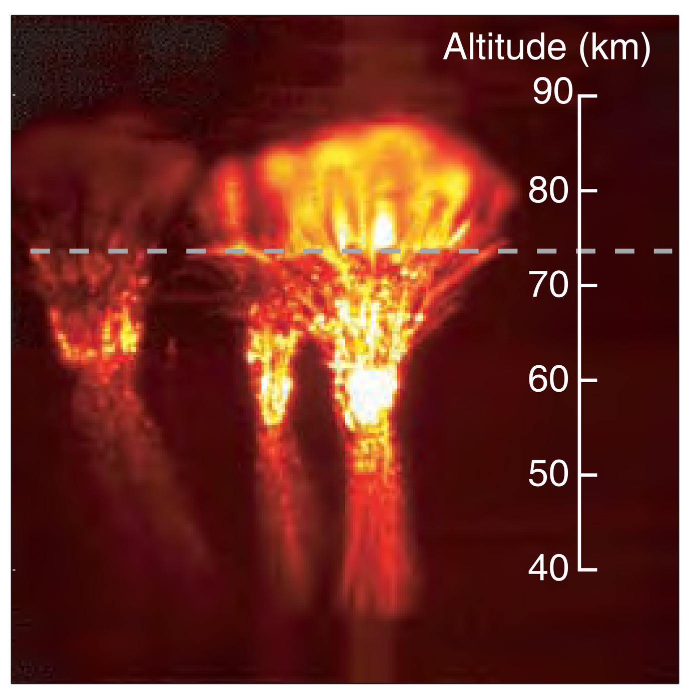
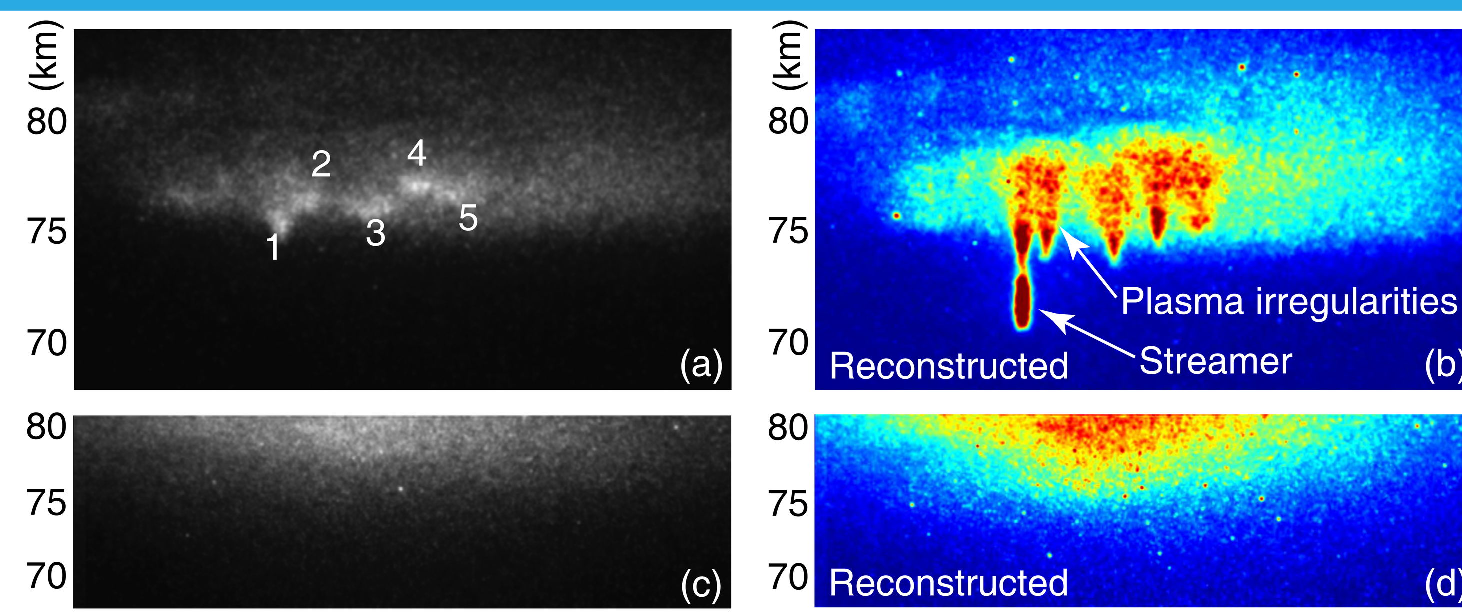
I. Scientific Problem & Background

Plasma irregularities are necessary for sprite streamer initiation
What is the source of these inhomogeneities at sprite altitudes?



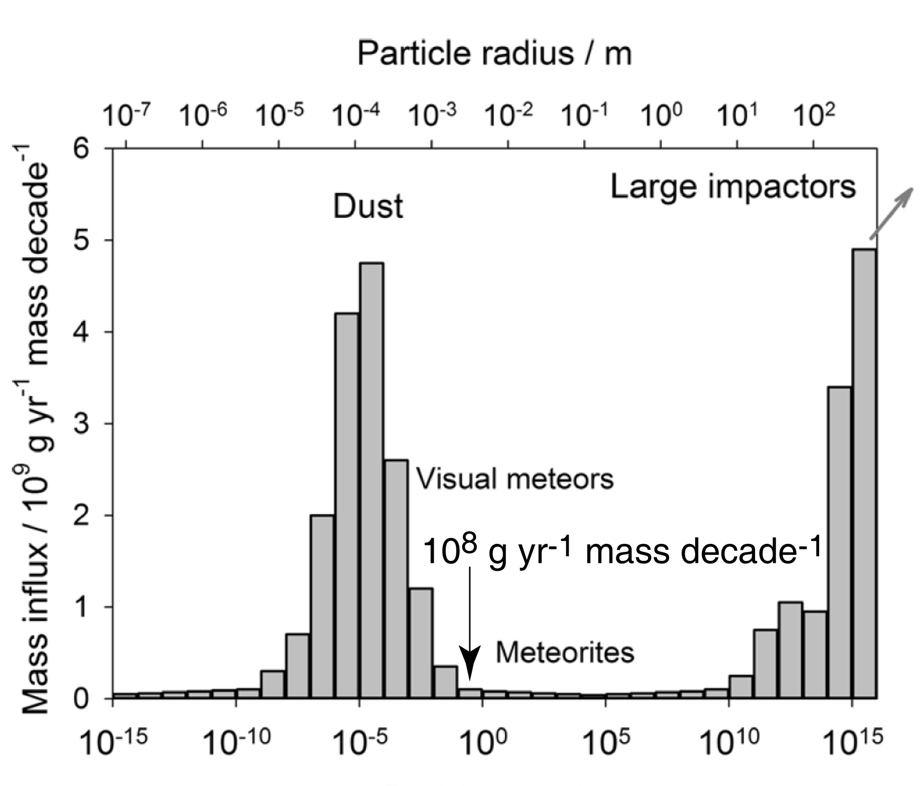
[Pasko and Stenbaek-Nielsen, GRL, 29, 10, 2002].



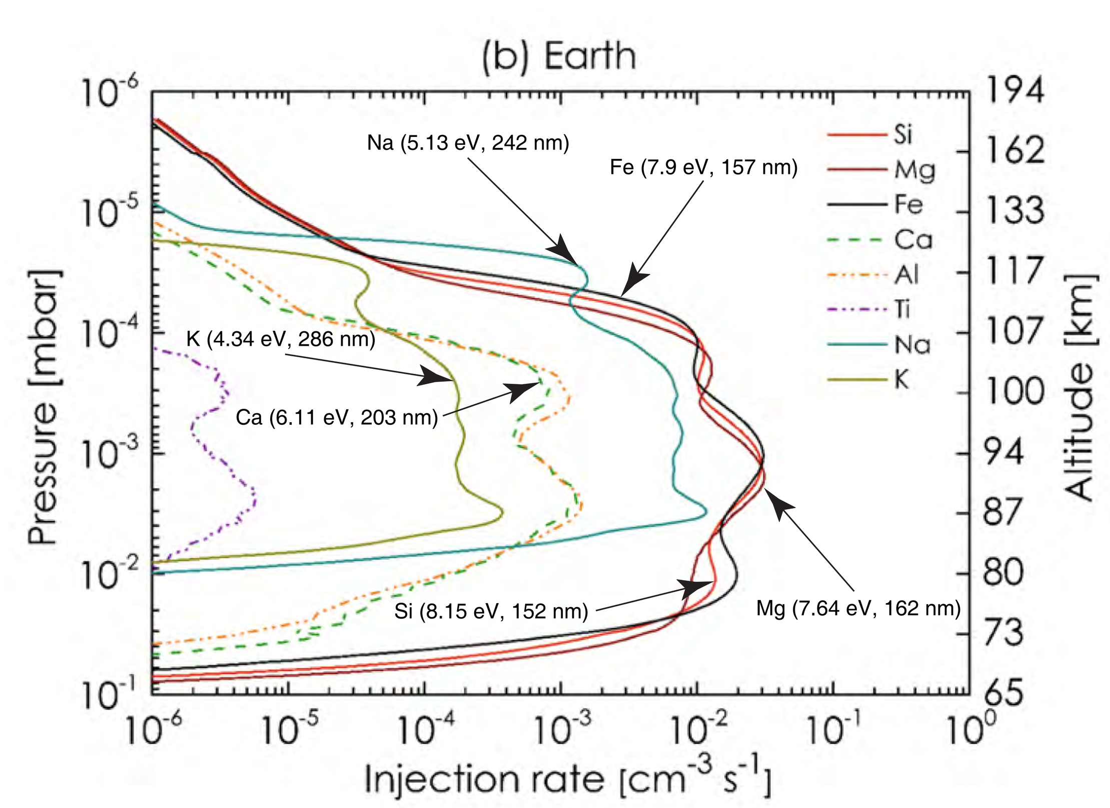
(a) A frame of the sprite halo event observed on 20 July 2012 and (b) the reconstructed image showing five plasma irregularities. (c) A frame of the halo event observed on 14 July 2010 and (d) the reconstructed image that shows only large-scale halo emissions [Qin et al., Nat. Commun., 5, 3740, 2014].

II. Deposition of Metals in Upper Atmosphere

As a result of meteoric ablation Fe, Mg, Si, Na, Ca, and K atoms form well defined layers in the Earth's atmosphere [Plane et al., Chem. Rev., 115, 4497, 2015], and the overall injection rates of these elements form broad peaks in the altitude range between 70 and 120 km [Plane et al., Space Sci. Rev., 214, 23, 2018]. The local concentration of these elements is expected to depend on meteor mass, velocity, altitude of deposition, and also on the stage of meteor trail expansion. Although these elements initially appear in ionized form, the ions quickly oxidize and then recombine with electrons resulting in the neutral atomic form of these species [Silber et al., MNRAS, 469, 1869, 2017, and references therein] with typical lifetimes measured in hours [Plane et al., Chem. Rev., 115, 4497, 2015]. In terms of relative concentration Fe, Mg, and Si typically dominate, followed by Na, Ca, and K [Plane et al., Space Sci. Rev., 214, 23, 2018; Granier et al., GRL, 16, 243, 1989].



Estimated mass accretion rates of extraterrestial objects at the top of the Earth's atmosphere [Kyte and Wasson, Science, 232, 1225, 1986; Plane et al., Space Sci. Rev., 214, 23, 2018]



Meteoric ablation rate profiles for individual elements [Carrillo-Sanchez et al., GRL, 43, 11979, 2016; Plane et. al., Space Sci. Rev., 214, 23, 2018]

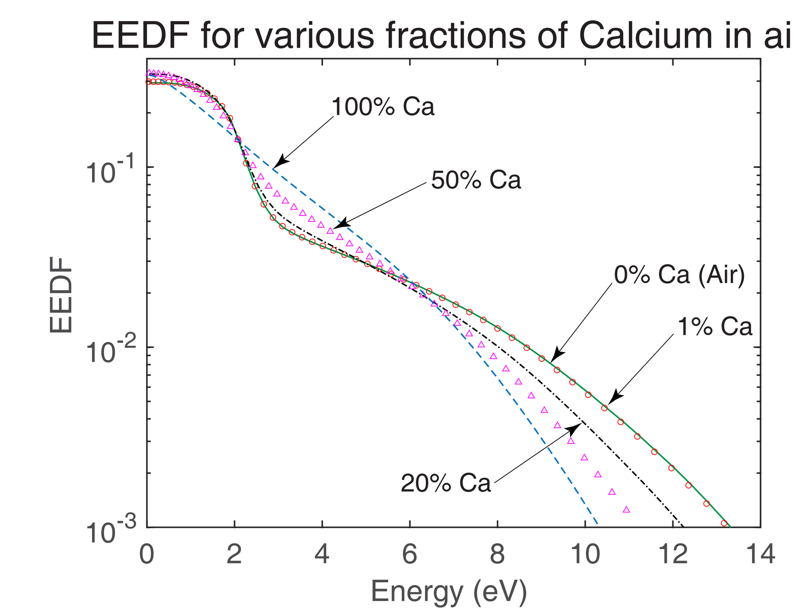
III. Ionization of Metallic Species

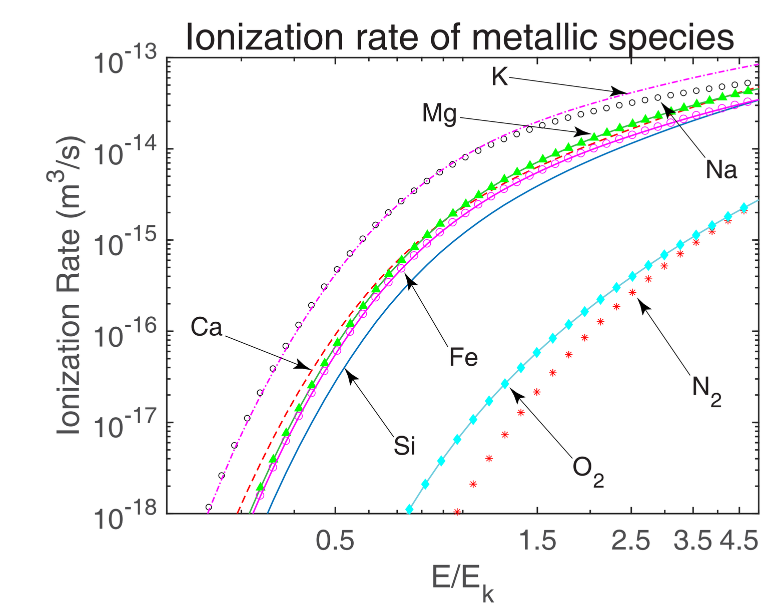
It is remarkable that all these metallic species have ionization thresholds: Fe (7.9 eV, 157 nm), Mg (7.64 eV, 162 nm), Si (8.15 eV, 152 nm), Na (5.13 eV, 242 nm), Ca (6.11 eV, 203 nm), and K (4.34 eV, 286 nm) much below the main constituents of air: N_2 (15.6 eV, 80 nm) and O_2 (12.06 eV, 102.5 nm), allowing them to be effectively ionized in collisions with relatively low energy electrons. These species can also be photoionized by UV photons associated with various band systems of N_2 emitted by sprite halo discharges.

IV. Electron-Impact Ionization

We calculate electron-impact ionization rates of these metals by inputting published ionization cross section data [e.g., Boivin et al., J. Phys. B: At. Mol. Opt. Phys., 31, 2381, 1998; Kim et al., J. Phys. B: At. Mol. Opt. Phys., 40, 1597, 2007] to BOLSIG+ software [G. J. M. Hagelaar, L. C. Pitchford, PSST, 14, 722, 2005].

• Density of metallic species deposited in the atmosphere is low and does not modify the electron energy distribution function (EEDF) of air. Therefore, the EEDF of air may be used to calculate the ionization rate of the metals.

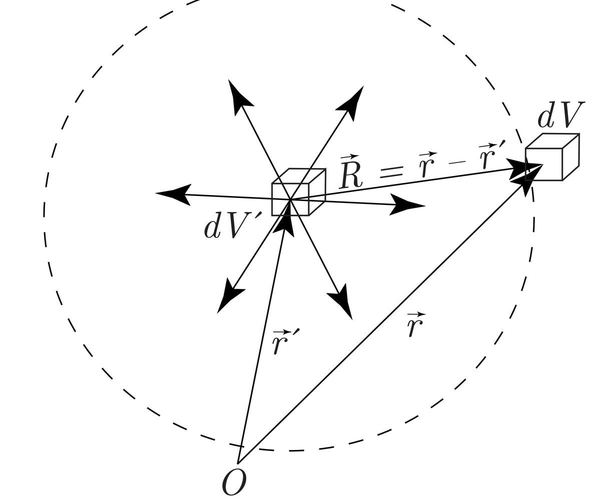




V. Photoionization

For photoionization calculations we assume that UV photons originate from the same singlet states of N_2 that lead to classical photoionization of O_2 in air [Zheleznyak et al., High Temp., 20, 357, 1982]. In addition, we consider UV emissions from Lyman-Birge-Hopfield (LBH) band system of N_2 which has an emission spectrum in the range 120-280 nm [A. V. Vallance Jones, Aurora, 134, 1974] and is abundantly produced in sprites. We note that LBH N_2 emissions are only able to photoionize metallic species, while emissions originating from the N_2 singlet states are capable of photoionizing both O_2 and metallic species. In order to calculate the photoionization rates due to seeds of metallic species, we develop first principles models of radiative transfer of photoionizing photons through the air medium.

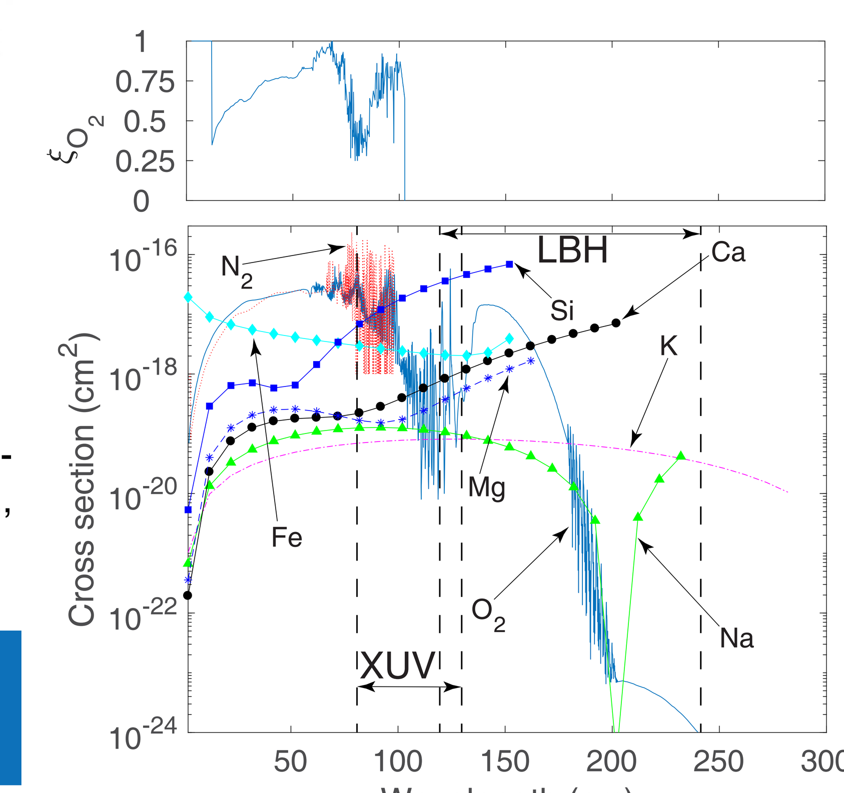
Geometry of photoionization problem



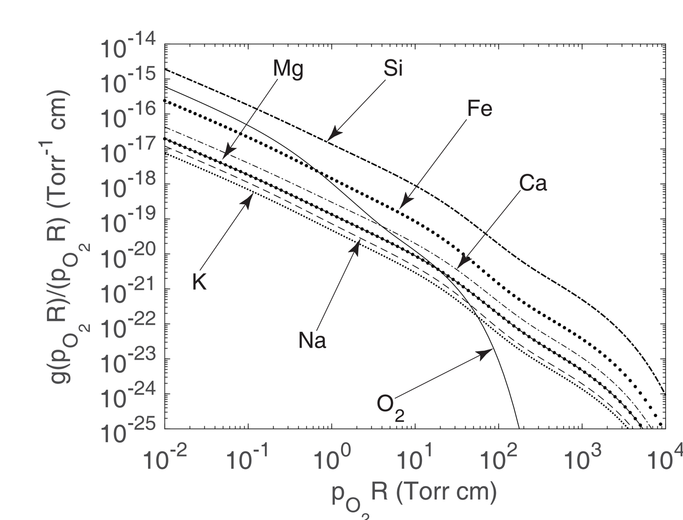
Source photon emission rate per unit volume; photon propagator; pressure

$$S_{\mathrm{ph}_1}(\vec{r}) = \int_{V'} I(\vec{r}')\frac{g(pR)}{4\pi R^2}dV'$$

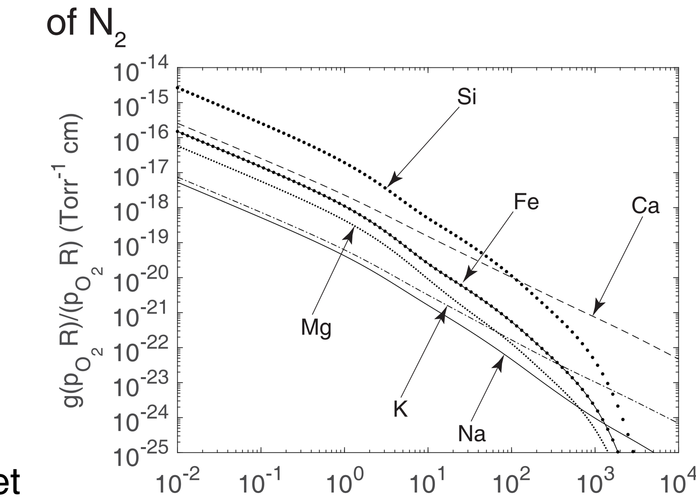
photoionization rate per unit atom/molecule per unit volume of photoionized species



Photoabsorpion cross sections are from [Verner et al., Asrophys. J., 465, 487, 1996; Bautista and Kallman, Asproph. J. Suppl. Ser., 134, 139, 2001, https://heasarc.nasa.gov/lheasoft/xstar/xstar.html]



Photon propagator for XUV band systems of N_2



Photon propagator for LBH band system of N_2

VI. Streamer Initiation

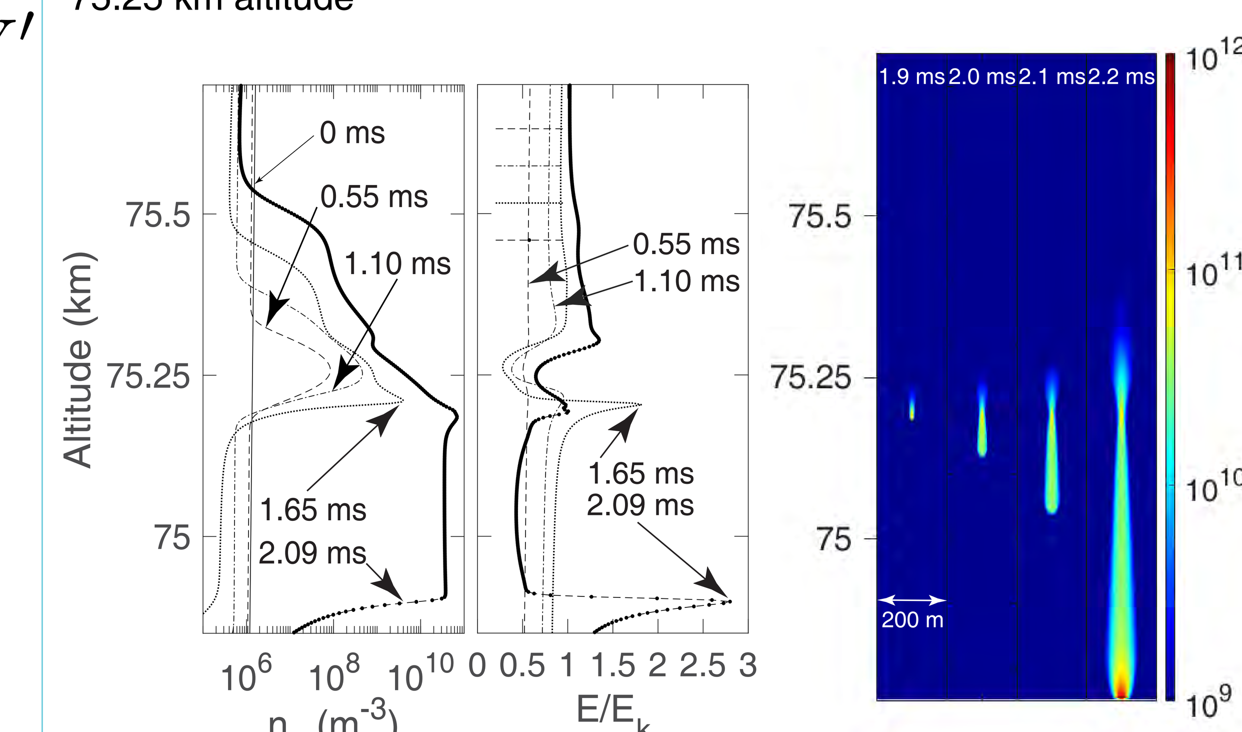
We employ a plasma fluid model of sprite halo to compare streamer initiation from a gas mixture including various densities of these metals with previous works which artificially assumed high electron density regions in the simulation domain [e.g., Qin et al., GRL, 40, 4777, 2013; Qin et al., JGR, 118, 2623, 2013].

• The charge moment change due to the lightning discharge is Qh_Q = 600 C km.
• Lightning current moment is

$$ih_Q(t) = Qh_Q\frac{1}{12}\frac{1}{\tau_0}\frac{t}{\tau_0}\exp[-(\frac{t}{\tau_0})^{1/2}],\ \tau_0 = 25\mu s$$

[Cho and Rycroft, J. Atmos. Sol. Terr. Phys, 1998].

Streamer initiaton by Ca seed with peak density 10^{13} cm^{-3} and 30 m scale at 75.25 km altitude



Conclusions

• A model framework allowing quantitative analysis of electron impact ionization and photoionization of metallic species in the Earth's atmosphere has been developed.
• Analysis of typical sprite streamer and sprite halo scenarios indicates that the ionization and photoionization of metallic species can contribute to initiation and morphological features (i.e., branching) of sprite streamers.

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