JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, A00E23, doi:10.1029/2009JA014685, 2010

Analysis of UV flashes of millisecond scale detected by a low-orbit satellite

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Received 27 July 2009; revised 19 October 2009; accepted 23 November 2009; published 8 May 2010.

[1] The microsatellite Tatiana recently detected two scales of the UV flash duration: 1–4 ms and 10–64 ms. This paper studies the atmospheric electricity phenomena that can serve as a source for short-millisecond-range flashes. It is shown that UV flashes in the millisecond scale detected by Tatiana may be explained as generated by gigantic blue jets (GBJ). The influence of an assumed self-consistent governing electric field in the GBJ streamer zone on the UV pulse shape and duration is revealed. It is also shown that red sprites can be a source for UV flashes with similar temporal profiles but at much lower intensity. The model results are also compared with the observations made by the Imager of Sprites and Upper Atmospheric Lightnings imager on board the FORMOSAT-2 satellite.

Citation: Shneider, M. N., and G. M. Milikh (2010), Analysis of UV flashes of millisecond scale detected by a low-orbit satellite, *J. Geophys. Res.*, *115*, A00E23, doi:10.1029/2009JA014685.

1. Introduction

[2] Recently the UV instrument flying on board the microsatellite Tatiana detected two scales of UV flash duration: 1–4 ms and 10–64 ms, which originated in the equatorial region of the Earth [*Garipov et al.*, 2005, 2006]. The satellite, which belongs to Moscow State University, was orbiting at a height of 950 km along a circular orbit with an inclination of 82°. The detector operates in the wavelength rage 300–400 nm. Also *Garipov et al.* [2005] made the energy estimates that took into account geometric factors along with the quantum efficiency of the detector, as well as the atmospheric absorption. These estimates show the detected flashes correspond to about 10^{22}–10^{23} radiated UV photons and in a few cases reach 10^{24} photons. The observed UV pulses are most probably caused by gigantic blue jets (GBJ); their short scale (1–4 ms) corresponds to the lifetime of a long streamer (having 10–30 km length), while the long scale (10–64 ms) corresponds to the lifetime of a slow-moving leader or the streamer zone of a leader [*Milikh and Shneider*, 2008]. However, any phenomena in the atmosphere that produces ionization could be an optical/UV source. The objective of this paper is to study the atmospheric electricity phenomena that could be a source of the observed UV flashes. The list of those phenomena includes, but is not limited to, blue jets, red sprites, and elves. All of these are associated with the air breakdown in the middle atmosphere due to the electric field generated by a thunderstorm. The quantitative analysis is based on earlier developed models of long streamers in the atmosphere [*Raizer et al.*, 1998] and blue jets [*Raizer et al.*, 2007]. In our analysis of the possible sources of the observed UV flashes we rely on the following criteria: temporal characteristics of the UV radiation, total radiated energy in the given spectral range, and geographic location of the UV sources.

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0148-0227/10/2009JA014685

2. Gigantic Blue Jets

[3] First we consider GBJ, first discovered by *Pasko et al.* [2002], as a source of the UV flashes. As shown by *Garipov et al.* [2010], the UV flashes were detected mainly over oceans and shores where the rate of lightning flashes is low. At the same time GBJ are also originated over oceans or shores, which indicates that both phenomena could be of the same origin. Furthermore, the average energy of the radiated UV emission 10–10^3 kJ is in the range of the energy of GBJ as estimated by *Kuo et al.* [2008] from observations made by the Imager of Sprites and Upper Atmospheric Lightnings (ISUAL) imager on board the FORMOSAT-2 satellite.

[4] To describe the UV flashes due to GBJ, we apply a model [*Milikh and Shneider*, 2008] based on the earlier analysis by GBJ [*Raizer et al.*, 2006, 2007]. We consider that GBJ originate from thunderclouds at 15, 18, and 20 km, although we assume the same length of the respective leader, Δ_L = 7.2 km. The latter corresponds to the characteristic pressure scale. A blue jet (BJ) consists of a bunch of streamers, propagating in the self-formed averaged electric field E_s [*Raizer et al.*, 2007]. Therefore, we consider the UV emission generated by a trunk starting from the leader tip and propagating up to low ionosphere in a few milliseconds, similar to a streamer zone of a leader. We follow the BJ model described by *Raizer et al.* [2007], which is based on a model of a single streamer that starts at the leader tip and

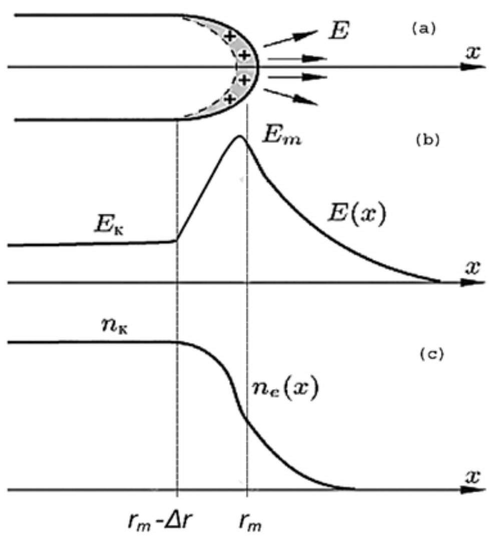

Figure 1. Schematic of a streamer tip as well as the qualitative distribution of the electron density and electric field along the streamer axis.

moves upward in the self-consistent governing field formed in the streamer zone of a leader. This field is generated by the combined effect of the cloud charges along with the charges of a huge number of streamers that are continuously being created and destroyed. Note that it is an outstanding problem to develop a comprehensive model regarding the formation of the self-consistent field in the streamer zone of a leader.

[5] Therefore, we consider a single streamer moving in a hypothetical governing field $E_s(x)$ and potential $U_0(x)$. On the basis of the similarity law, justified by *Raizer et al.* [2007], we assume that in the exponential atmosphere the self-consistent field changes according to the relation $E_s/N =$ const [*Liu and Pasko*, 2006; *Raizer et al.*, 2007, 2010]. Thus we define the absolute value of E_S in the same way as for the uniform atmosphere, on the basis of the threshold electric field where the growth of the streamers is unlimited [*Raizer et al.*, 2006].

[6] Our simulations [*Milikh and Shneider*, 2008] show that the UV emission is mostly generated by the strong field near the streamer tip, and the predominant role is played by the N_2(2P) band. Therefore, our model of UV flashes includes the following steps: (1) We apply the model of long ascending streamers in the exponential atmosphere and find the spatial and temporal distribution of the electric field near the streamer tip; (2) using the above electric field we compute the excitation rate of the N_2(C) electronic layer that generates the N_2(2P) band; and (3) we consider the quenching collision of N_2(C) electronic layer and then describe the radiation transport in the atmosphere, to determine the number of photons reaching the UV detector. As described in *Milikh and Shneider* [2008], the approximate electron density distribution in the streamer is given by

$$n_e(x) \approx \left(n_{k,0} - n_{e,0}\right) \exp[(r_m - \Delta r - x)/\Delta r] + n_{e,0}, \quad x \geq r_m - \Delta r. \tag{1}$$

Neglecting the electric field in a plasma column as compared with E_m (see Figure 1), we can approximate the electric field as

$$E(x) \approx [1 - (r_m - \Delta r - x)/\Delta r]E_m, r_m - \Delta r \leq x \leq r_m \tag{2}$$

$$E(x) \approx E_m r_m/(r_m + x), \quad x > r_m. \tag{3}$$

The values $n_{k,0}$, $n_{e,0}$, Δr, r_m, and E_m in equations (1)–(3), as well as the streamer tip velocity, v_s, correspond to the altitude h. They have been determined by *Raizer et al.* [2008]. The approximate scale of the charge separation region in the streamer tip can be estimated as [*Bazelyan and Raizer*, 1998, 2000]

$$\Delta r \approx v_s/\nu_i(E_m) \sim r_m/\ln\left(n_{k,0}/n_{e,0}\right), \tag{4}$$

where $n_{k,0}$ and $n_{e,0}$ are the electron number densities behind the ionization wave and the bulk electron density, respectively, at the altitude h, and $\nu_i(E_m) \equiv \nu_i(E_m/N(h))$ is the ionization frequency at the maximal electric field in the streamer tip region (Figure 1).

[7] We assume that, at sea level, $n_{e,0} = 10^2$ cm^{-3} and $n_{e,0}(h) \sim n_{e,0}(0)N(h)/N_0$. Owing to the air ionization by a strong field at the streamer tip, a plasma is formed with the electron density: $n_{k,0} \approx 10^{14}(N/N_0)^2$ cm^{-3}, where $N_0 = 2.5 \times 10^{19}$ cm^{-3} is the air density at sea level. Note that because $n_{k,0} \gg n_{e,0}$, results of the calculations are almost independent of the assumed value of $n_{e,0.}$

[8] We applied the numerical model for streamer propagation described by *Raizer et al.* [2007] to compute the spatial distribution of the electric field, then used this field as an input into our kinetic code [*Milikh et al.*, 1998], which calculates the excitation rate of the N_2(2P) electronic state of molecular nitrogen.

[9] The rate of the optical excitation in the streamer tip region can be determined by

$$\frac{dN^*_{\text{str}}}{dt} = 2\pi \int_{r_m - \Delta r}^{\infty} k_{\text{ex}}[E(x)/N(h)]N_{N_2} n_e(x) r_m^2(h) dx, \tag{5}$$

where $N^*_{\text{str}}(t)$ is the total number of the excitations produced by a single developing streamer channel at the time t, and k_{ex} is the excitation rate coefficient.

[10] It follows from observations that BJ looks like an expanding spherical cone with some solid angle, θ, between 2° and 15°. L is the cone length along the axis, r is the cone radius. Neglecting the initial BJ radius (at $L = 0$), the radius of the expanding cone of the length, L, is $R(L) \approx L \tan(\theta/2)$. The maximal number of streamers in the BJ head at altitude, h, can be estimated by introducing a new factor $\xi \approx [R(L)/r_m(h)]^2$. As in the work of *Milikh and Shneider* [2008], we introduce the packing factor ($F_{\text{pack}} \ll 1$), which is the ratio of the area covered by the streamers to the total area of the leader head. This factor is due to the streamers repulsion, which does not allow them to be too close to each other. Therefore, the total rate of excitations in the BJ head region due to the streamer bunch is

$$\frac{dN^*}{dt} = \xi \frac{dN^*_{\text{str}}}{dt} = 2\pi R^2(L) F_{\text{pack}} \int_{r_m - \Delta r}^{\infty} k_{\text{ex}}[E(x)/N(h)] N_{N_2} n_e(x) dx. \tag{6}$$

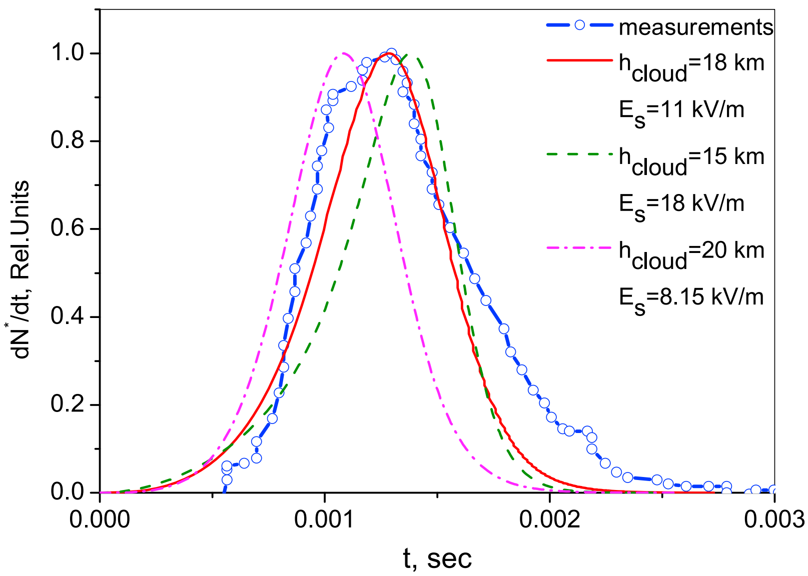

Figure 2. UV pulse shapes generated by the blue jet, computed for the different initiation heights, and that detected by the Tatiana microsatellite (white circles) [*Garipov et al.*, 2005]. The emission intensity is normalized by its peak value.

As mentioned by *Milikh and Shneider* [2008], the temporal behavior of the intensity of the UV flashes does not depend on the cone angle, θ, but the total number of excitations (total number of emitted photons) does depend on the assumed cone angle. This can be estimated as

$$N^* = \int_0^\infty \frac{dN^*}{dt} dt. \quad (7)$$

The computed shape and duration of the radiated UV pulses strongly depend on the assumed value of the governing field E_s. *Raizer et al.* [2007] have shown that the values $(E/N)_s$ computed for different leader initiation heights, obey the similarity law with accuracy within a few percent. Normalized UV pulses as detected by the Tatiana microsatellite (white circles) [*Garipov et al.*, 2005] are shown in Figure 2 and compared with those computed for the GBJ and having different initiation heights: $h_i = h_{\text{cloud}} + \Delta_L$. Note that the observed UV pulse fits well with the BJ development in the governing electric field $E \approx E_s$. Figure 3 shows the computed UV pulse shapes due to GBJ having an initiation height of 18 + 7.2 = 25.2 km and different governing fields E_s, along with that observed by the Tatiana microsatellite (white circles). The best agreement between the theory and observations is reached at E_s = 0.11 kV/cm. A small devi-

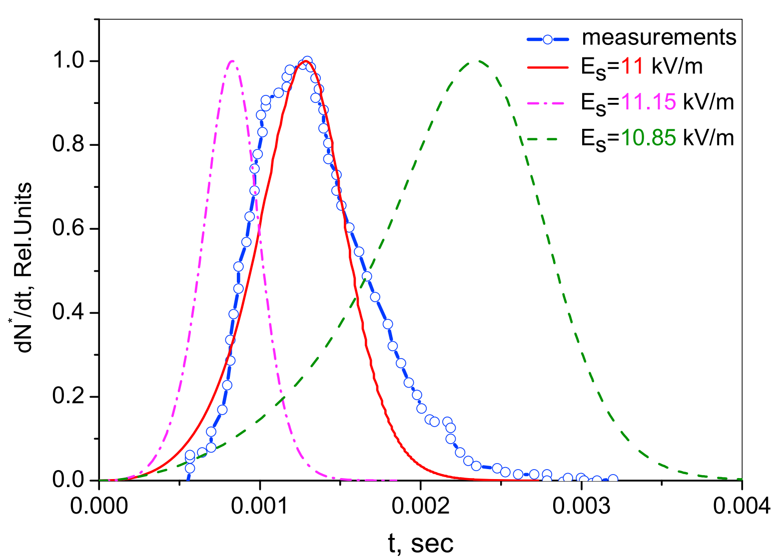

Figure 3. Normalized UV pulse shapes generated by the blue jet computed for h_{cloud} = 18 km, the leader length Δ_L = 7.2 km, and at different governing fields, along with that that detected by the Tatiana microsatellite (white circles).

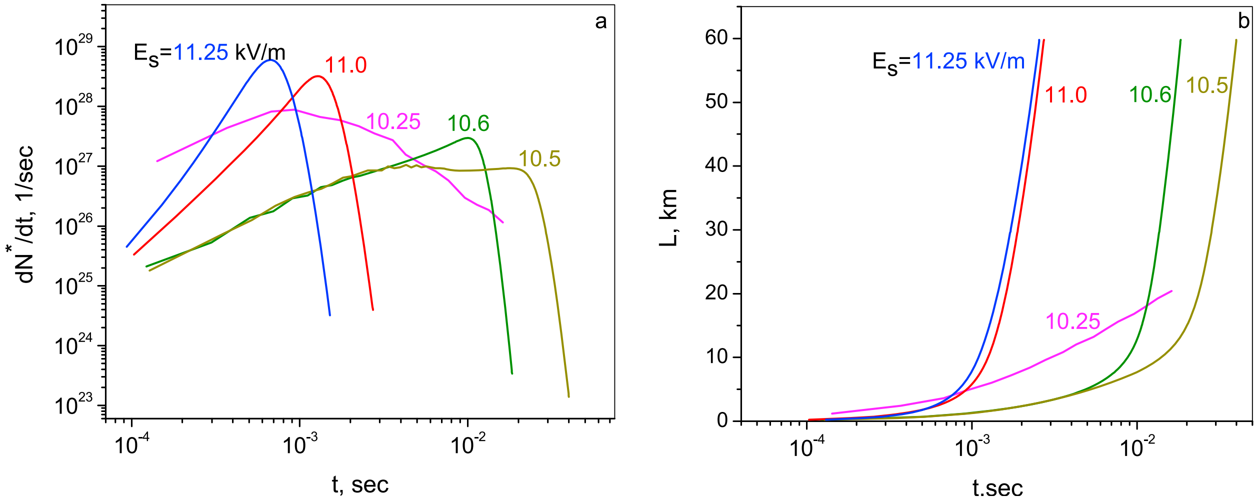

Figure 4. Study of the critical governing field with h_{cloud} = 18 km, leader length Δ_L = 7.2 km, cone angle Θ = 10°, and packing factor F_{pack} = 0.1: (a) UV radiation flashes and (b) computed gigantic blue jet (GBJ) prong lengths at different governing fields E_s. Observed UV pulse shape fits well with E_s = 0.11 kV/cm.

ation (<1.5%) from this value in the governing field results in the essential variation of the computed UV pulse duration. The dependencies of computed UV radiation intensities on assumed values of E_s, at the initiation height of 18 km, cone angle Θ = 10°, and packing factor F_{pack} = 0.1, are shown in Figure 4a. Corresponding computed GBJ prong lengths are shown in Figure 4b. As mentioned above, the observed UV pulse shape fits well when E_s = 0.11 kV/cm. At E_s < 10.5 kV/m, the streamer cannot propagate from $h_i = h_{\text{cloud}} + \Delta_L$ to the ionosphere. So the streamer, propagating in the self-consistent field E_s = 0.1025 kV/cm, stops when its length is L < 20 km. At E_s > 0.11 kV/cm, streamers propagate up to the ionosphere (altitude, ~80 km). However, they do it much faster than at E_s = 0.11 kV/cm, and the corresponding durations of the model UV flashes are much shorter than that observed by the Tatiana satellite.

[11] Finally we estimate the number of photons radiated by a leader head for different values of the cone angle and by assume that the packing factor F_{pack} = 0.1. Previously, we determined that 6.6×10^{23} photons are radiated if θ = 2.5°, while 2.6×10^{24} photons are radiated if θ = 5.0° [*Milikh and Shneider*, 2008]. We recall that from the observations of the UV detector on board the Tatiana microsatellite, the causative source of UV emission was estimated to be 10^{22}–10^{23} photons per flash, and on a few occasion even 10^{24} photons per flash. This is in agreement with our model.

[12] Although our main interest is in studies of UV flashes due to GBJ we found very instructive the optical images of GBJ recorded 28 May 2007 by an ISUAL instrument onboard FORMOSAT satellite [*Kuo et al.*, 2008]. Figure 5 shows a sequence of the ISUAL images of GBJ adapted from *Kuo et al.* [2008] along with the excitation rate of N_2(2P) emission by an upward moving streamer computed by our model. The main features of the sequences of the images are as follows: The leader was initiated from the top of the cloud and has 5–10 km length, consistent with the leader length of 7.2 km in our model. GBJ structure forms in a time shorter than 30 ms (the time between Figure 5b and Figure 5c), which indicates that fast running streamers are involved in the processes. Finally, the brightness of the optical emission peaks at 40–45 km. The emission is caused by N_2(1P) and N_2(2P) bands [*Kuo et al.*, 2008]. Our model reveals that the brightness of N_2(2P) band attributable to the bunch of streamers peaks at 35–45 km regardless of the cloud height (Figure 5e). We expect similar results for the N_2(1P) band since the excitation cross sections of 1P and 2P bands are not much different.

[13] Moreover, since the radiation source is located at 35–45 km, i.e., above the peak of the ozone layer, the UV emission generated by GBJ and observed by a satellite should not be affected by the atmospheric absorption. This differs from ground-based observations of GBJ, in which case UV emission from GBJ is a subject to the ozone absorption and the tropospheric scattering by aerosols.

3. Red Sprites

[14] Our present analysis is based on the streamer theory of red sprites introduced by *Raizer et al.* [1998]; however, we generalize this by considering streamers initiated at different altitudes. Consider a streamer that starts at altitude h_i from a conducting patch in the lower ionosphere and propagates downward along the coordinate $x = h_i - h$ in the nonuniform atmosphere. The potential of the external field is given by

$$U_0(x) = -\phi_0 \frac{4(x/h_i)}{\left[1 - (x/h_i)^2\right]^2},$$

where $\phi_0 \approx 0.97(80/h_i)^2$ is in megavolts and h_i is in kilometers. The model for sprite streamer propagation is the same as in the work of *Raizer et al.* [1998], whereas the model of optical radiation is similar to that developed for the GBJ [*Milikh and Shneider*, 2008]. We took into account the fact that the optical emission is predominantly generated by the excited N_2(B) electronic state of molecular nitrogen, which radiates in the N_2(1P) band.

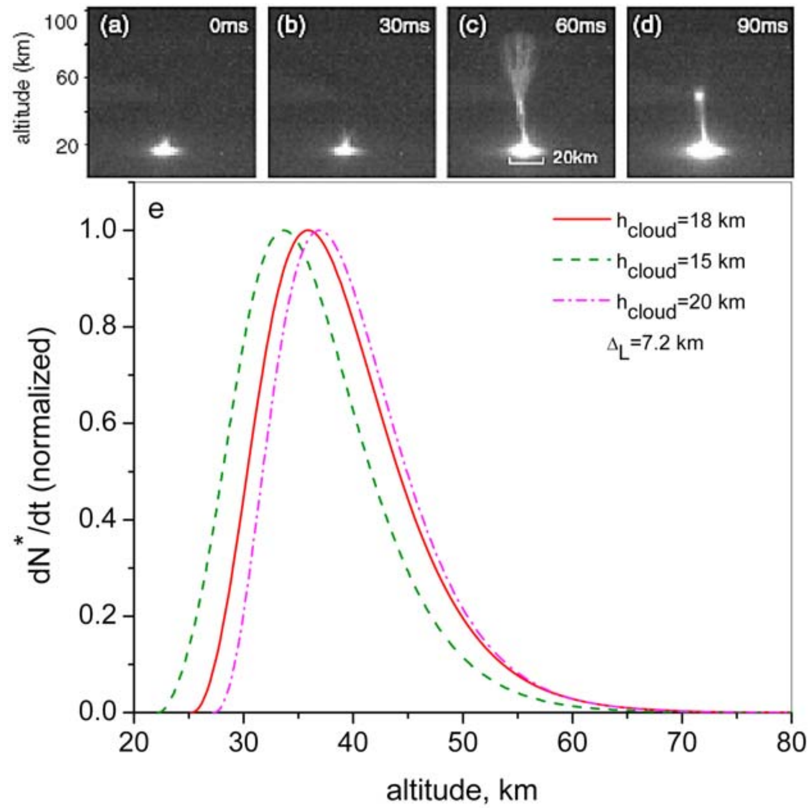

Figure 5. (a–d) Time sequences of GBJ obtained by the Imager of Sprites and Upper Atmospheric Lightnings instrument on 28 May 2007 (adapted from *Kuo et al.* [2008]). (e) Model excitation rate of N_2(2P) normalized by its peak value. The emission is generated by GBJ launched from the different cloud altitudes.

[15] Unlike GBJ, the sprites are considered to be a number of noninteracting streamers; therefore, the instantaneous rate of the excitation in the whole streamer tip region (qualitative distributions of parameters are shown in Figure 1) can also be determined by equation (5).

[16] The results of computations describing the red sprites initiated at the different altitudes are shown in Figures 6 and 7. Note that our model predicts the maximum excitation rate (the maximum emissivity) at altitude ~60–65 km (Figure 6a), which fits well with the observations shown in Figure 6b.

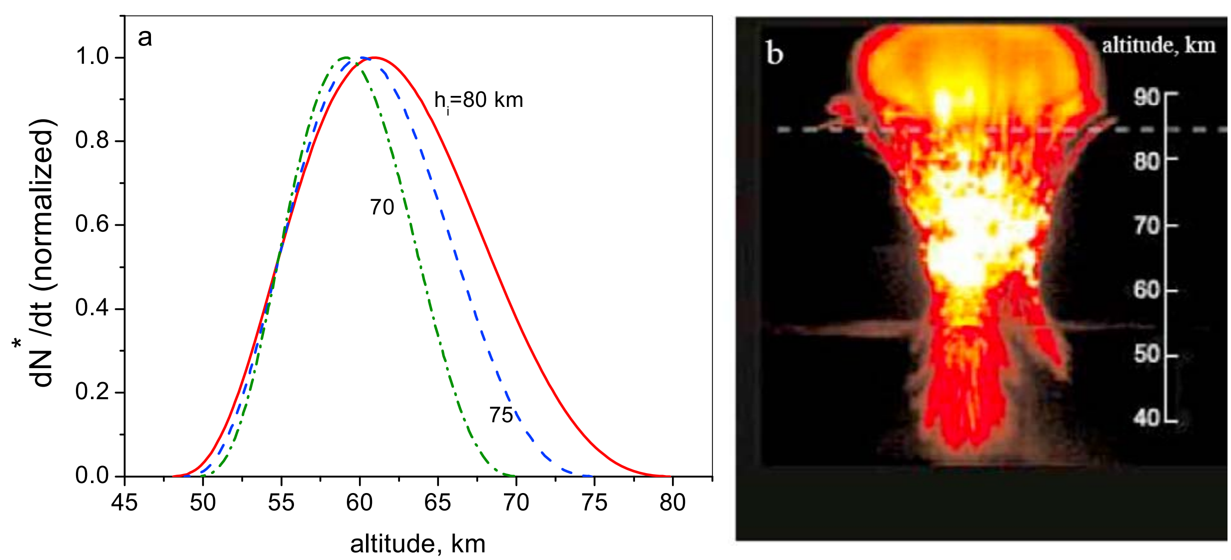

Figure 6. (a) The excitation rate of N_2(1P) emission normalized by its peak value, generated by the red sprites launched from the different altitudes. (b) Photo of red sprites (adapted from *Stenbaek-Nielsen and McHarg* [2008]).

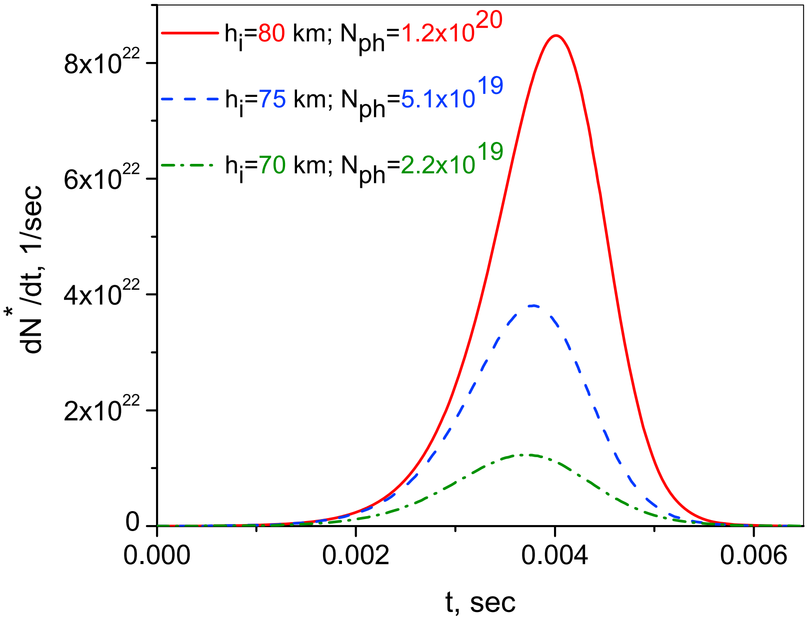

Figure 7. Temporal radiation intensity profiles for red sprites initiated at different altitudes. The corresponding computed total numbers of photons generated during the red sprite development are shown.

The shape and duration of the radiation pulses induced by the red sprites (Figure 7) are similar to that observed by the Tatiana satellite, but the total number of photons radiated by a single streamer is two to five orders less than that generated by the GBJ. In fact, our calculations (see Figure 6) show that a single streamer belonging to a red sprite launched from the altitude of 80 km radiates about 10^{20} photons in the N_2(1P) band. If the streamer starts from a lower altitude, this number is even smaller. Therefore thousands streamers are needed to produce an optical intensity similar to that of GBJ. Such a number of streamers is more than are expected in a single red sprite.

4. Elves

[17] On the basis of numerous observations of elves [see, e.g., *Inan et al.*, 1997; *Israelevich et al.*, 2004] and detailed numerical modeling [see, e.g., *Inan et al.*, 1996; *Nagano et al.*, 2003], we conclude that the ionization and radiation pulses induced by the elves are very short, lasting less than 1 ms, and therefore cannot be considered as an appropriate source of the UV flashes observed by the Tatiana microsatellite.

5. Conclusions

[18] In conclusion, we discussed whether thunderstorm-related phenomena can serve as a source for the millisecond-scale UV flashes recently observed by the microsatellite Tatiana. These phenomena include GBJ, red sprites, and elves. The analysis relies on temporal characteristics of the UV radiation, total radiated energy in the UV range, and geographic location of the UV sources.

[19] We showed that GBJ are the most probable source for the UV flashes. The quantitative analysis shows that the modeled UV pulses fit well with the observations if a proper choice of the governing electric field E_s is accepted. We also found that the computed shape and duration of the radiated UV pulses strongly depend on the assumed value of E_s. The latter fact indicates the existing necessity to develop a comprehensive model of formation of the self-consistent governing field in the streamer zone of a leader, which will be a subject of our future studies.

[20] The results of computations describing the UV emissions due to red sprites reveal that the shape and duration of the UV pulses induced by the red sprites fit well with the observations made by the Tatiana satellite. However, 10^4–10^5 streamers would be needed to produce the number of photons observed in the UV flashes.An analysis of telescopic images of giant sprites [*Gerken and Inan*, 2002] could presumably produce a better estimate of the total radiated emission for comparison with the intensity of the UV flashes. It implies that an increase in the detection sensitivity of the UV monitor may help one to observe the UV flashes as induced by red sprites. In this case, the observations could detect a great number of UV flashes over the region where red sprites are plentiful. Finally, elves having duration less than 1 ms cannot be considered as an appropriate source for the observed UV flashes.

[21] **Acknowledgments.** We appreciate valuable discussions with Yoav Yair, Boris Khrenov, and Victor Pasko. The work was supported by NSF grant ATM-0833921.

[22] Amitava Bhattacharjee thanks Earle Williams and another reviewer for their assistance in evaluating this manuscript.

References

Bazelyan, E. M., and Y. P. Raizer (1998), *Spark Discharge*, CRC Press, Boca Raton, Fla.

Bazelyan, E. M., and Y. P. Raizer (2000), *Lightning Physics and Lightning Protection*, IOP, Bristol, U. K.

Garipov, G. K., et al. (2005), Ultraviolet flashes in the equatorial region of the earth, *JETP Lett.*, *82*, 185–189, doi:10.1134/1.2121811.

Garipov, G. K., et al. (2006), Ultraviolet radiation detector of the MSU research educational microsatellite, *Instrum. Exp. Technol.*, *49*, 126–132, doi:10.1134/S0020441206010180.
Gerken, E. A., and U. S. Inan (2002), A survey of streamer and diffuse glow dynamics observed in sprites using telescopic imagery, *J. Geophys. Res.*, *107*(A11), 1344, doi:10.1029/2002JA009248.
Inan, U. S., W. A. Sampson, and Y. N. Taranenko (1996), Space-time structure of optical flashes and ionization changes produced by lightning-EMP, *Geophys. Res. Lett.*, *23*, 133–136, doi:10.1029/95GL03816.
Inan, U. S., et al. (1997), Rapid lateral expansion of optical luminosity in lightning-induced ionospheric flashes referred to as "elves," *Geophys. Res. Lett.*, *24*, 583–586, doi:10.1029/97GL00404.
Israelevich, P. L., et al. (2004), Transient airglow enhancements observed from the space shuttle Columbia during the MEIDEX sprite campaign, *Geophys. Res. Lett.*, *31*, L06124, doi:10.1029/2003GL019110.
Kuo, C. L., et al. (2008), Radiative emission and energy deposition in transient luminous events, *J. Phys. D*, *41*, 234014, doi:10.1088/0022-3727/41/23/234014.
Liu, N., and V. P. Pasko (2006), Effects of photoionization on similarity properties of streamers at various pressures in air, *J. Phys. D*, *39*, 327–334, doi:10.1088/0022-3727/39/2/013.
Milikh, G. A., and M. N. Shneider (2008), Model of UV flashes due to gigantic blue jets, *J. Phys. D*, *41*, 234013, doi:10.1088/0022-3727/41/23/234013.
Milikh, G., J. A. Valdivia, and K. Papadopoulos (1998), Spectrum of red sprites, *J. Atmos. Sol. Terr. Phys.*, *60*, 907–912, doi:10.1016/S1364-6826(98)00032-7.
Nagano, S., K. Yagitani, S. Miyamura, and S. Makino (2003), Full-wave analysis of elves created by lightning-generated electromagnetic pulses, *J. Atmos. Sol. Terr. Phys.*, *65*, 615–625, doi:10.1016/S1364-6826(02)00324-3.
Pasko, V. P., M. A. Stanley, J. D. Mathews, U. S. Inan, and T. G. Woods (2002), Electrical discharge from a thundercloud top to the lower ionosphere, *Nature*, *416*, 152–154, doi:10.1038/416152a.
Raizer, Y. P., G. M. Milikh, M. N. Shneider, and S. V. Novakovski (1998), Long streamers in the upper atmosphere above thundercloud, *J. Phys. D*, *31*, 3255–3264, doi:10.1088/0022-3727/31/22/014.
Raizer, Y. P., G. M. Milikh, and M. N. Shneider (2006), On the mechanism of blue jet formation and propagation, *Geophys. Res. Lett.*, *33*, L23801, doi:10.1029/2006GL027697.
Raizer, Y. P., G. M. Milikh, and M. N. Shneider (2007), Leader-streamer nature of blue jets, *J. Atmos. Sol. Terr. Phys.*, *69*, 925–938, doi:10.1016/j.jastp.2007.02.007.
Raizer, Y. P., G. M. Milikh, and M. N. Shneider (2010), Streamer and leader-like processes in the upper atmosphere, *J. Geophys. Res.*, doi:10.1029/2009JA014645, in press.
Stenbaek-Nielsen, H. C., and M. G. McHarg (2008), High time-resolution sprite imaging: Observations and implications, *J. Phys. D*, *41*, 234009, doi:10.1088/0022-3727/41/23/234009.

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