Molecular nitrogen LBH band system far-UV emissions of sprite streamers

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[1] The time dependent optical emission model developed by Liu and Pasko (2004) is applied to studies of far-UV emissions of sprite streamers due to N_2 Lyman-Birge-Hopfield (LBH) band system. Modeling results indicate that the LBH emissions of sprite streamers at 70 km are generally stronger by up to a factor of 10 than those from the first negative band system of N_2^+, and experimental measurements of the ratio of these two emissions at sprite altitudes can be used to determine poorly known quenching altitude of the N_2 ($a^1\Pi_g$) state. **Citation:** Liu, N., and V. P. Pasko (2005), Molecular nitrogen LBH band system far-UV emissions of sprite streamers, *Geophys. Res. Lett.*, *32*, L05104, doi:10.1029/2004GL022001.

1. Introduction

[2] Optical and near-UV emissions from the first positive ($1PN_2$) and the second positive ($2PN_2$) band systems of N_2 and the first negative band system of N_2^+ ($1NN_2^+$) are well known to appear in the spectrum of sprites according to ground and aircraft based observations [e.g., *Bucsela et al.*, 2003, and references therein] and theoretical studies [e.g., *Liu and Pasko*, 2004] (hereinafter referred to as LP). The recent successful launch of the ISUAL instrument on ROCSAT-2 satellite [*Chern et al.*, 2003] provides new opportunities for studies of far-UV (FUV) emissions of sprites, which are not observable by the ground and aircraft based instruments due to the strong absorption by atmospheric O_2 [*Chern et al.*, 2003, Figure 1]. The ISUAL instrument includes a spectrophotometer with bandpass 150–280 nm, which overlaps with the emission spectrum 120–280 nm of N_2 Lyman-Birge-Hopfield (LBH, $a^1\Pi_g \rightarrow X^1\Sigma_g^+$) band system [*Chern et al.*, 2003].

[3] Sprites commonly consist of large numbers of needle-shaped filaments of ionization [e.g., *Gerken and Inan*, 2003] which typically initiate at altitudes 70–75 km in a form of upward and downward propagating streamers [e.g., *Stanley et al.*, 1999]. Recent modeling studies indicate that streamers propagating in strong fields $E > E_k$ (E_k is the conventional breakdown threshold field) experience acceleration and expansion in good agreement with the above cited observations [LP].

[4] It is well known that a formed streamer can propagate in an electric field substantially lower than E_k ($E_k \simeq 32$ kV/cm at ground pressure and scales proportionally to neutral density at higher altitudes). Experimental and numerical simulation results have demonstrated that the minimum field required for the propagation of positive streamers in air at ground pressure stays close to the value 5 kV/cm [e.g., *Babaeva and Naidis*, 1997, and references therein]. The existing sources about the similar field for the negative streamers indicate that this field is a factor of 2–3 higher than the corresponding field for the positive streamers [*Raizer*, 1991, p. 361; *Babaeva and Naidis*, 1997]. For the sprite phenomenon, the lightning-driven quasi-static electric field is smaller than E_k in the region below the sprite initiation altitude [*Pasko et al.*, 2000, Figure 1a] and the streamers advancing in the weak electric fields ($E < E_k$) likely occupy a substantial part of the overall sprite volume. The studies of emissions of sprite streamers in weak fields are therefore important for correct interpretation of experimental data.

[5] The purpose of this paper is to report modeling results of LBH emissions from sprite streamers, obtained by using a newly developed LBH emission model and a modified streamer model reported by LP, with particular emphasis on comparison of optical and FUV emissions of streamers developing in weak fields at sprite altitudes.

2. Model Formulation

[6] We ignore the radiative and collisional cascading between N_2 singlet states $a^1\Pi_g$, $a'^1\Sigma_u$ and $w^1\Delta_u$, which can increase the total emission from the LBH band system by a factor of ~1.6 [*Eastes*, 2000]. The optical emission model [LP] is modified by including the excitation frequency of N_2 $a^1\Pi_g$ state (Figure 1a), and the corresponding transition rate and quenching rates for the LBH emission. The transition rate is estimated by using the radiative lifetime corresponding to $v' = 3$ (5.5×10^{-5} s) of state $a^1\Pi_g$, which is in the middle of the narrow radiative lifetime interval [5.28, 5.98] $\times 10^{-5}$ s for the levels $v' = 0$–12 of the same state [*Gilmore et al.*, 1992, Table 19]. The obtained transition rate 1.8×10^4 1/s is 2.5 times larger than that provided in [*Vallance Jones*, 1974, p. 119]. The resources of quenching rates of $a^1\Pi_g$ state are very limited. Following the modeling study of LBH emissions in the dayglow conducted by *Eastes* [2000], we assume that: 1) the quenching of $a^1\Pi_g$ by N_2 proceeds at the same rate as for the N_2 $B^3\Pi_g$ state; 2) the quenching by O_2 is an order of magnitude faster than quenching by N_2; 3) the quenching by atomic oxygen O is two orders of magnitude faster than by N_2. The above assumptions are supported by experimental [*Veis et al.*, 1993, and references therein] and modeling [*Kirillov*, 2004] results. Quenching of the $B^3\Pi_g$ state by N_2 has the rate constant 10^{-11} cm^3/s [*Vallance Jones*, 1974, p. 119], therefore the estimated quenching rate constants of $a^1\Pi_g$ state by N_2, O_2 and O, which we use in our model, are 10^{-11}, 10^{-10} and 10^{-9} cm^3/s, respectively. The derived quenching altitude of $a^1\Pi_g$ state is ~77 km.

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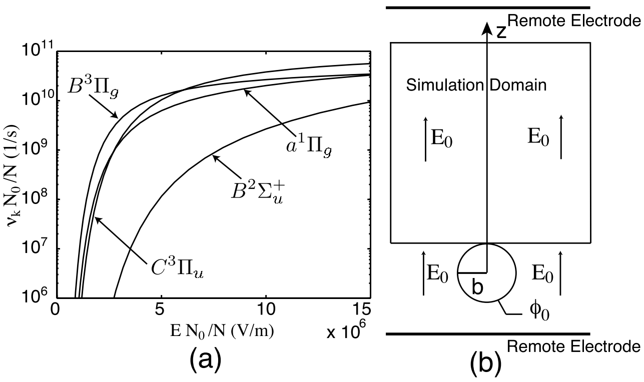

Figure 1. (a) The excitation frequencies ν_k as a function of reduced electric field in air. (b) Simulation domain for streamers developing in weak electric fields.

[7] The streamer model equations are the same as those used by LP. In order to model the streamer propagation in both strong and weak electric fields, we adopt a simple setup (Figure 1b) proposed by *Babaeva and Naidis* [1997] by introducing a small conducting sphere into a weak uniform electric field E_0 to strongly enhance the field around the sphere for initiation of streamers. For initiation of a streamer propagating at a typical sprite altitude of 70 km, we place a cloud of plasma with peak density 5×10^9 m^{-3} and spherically symmetric Gaussian spatial distributions with characteristic scale 1.5 m on the axis of symmetry in the vicinity of the sphere. The radius b of the sphere is 15 m, and the potential ϕ_0 is determined analytically [*Babaeva and Naidis*, 1997] to obtain the electric field $\sim 3E_k$ at the sphere surface. Below, we report modeling results for two study cases: one is for $E_0 = 5\ N/N_0$ kV/cm (weak field $E_0 \ll E_k$); the another is for 33 N/N_0 kV/cm (strong field $E_0 > E_k$), where N and N_0 are neutral densities at the altitude of 70 km and at the ground level, respectively.

3. Results and Discussion

[8] Figure 2 shows results of model calculations corresponding to a positive streamer for the case of $E_0 = 5\ N/N_0$ kV/cm. The streamer first expands quickly until it travels 30 m distance (Figure 2a). Then after experiencing a small contraction, the streamer reaches a stable propagation stage with a constant radius at 60 m away from the starting point. Initially, the enhancement of the homogeneous external field E_0 due to the conducting sphere extends to a distance of 4b (60 m) away from the sphere, and the observed fast expansion of streamers in this high field region agrees with the discussion of LP, section 4.3. When the streamer leaves the high field region, the field in the streamer channel (Figure 2c) is very close to the external field E_0. There is no further potential drop accumulation in the streamer head, and it starts the stable propagation stage.

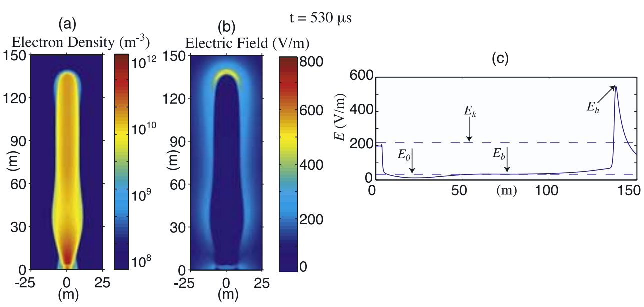

Figure 2. A cross-sectional view of the distribution of the electron number density (a) and electric field (b); and the profile of the electric field (c) along the axis for a positive streamer developing in a field $E_0 = 5\ N/N_0$ kV/cm at altitude 70 km.

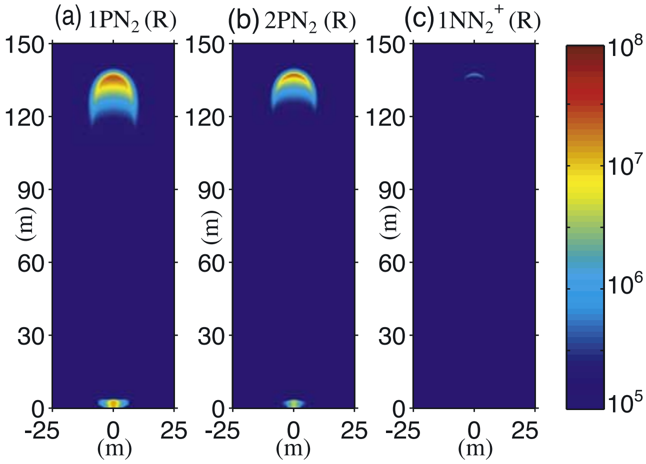

Figure 3. The intensity of optical emissions in selected bands associated with the model positive streamer developing in a field $E_0 = 5\ N/N_0$ kV/cm at altitude 70 km.

[9] Figure 3 illustrates distributions of the intensities of optical emissions (in Rayleighs) corresponding to the same instant of time as specified in Figure 2. The major difference between the optical emissions from the model streamers propagating in weak electric fields and those for the strong field cases reported by LP is the dark streamer channel. For a streamer developing in weak electric fields, the channel

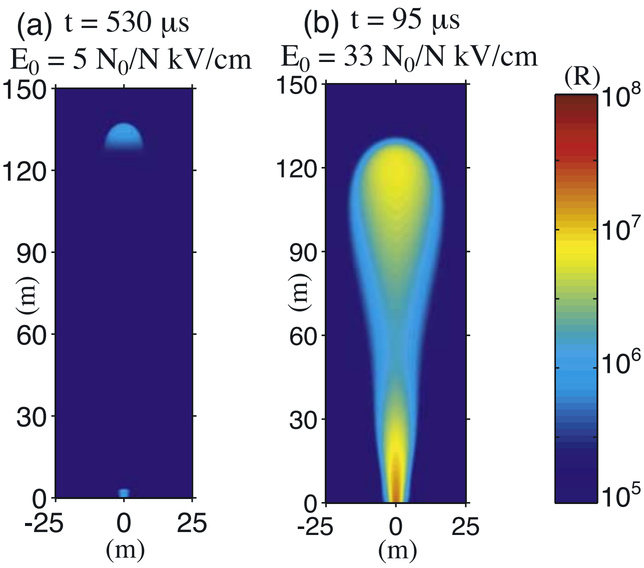

Figure 4. The intensity of LBH emissions associated with the model positive streamers developing at altitude 70 km: (a) $E_0 = 5\ N/N_0$ kV/cm ($0.16E_k$) and (b) $E_0 = 33\ N/N_0$ kV/cm ($1.03E_k$).

field (Figure 2c) is very small and unable to effectively excite the electronic states of N_2 (Figure 1a), so that the emission intensities in the streamer channel are several orders of magnitude lower than those in the streamer head. Another important aspect is the enhancement for all the optical emissions in the streamer head (Figure 3). The formation time of the model streamer is several hundreds of μs, which is much longer than the effective lifetimes of the upper states of all of the optical emission band systems considered. The molecules excite, then radiate or degenerate due to quenching locally, and therefore the strong optical emissions are confined to the streamer head and do not spread along the streamer channel (see related discussion in Section 3 of LP). These results indicate that the observed streamer filaments in many cases may be produced by time averaging of optical luminosity coming from localized regions around streamer tips as streamers move through an observing instrument's field-of-view (FOV). Recent time resolved (~1 ns) imaging of laboratory streamers in point-to-wire or point-to-plane discharge geometry conducted at ground and near ground pressures indicates that only the streamer heads are visible in the high time resolution pictures of streamers, and only the time integrated pictures show luminous streamer filaments [e.g., *van Veldhuizen and Rutgers*, 2002; *Yi and Williams*, 2002]. Although the quenching processes introduce non-similarities of the streamers and their optical emissions at different pressures [e.g., LP], our modeling results qualitatively agree with the above cited experimental results at high pressures.

[10] Figure 4a reports the modeling results of FUV emissions of LBH band system associated with the streamer shown in Figure 2. Comparing Figure 4a with Figure 3c, we observe that the FUV emission is stronger than the blue and near-UV emission of $1NN_2^+$. At the streamer tip (where the field is maximum), the ratio between the intensities of those two emissions is $\gamma = 1.75$, while γ is equal to 125 in the streamer body. The difference is explained by different excitation energy thresholds of LBH (8.55 eV) and $1NN_2^+$ (18.8 eV), and the different electron mean energies in the body and in the tip of the streamer. The excitation of LBH is much more effective than $1NN_2^+$ in the streamer body, where the electron mean energy is lower (~1 eV), while both of the LBH and $1NN_2^+$ are effectively excited in the streamer tip, where the electron mean energy is higher (~7.5 eV). The above cited energies are estimated using the corresponding electric fields through local field approximation [LP and references therein].

[11] An altitude profile of the ratio of N_2 ionized-to-neutral emission with high spatial resolution (~1 km) was reported by *Morrill et al.* [2002]. The profile shows that the ratio is small (effectively corresponding to large γ value discussed above) in the region above ~55 km, while increases in the region below ~55 km. Our results support one of the interpretations given by the authors that the emissions from the region below 55 km are dominated by those coming from the streamer head and the upper region with the low ratio of N_2 ionized-to-neutral emission corresponds to the streamer body. The electron mean energy in the streamer body obtained in our study agrees with [*Morrill et al.*, 2002], however, there is a large difference between the two mean energies in the streamer head, which may be explained by the low temporal resolution of the observation.

[12] Figure 4b illustrates the LBH emission at the moment of time 95 μs from a streamer developing in a strong field $E_0 = 33$ N/N_0 kV/m ($E_0 > E_k$). The relatively strong LBH emissions in the streamer channel and the absent enhancement of the emissions in the head are explained in this case similarly to the modeling results on $1PN_2$ emissions presented by LP, Section 3 (i.e., by relatively long lifetime of $a^1\Pi_g$ state in comparison with the overall streamer formation time). The mean energies of electrons in the streamer tip and the body are 9.3 and 1.8 eV, respectively.

[13] Recently, ISUAL instrument on ROCSAT-2 satellite has successfully observed FUV emissions from sprites [*Mende et al.*, 2004; *Frey et al.*, 2004]. Below we estimate the ratio (γ') of LBH and $1NN_2^+$ emission intensities due to our model sprite streamers entering the ISUAL spectrophotometer channel 1 (150–280 nm) and channel 3 (391.4 nm) after passing through the upper atmosphere. We assume that ratios of the band intensities to the total intensity of a particular transition band system are the same for both sprite streamers and aurora [*Vallance Jones*, 1974, Tables 4.9 and 4.14]. The atmospheric absorption is negligible for $1NN_2^+$ emissions, and the relative fraction of the total $1NN_2^+$ intensity received by channel 3 is 65%. Using absorption cross-sections of O_2 [e.g., *Yoshino et al.*, 1992; *Minschwaner et al.*, 1992; *Amoruso et al.*, 1996; *Yoshino et al.*, 2005], we find that the LBH emissions with wavelengths shorter than ~180 nm are heavily absorbed even for observations made from space. This result is consistent with the atmospheric attenuation of solar irradiance by O_2 [*Huffman*, 1985] and the conclusion that the emissions causing photoionization of O_2 (98.0–102.5 nm) are not observable from space [LP]. We multiply the LBH band intensity ratios by wavelength dependent atmospheric transmission curve (due to O_2 absorption), and sum the resulting values to obtain the relative fraction of LBH emissions transmitted to ISUAL. Assuming that the sprite-satellite distance is 2500 km and the emission altitude is 70 km, we obtain that 11% of the total intensity of LBH emissions is able to reach the spectrophotometer, and estimate $\gamma' = \frac{11}{65}\gamma$. In the real observation, the FOV of the spectrophotometer is much larger than the size of a streamer, and we need to use the spatially averaged intensity ratio γ of the entire streamer, which is almost unvarying for the case of $E_0 = 5$ N/N_0 kV/cm, with a value of $\gamma = 9.2$, and slowly increases and approaches a value of $\gamma = 5$ during the simulation period for the case of $E_0 = 33$ N/N_0 kV/cm, according to our modeling results for streamers at 70 km altitude. The ratio γ' is ~1.6 and ~0.85 for the weak and strong fields, respectively. We emphasize that γ' discussed here includes total number of model photons appearing in passbands of two ISUAL photometers. The interpretation of responses of photometers depends on details of their calibration, which is presently ongoing (S. Mende, private communication, 2005), and related discussion as well as comparisons with actual ISUAL data are beyond the scope of the present paper.

[14] We note that the modeling results strongly depend on the accuracy of the transition and quenching rates of the $a^1\Pi_g$ state. If we take the transition rate as 7.2×10^3 1/s [*Vallance Jones*, 1974, p. 119] and make the same assumptions about quenching rates, the quenching altitude will be ~82 km. Again, if we calculate the spatially averaged intensity ratio of LBH and $1NN_2^+$ emissions from a streamer

in the weak field, a value of $\gamma = 4.3$ is obtained. The relative change with respect to the previous result $\gamma = 9.2$ is $9.2/4.3 = 2.1$ and is very close to an expected factor $\exp(5/7) = 2.0$ due to 5 km reduction in quenching altitude, where 7 km is an approximate scale height of the atmosphere.

[15] Assuming that the quenching altitude of LBH is 77 km and accounting for atmospheric transmission and quenching effects discussed above we estimate that γ' would be in the interval [0.09, 2.9] for a sprite with the brightest part spanning from 55 to 75 km altitude (this estimate is subject to <30% error due to realistic variability in satellite viewing geometry). It should be noted that our calculation results cannot be directly compared to the experimental data on elves, since (1) in contrast to sprite streamers elves appear well above LBH quenching altitude, and (2) emissions from streamers are mostly controlled by very high electric fields ($\geq 3E_k$) around streamer heads which may not be easily attainable in elves [*Inan et al.*, 1997].

[16] If we assume that the transition rate of $a^1\Pi_g$ state estimated in [*Gilmore et al.*, 1992] is accurate, the quenching altitude h_Q of LBH emissions could be in principle estimated from the high spatial resolution experimental data of intensity ratio of LBH and $1NN_2^+$ emissions. If the intensity ratio γ is obtained for a streamer developing at 70 km, the quenching altitude of LBH emissions can be estimated as $h_Q = 77 + 7\ln(9.2/\gamma)$. For a streamer at an altitude h different from 70 km: $h_Q = 77 + 7\ln(\frac{9.2\exp[(70-h)/7]}{\gamma})$. It should be noted that the above expressions are only applicable to situations when the $a^1\Pi_g$ state is heavily quenched and under an assumption that most of LBH and $1NN_2^+$ emissions come from regions around tips of streamers propagating in weak ($E \leq E_k$) electric fields.

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