Hunting GhOSTs: Investigation of Potential Mechanisms Responsible for Green Emissions Observed at Sprite Tops

Brandon Smith[1], Reza Janalizadeh[2], and Victor P. Pasko[1]
(bls6238@psu.edu; reza.janalizadehchoobbasti@nasa.gov; vpasko@psu.edu)

[1]School of Electrical Engineering and Computer Science, The Pennsylvania State University, University Park, PA 16802, USA
[2]NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Bldg 21, Code 674, MD 20771, USA

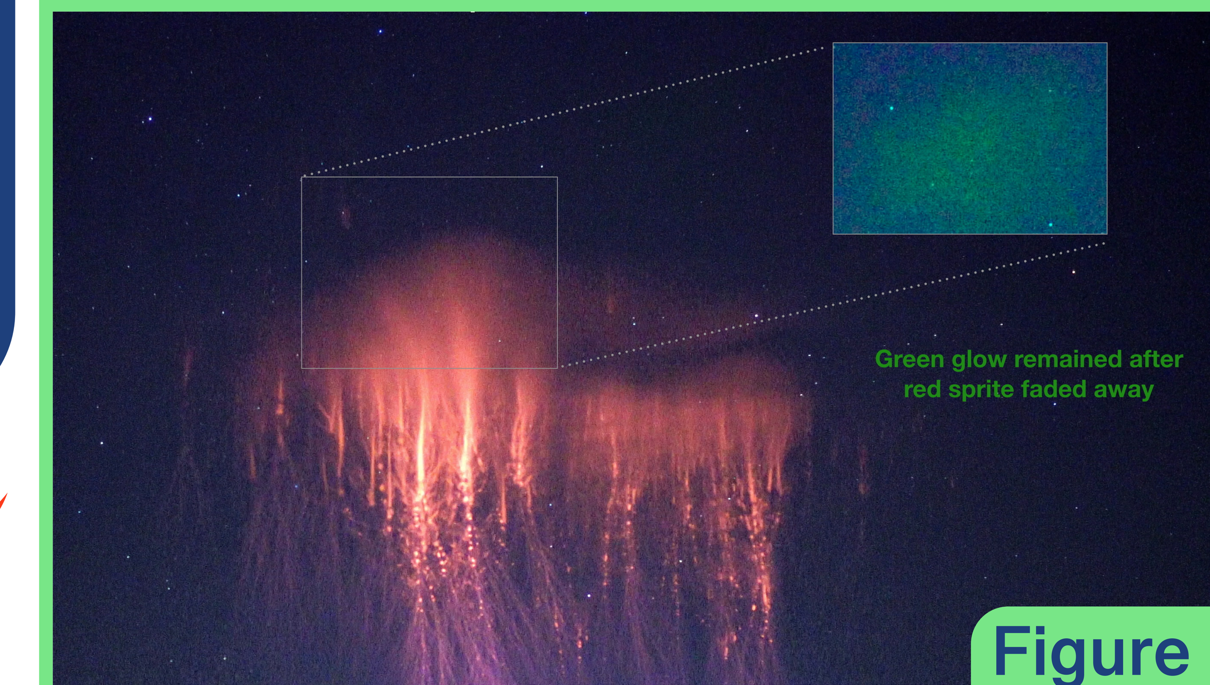


Figure 1
Color image of a sprite with persistent green region overlayed [Lyons, *Weatherwise*, 75:6, 14-23, 2022].

1. Abstract

Sprites are predominantly red color electrical discharges that occur at mesospheric/lower ionospheric altitudes in response to lightning activity in the troposphere [e.g., Stenbaek-Nielsen et al., *GRL*, *52*, e2024GL112537, 2025; and references therein]. It has been recently discovered that some sprites occasionally exhibit enigmatic green emissions at their tops, referred to as Green emissions from excited Oxygen in Sprite Tops (GhOSTs) [e.g., Lyons, 2022, and discussion therein]. Since their discovery by citizen scientists in 2019, green ghosts have received attention from the research community and general public capturing images of the elusive events. This phenomenon has gained interest for its characteristic green color (most likely produced due to the O(^{1}S → ^{1}D) transition, that manifests as the 557.7 nm green line emission) [Passas-Varo et al., *Nat. Commun.*, *14*, 7810, 2023], long duration [Stenbaek-Nielsen et al., *Authorea*, 10.1002/essoar.10504953.1, 2020], and reignitions corresponding to secondary sprite occurrences elsewhere [Huang et al., *GRL*, *51*, e2024GL108397, 2024]. Previous studies have examined the possible role of some electron impact excitation processes in the generation of green emissions [Celestin et al., Abstract AE33A-2839, AGU Fall Meeting, San Francisco, CA, 11-15 Dec., 2023]. Electron impact excitation of atomic oxygen (e + O → O + O(^{1}S)), electron impact dissociative excitation of molecular oxygen (e + O_2 → e + O + O(^{1}S)), and energy transfer (N_2(A) + O → N_2 + O(^{1}S)) all serve as potential viable candidates [Vallance Jones, *Aurora*, *142-143*, 1974; Itikawa and Ichimura, *J. Phys. Chem. Ref. Data*, *19*, 637–651, 1990]. In this work we compare the contribution of the above mechanisms to green emissions from O(^{1}S) under the application of a lightning-induced electric field to the lower ionosphere.

2. Model Formulation

- We consider the contribution of mechanisms below in populating O(^{1}S) as the upper state of 557.7 nm green line emission:

(a) Dissociative Excitation of Molecular Oxygen
e + O_2 → e + O + O(^{1}S)

(b) Electron Impact Exciation of Atomic Oxygen
e + O → O + O(^{1}S)

(c) Energy Transfer from N_2
e + N_2 → N_2(A)
N_2(A) + O → N_2 + O(^{1}S)

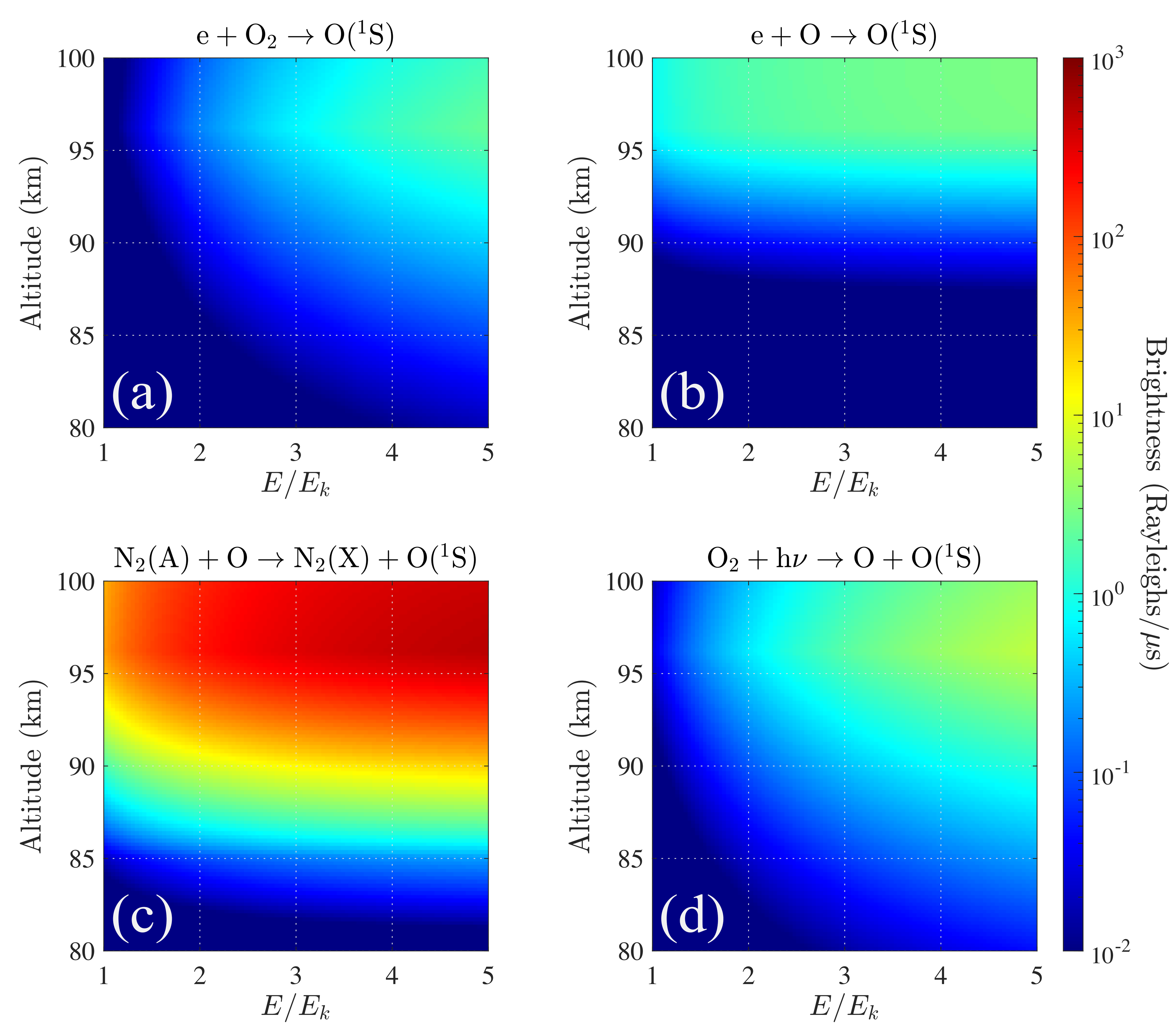
(d) Photolysis of O_2 from N_2 Singlets
e + N_2 → N_2^*
N_2^* → N_2 + $h\nu$
$h\nu$ + O_2 → O + O(^{1}S)

Singlet states involved in photolysis: N_2^*=($b^1\Pi_u$, $b'^1\Sigma_u^+$, $c_3{}^1\Sigma_u$, $o_3{}^1\Sigma_u$, $c_4'{}^1\Pi_u$)

- The chosen singlet states involved in photolysis are the same states responsible for photoionization in air studied in the context of non-thermal gas discharges [Janalizadeh and Pasko, *Plasma Sources Sci. Technol.*, *28* (10), 105006, 2019].
- Ambient electron density profile described by Qin et al. [*JGR*, 116, A06305, 2011; Wait and Spies, *Tech note 300,* Colorado: National Bureau of Standards, 1964] corresponds to background ionosphere electron density. Assuming β = 0.5 km^{-1} and h′ = 85 km.
- Our atomic oxygen profile was generated using NRLMSIS neutral atmospheric model (ccmc.gsfc.nasa.gov/models/NRLMSIS~2.0) [Emmert et al., *Earth and Space Science*, *8*(3), e2020EA001321, 2021].
- The total lifetime of O(^{1}S) is set as $\tau_{557} = 0.794$ s [Vallance Jones, 1974, p. 48]. Additionally, the quenching altitude of O(^{1}S) is assumed to be 95 km [Vallance Jones, 1974, p. 119], significantly reducing brightness at lower altitudes.
- The duration of the source electric field plays a significant role in resultant brightness. The source lifetime τ* may vary from 10 - 1000 μs, encompassing possible source phenomena such as narrow bipolar events (NBEs) of ~10 μs [Rison et al., *Nat. Commun. 7,* 10721, 2016], elves of ~100 μs [Fukunishi et al., *GRL, 23* (16), 2157-2160, 1996; Inan et al., *GRL, 24* (5), 583-586, 1997], and sprite halos ~1000 μs [Barrington-Leigh et al., *JGR, 106* (A2), 1741-1750, 2001; Marshall et al., *JGR, 115,* 1-17, 2010].
- Electric field values explored here are supported by previous work investigating the upward propogation of pulses, which find that electric field magnitudes in this region may exceed 3E_k [Luque et al., *JGR,* 130, e2024JD042121, 2025].
- We assume a horizontal line of sight through a source 60 km in diameter. We express all units in Rayleighs per microsecond of the source (R/μs), allowing for brightness to be found conveniently by multiplication with the source duration.

2. Results and Discussion

- In agreement with findings of Celestin et al. [2023], the quenching of N_2(A) by atomic oxygen O represents the dominant source of 557.7 nm emissions above approximately 85 km.
- The source duration τ* leads to large variations in peak brightness, e.g., at 3E_k the maximum value for photolysis may range from 20 - 2000 Rayleigh depending on the chosen source, where Ek is the conventional breakdown threshold field [e.g, Qin et al., 2011].
- With small duration sources the apparent brightness is comperable or slightly larger than ambient airglow at night, which exists on the order of 100 Rayleighs [Bates, *Planet. Space Sci., 29*(10), 1061-1067, 1981].



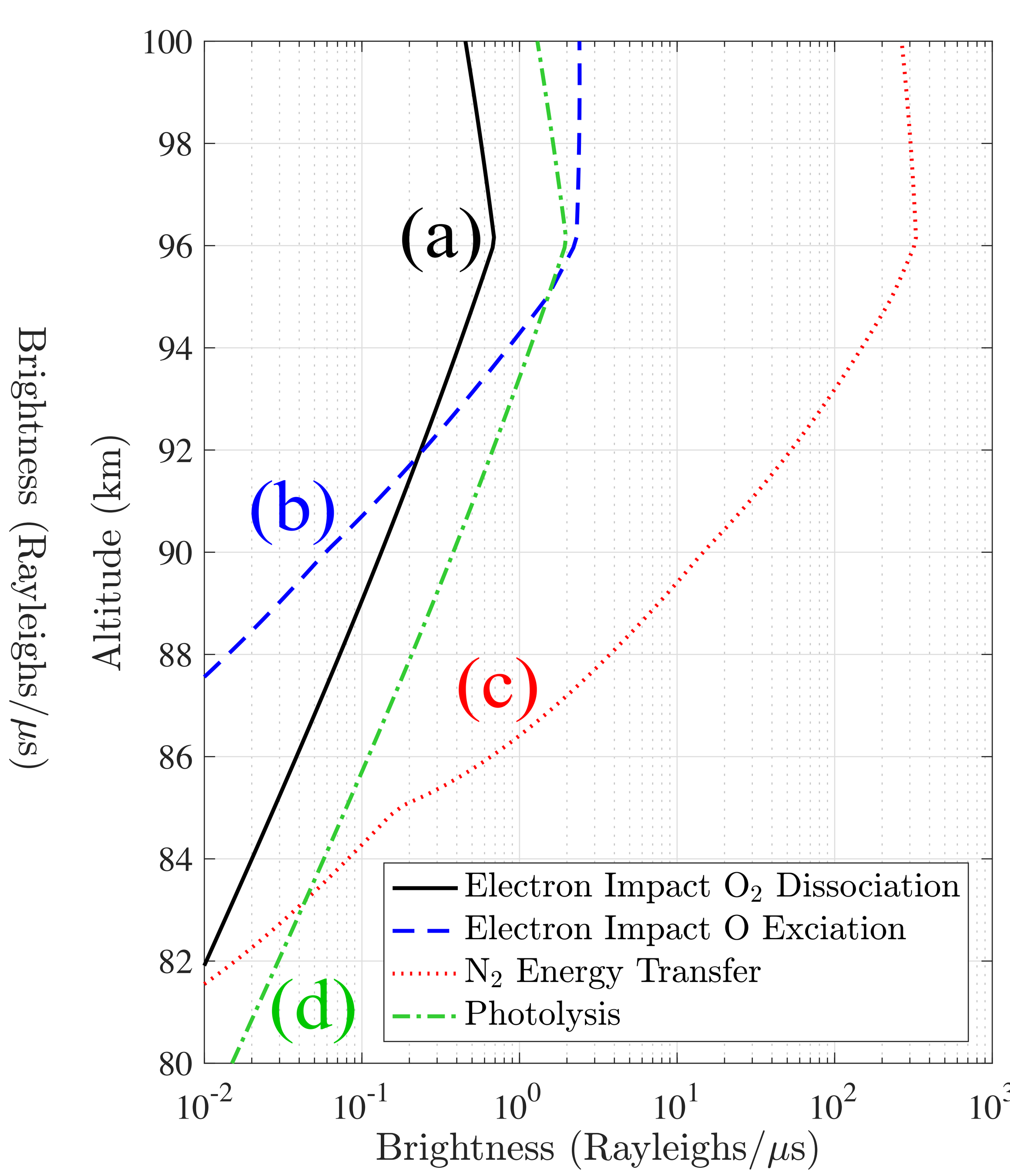


Figure 2
Contribution of various processes, specifically (a) aissociative excitation of molecular oxygen, (b) electron impact exciation of atomic oxygen, (c) energy transfer from N_2, and (d) photolysis of O_2 due to N_2 singlet photons to brightness of 557 nm green line emissions from O(^{1}S) as a function of altitude and applied electric field

Figure 3
Comparison of all processes at E = 3E_k. (a) aissociative excitation of molecular oxygen, (b) electron impact exciation of atomic oxygen, (c) energy transfer from N_2, and (d) photolysis of O_2 due to N_2 singlet photons

4. Conclusions

- A parametric model allowing to provide quantitive estimates of green line (O(^{1}S), 557.7 nm) emissions at lower ionospheric altitudes excited by electromagnetic fields produced by lightning activity at tropospheric altitudes is developed.
- The model includes the most important channels of electron impact excitation of O, O_2 and N_2, and photolysis of O_2 due to strong ultraviolet emissions from singlet states of N_2.
- Our results indicate that at lower altitudes, below 85 km, the N_2(A) and photolysis mechanisms lead to comparable quantitative results, with photolysis dominating below ~80 km.
- Sequences of strong lightning electromagnetic pulses [Marshall, 2010; Luque et al., 2025; and references therein] occurring on ~1 sec time scales could lead to O(^{1}S) 557.7 nm emissions that would be observable above background airglow levels.

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