Modeling of optical emissions produced by sprite streamers in preparation for the TARANIS space mission

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In order to prepare for the TARANIS space mission, which is going to make observations of transient luminous events (TLEs), in this work, we quantify intensities of optical emissions produced by sprite streamers. We simulate streamer discharges using a classical plasma fluid approach. We derive the density of excited species and the corresponding optical emissions. Results are then used to make quantitative predictions on the signals that will be detected by the TARANIS-MCP instrument.

1. Introduction

Sprites are luminous discharges taking place between ~40 and ~90 km altitude. They result from the high altitude quasi-static electric field perturbation caused by cloud-to-ground (CG) lightning discharge.

The French Space Agency (CNES) micro-satellite TARANIS [1] will be dedicated to the observation of transient luminous events (TLEs), among which sprites are a most remarkable phenomenon. TARANIS will be equipped with micro-cameras and photometers (MCP instrument [1]) that will detect optical emissions from TLEs. In preparation for the TARANIS space mission, we will model the optical emissions of sprite streamers.

2. Streamer model

The streamer model is based on the drift-diffusion equations for charged species. These equations are numerically solved using the finite volume method in cylindrically symmetric geometry. The drift-diffusion equations are coupled with Poisson's equation:

$$\frac{\partial n_{\mathrm{e}}}{\partial t} + \nabla . n_{\mathrm{e}} \vec{v}_{\mathrm{e}} - D_{\mathrm{e}} \nabla^2 n_{\mathrm{e}} = S_{\mathrm{e}}^{+} - S_{\mathrm{e}}^{-} \qquad (1)$$

$$\frac{\partial n_{\mathrm{p}}}{\partial t} = S_{\mathrm{p}}^{+} - S_{\mathrm{p}}^{-} \qquad (2)$$

$$\frac{\partial n_{\mathrm{n}}}{\partial t} = S_{\mathrm{n}}^{+} - S_{\mathrm{n}}^{-} \qquad (3)$$

$$\nabla^2 \phi = -\frac{q}{\varepsilon_0}(n_{\mathrm{p}} - n_{\mathrm{n}} - n_{\mathrm{e}}) \qquad (4)$$

where subscripts 'e' , 'p' and 'n' refer to electrons, positive and negative ions, respectively, n_i is number density of species i, v_e is the electron drift velocity [2], D_e, q, ε_0 are the electron diffusion coefficient [2], the absolute value of the electron charge and the permittivity of free space, respectively. On time scale of interest, ions are considered to be motionless. The S^+ and S^- terms stand for the rates of production and loss of charged particles, respectively.

The photoionization processes are important in sprite streamers [3]. They are taken into account using a quasi-neutral background of homogeneous electron and positive ion density.

2. Optical emissions

In this work, we focus on the study of the optical emissions of N_2 molecules [3, 4]. Using the streamer model described in the previous section, we first compute the evolution of the number density n_k of excited electronic state k of the N_2 molecule. The quantity n_k is described by the following partial differential equation [3]:

$$\frac{\partial n_k}{\partial t} = -\frac{n_k}{\tau_k} + \sum n_m A_m + \nu_k n_{\mathrm{e}} \qquad (5)$$

where $\tau_k = [A_k + \alpha_1 N_{N2} + \alpha_2 N_{O2}]^{-1}$ is the total lifetime of the state k, α_1 and α_2 are coefficients related to the quenching of the excited state k by molecules N_2 and O_2, respectively, N_{N2} and N_{O2} are molecular densities of N_2 and O_2, respectively, the sum over the terms $n_m A_m$ results from cascading from higher-energy states m, and ν_k and n_e are the excitation coefficient and electron density, respectively. Once n_k is found, we calculate the intensity (I_k) in Rayleighs of the corresponding optical emission including: first ($B^3\Pi_g \rightarrow A^3\Sigma_u^+$) and

second ($C^3\Pi_u \rightarrow B^3\Pi_g$) positive band systems of N_2 noted $1PN_2$ and $2PN_2$, respectively and the first negative band of N_2^+ noted $1NN_2^+$ ($B^2\Sigma_u^+ \rightarrow X\,^2\Sigma_g^+$) through the following integral [3]:

$$I_k = 10^{-6} \int_L A_k n_k dl \qquad (6)$$

where the quantity A_k [s^{-1}] is the Einstein coefficient for the spontaneous emission and L is the line of sight.

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5. References

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