Sprite Streamers Imaged at Different Exposure Times

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Abstract—**This paper investigates the appearance of sprite streamer discharges imaged at different exposure times. Both observational and modeling results are presented to illustrate that the formation of luminous filamentary channels in sprites is caused by bright and fast-moving sprite streamer heads.**

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

S TREAMERS occurring in transient laboratory discharges at atmospheric pressure are also found as basic components of large-scale electric discharges in the mesosphere and the lower ionosphere above thunderclouds, which were discovered about two decades ago and are now referred to as sprites in the field of atmospheric electricity see [1], and references therein. Active observational, theoretical, and modeling research work has been carried out to investigate the dynamics of sprites and sprite streamers and to understand their effects in the upper atmosphere. In this paper, we present the results of a study comparing the modeling results of sprite streamers with recent high-speed video observations with focus on the appearances of sprite streamers captured at different exposure times. A more complete report of this study can be found in [2].

The top panel in Fig. 1 shows a sprite event recorded by a high-speed camera with 50-μs exposure time at 50% duty cycle [3], [4]. The successive images [see Fig. 1(a)] show a downward propagating streamer that accelerates, expands, brightens, and then branches. The event is 332 km away from the observation site, resulting in an image resolution of 140 m/pixel. The integrated image [see Fig. 1(b)] shows a much larger view of the same sprite event, where many filamentary channels are present, representing typical images obtained by a video observation system with a low temporal resolution.

The center and bottom panels present fluid simulation results on the propagation and associated optical emissions of a sprite streamer before the branching state is reached [5]. The results are obtained by solving the drift–diffusion equation of charged particles and Poisson's equation for electric field. The finite-volume method is used to solve the drift–diffusion equation, whereas the successive overrelaxation method is used for Poisson's equation [5]. The optical emis-

sions simulated include those being observed from sprites, i.e., the first positive $[1PN_2, N_2(B^3\Pi_g) \to N_2(A^3\Sigma_u^+)]$, second positive $[2PN_2, N_2(C^3\Pi_u) \to N_2(B^3\Pi_g)]$ and Lyman–Birge–Hopfield (LBH) $[N_2(a^1\Pi_g) \to N_2(X^1\Sigma_g^+)]$ band systems of N_2, and the first negative band system of N_2^+ $[1NN_2^+, N_2^+(B^2\Sigma_u^+) \to N_2^+(X^2\Sigma_g^+)]$. The wavelength range of $1PN_2$ is in the red and infrared regions of the visible spectrum, whereas those of $2PN_2$, LBH N_2, and $1NN_2^+$ are in the ultraviolet (UV) and blue regions. Recent research indicates that far-UV emissions from the NO-γ band system may also be present in the sprite spectrum [6].

The model streamer is initiated near the top boundary of the simulation domain, which is set at 75-km altitude, and then propagates downward with acceleration, expansion, and brightening, which are consistent with the observations shown in Fig. 1(a) (see detailed discussion in [2]). The center panel illustrates instantaneous distributions of the electric field and optical emission intensities at 300 μs after the launch of the simulation. The emission intensity in Rayleighs (1 Rayleigh = 10^6 photons/cm^2-column/s) is calculated by integrating volume emission rates along a line of sight perpendicular to the streamer. The field distribution shows a strong enhancement in the streamer head and a moderate enhancement near the origin of the streamer, which leads to enhanced emission in those two regions. The relative intensity and spatial extent of different emissions is largely determined by the excitation threshold energy and the lifetime of the corresponding upper excited state. The excited states $N_2(B^3\Pi_g)$ have the lowest threshold energy, and the resulting $1PN_2$ emission is the strongest; $N_2^+(B^2\Sigma_u^+)$ has the highest threshold energy leading to the weakest emission of $1NN_2^+$, which also have a very short lifetime of $\sim$70 ns at this altitude so that the emission is confined to the small region of a peak field in the streamer head; and $N_2(a^1\Pi_g)$ has the longest lifetime of about 30 μs so the LBH N_2 emission spreads toward the trail of the streamer. The field enhancement and the resulting strong emission in the streamer trail are caused by an increasing streamer current due to expansion and acceleration of the streamer [7].

To examine the effects of the temporal resolution of an imaging system on the appearance of the recorded sprite streamers, we average the emission intensity of $1PN_2$ obtained from the model over five time intervals of the same ending at 300 μs but at different duration. The average intensity distribution for the 5-μs interval appears very similar to the instantaneous distribution [see Fig. 1(c)]. The bright streamer head is elongated, and the emission become less structured at a time resolution of 50 μs, which is the exposure time of the images shown in Fig. 1(a). If the time interval further increases to 300 μs, a continuous luminous streamer channel forms with a much reduced maximum intensity. Two timescales are important for understanding the time-averaging effects shown here as follows:

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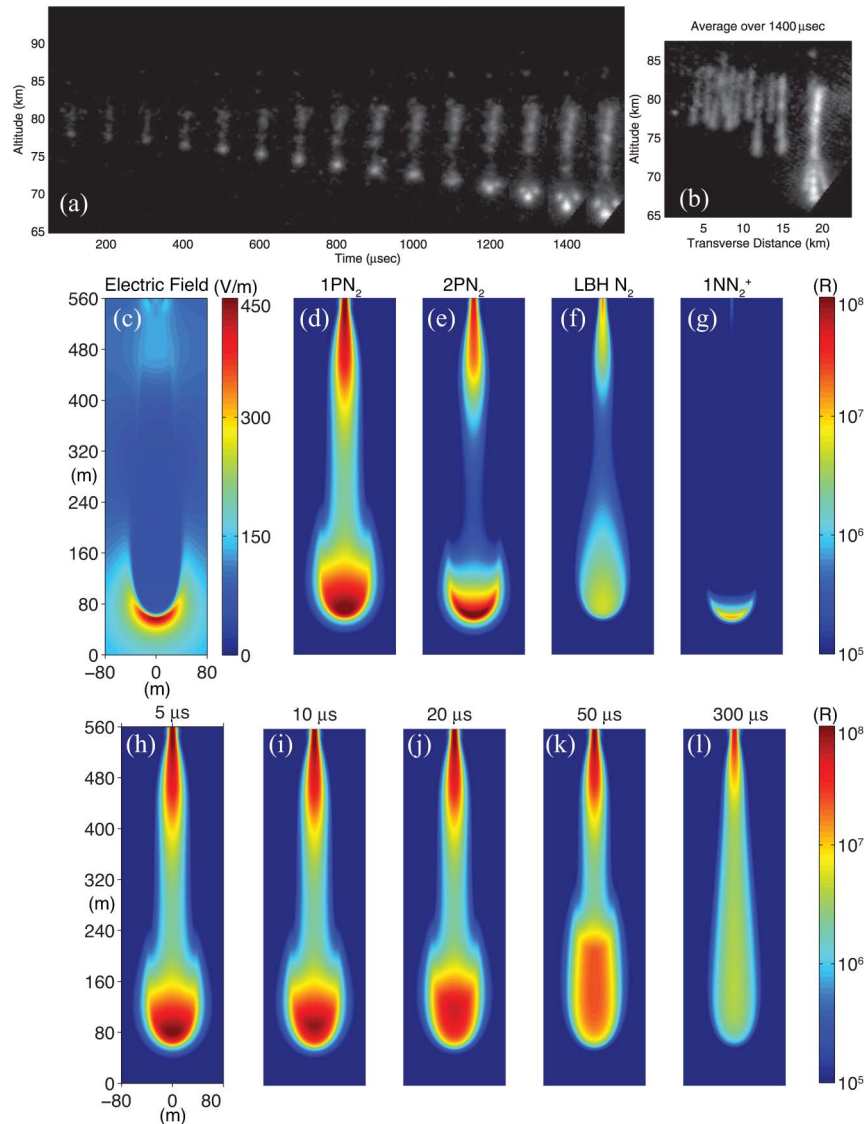M. G. McHarg is with Department of Physics, United States Air Force Academy, CO 80840 USA.

Fig. 1. [(a) and (b)] Observational and [(c)–(l)] modeling results on sprite streamers. (a) Successive images of a sprite streamer at 50-μs exposure time. (b) Integrated image of a sprite event. (c) Instantaneous distributions of the electric field. (d)–(g) Optical emission intensities of a model sprite streamer at 300 μs. (h)–(l) Sprite streamer imaged at different exposure times.

1) the lifetime of $N_2(B^3\Pi_g)$ leading to $1PN_2$ emissions is 5.6 μs at 75-km altitude and 2) the time required for the streamer to travel the characteristic vertical length scale of the streamer. The speed of the model streamer reaches 3.0×10^6 m/s at 300 μs, and the vertical length scale of the high-field region where excitation is predominantly produced in the streamer head [see Fig. 1(c)] is about 10 m. Therefore, the second timescale has a value of 3.3 μs. When the averaging time interval, i.e., the image exposure time, is similar to or less than both of those two timescales, the resulting image appears very similar to the instantaneous view of the streamer, as can be directly illustrated by the comparison of Fig. 1(d) and (h).

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