Photoionization and Optical Emission Effects of Positive Streamers in Air at Ground Pressure

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***Abstract*—A positive streamer in a weak electric field in air at ground pressure is investigated by utilizing a recently developed photoionization model based on the radiative transfer theory. The modeling results on the streamer emissions demonstrate that blue emissions of the second positive band system of N_2 dominate the streamer spectra, in contrast to streamers in predominately red sprite discharges observed at low air pressures at high altitudes in the Earth's atmosphere.**

***Index Terms*—Optical emissions, photoionization, sprites, streamer coronae.**

STREAMERS are narrow filamentary plasmas, which are driven by highly nonlinear space charge waves. They are the precursor of spark discharges. Lightning is a natural phenomenon directly related to streamer discharges. Streamer discharges are also a component of large-scale electrical discharges recently discovered in the mesosphere and lower ionosphere above large thunderstorms, which are termed as red sprites (see [1] and references therein). A recent review of experimental and numerical works on streamers has been provided in [2]. In this paper, we present modeling of a positive streamer and its associated optical emissions. Emissions from streamers mainly consist of band systems from N_2 and N_2^+: the first positive $[1PN_2, N_2(B^3\Pi_g) \rightarrow N_2(A^3\Sigma_u^+)]$ and second positive $[2PN_2, N_2(C^3\Pi_u) \rightarrow N_2(B^3\Pi_g)]$ band systems of N_2, and the first negative band system of $N_2^+[1NN_2^+, N_2^+(B^2\Sigma_u^+) \rightarrow N_2^+(X^2\Sigma_g^+)]$. The spectrum of $1PN_2$ is in the red region of the visible light, whereas the spectra of $2PN_2$ and $1NN_2^+$ are in the blue region.

A critical component of a streamer model is evaluation of the photoionization production by the discharge itself. Several photoionization models have recently been developed and reviewed in [3] and [4]. In this paper, we use the three-group improved Eddington (SP_3) approach based on the radiative transfer theory [3]. The model for optical emissions can be found in [5]. The simulation setup from [4] is adopted in this paper. A small conducting sphere (with a radius of 1 mm and an applied potential of 6500 V) is placed in an electric field $E_0 = 10^6$ V/m, and the bottom boundary $(z = 0)$ of the simulation domain is adjacent to the sphere surface [4]. The air pressure is fixed at a value of 760 torr. A positive streamer initially forms in the high field region, starting from a small plasma cloud in the vicinity of the sphere, and then propagates into the weak uniform field E_0 [4].

Fig. 1 shows the electric field, electron density, photoionization production rate, and intensities of $1PN_2$, $2PN_2$, and $1NN_2^+$ at three different instants of time. Both the electric field and photoionization production rate are maximized in the head region. The distributions of different optical emissions are confined to regions with different sizes. The localized emissions at the lower boundary of the simulation domain [Fig. 1(j)–(o)] are due to the enhancement of the electric field near the conducting sphere [Fig. 1(a)–(c)]. In the streamer head, where the electric field is maximum, the upper states $N_2(B^3\Pi_g)$, $N_2(C^3\Pi_u)$, and $N_2^+(B^2\Sigma_u^+)$ responsible for $1PN_2$, $2PN_2$, and $1NN_2^+$, respectively, are effectively excited. The lifetimes of $N_2(B^3\Pi_g)$, $N_2(C^3\Pi_u)$, and $N_2^+(B^2\Sigma_u^+)$ states at ground pressure are 5, 0.6, and 0.1 ns, respectively. As a result, on a timescale of the simulation presented in Fig. 1 (18 ns), the $1NN_2^+$ band system has the smallest emission region, whereas the $1PN_2$ emissions spread toward the origin of the streamer and form a long trail. All of the emissions are confined to a region around the streamer head, and there is no continuous visible streamer channel. This result is consistent with high time resolution imaging of streamers in laboratory experiments [2] and with recent high-speed video recordings of sprites [6], indicating that emissions of streamers mostly originate from the streamer head. Another pronounced feature is that the intensity of $2PN_2$ is the strongest among these three emissions, which is consistent with well-documented phenomenology of streamers at near-ground pressures in air (see [1] and references therein). However, it is well known that streamers have a predominantly red color at low air pressure in red sprite discharges at high altitudes in the Earth's atmosphere (see [1] and references therein). The color difference of streamers at different altitudes is caused by the quenching of the excited species, which emit photons in different regions of the visible spectrum. The quenching altitudes of $N_2(B^3\Pi_g)$, $N_2(C^3\Pi_u)$, and $N_2^+(B^2\Sigma_u^+)$ states are 53, 30, and 48 km, respectively (e.g., [1]). Since the quenching altitude of the $N_2(B^3\Pi_g)$ state is much higher than that of the $N_2(C^3\Pi_u)$ state, the $N_2(B^3\Pi_g)$ state, leading to red $1PN_2$ emissions, is more heavily quenched at ground pressure than

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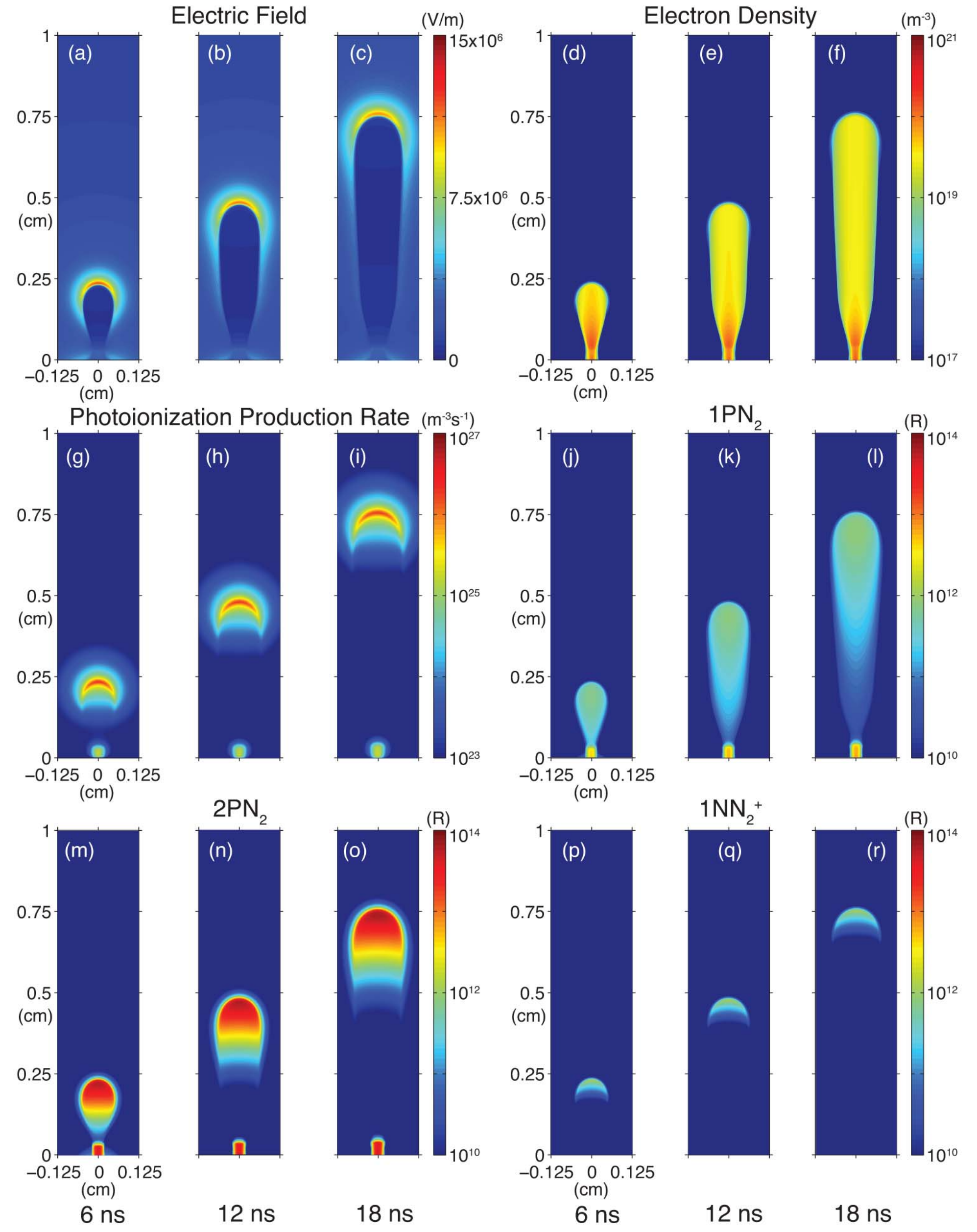

Fig. 1. Simulation results on a positive streamer originating in a strong field region near the lower boundary and propagating into a weak uniform electric field $E_0 = 10$ kV/cm in air at ground pressure at three instants of time: 6, 12, and 18 ns. (a)–(c) Electric field (in volts per meter). (d)–(f) Electron density (in number of electrons per cubic meter). (g)–(i) Photoionization production rate (in number of electrons per cubic meter per second). Intensity of the (j)–(l) first positive and (m)–(o) second positive band systems of N_2 and (p)–(r) first negative band system of N_2^+ (Rayleighs).

the $N_2(C^3\Pi_u)$ state, leading to predominantly blue emissions of the $2PN_2$ band system, as documented in Fig. 1.

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