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

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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. 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.

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 10–10²³ 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.

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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.

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 $E_s/N = \text{const}$ [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].

Our simulations [Milikh and Schneider, 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$_2$(2P) 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 Schneider [2008], the approximate electron density distribution in the streamer is given by

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

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

$$E(x) \approx \left[1 - (r_m - \Delta r - x)/\Delta r\right]E_m, \quad r_m - \Delta r \leq x \leq r_m \quad (2)$$

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

The values $n_{k,0}$, $n_{c,0}$, $\Delta r$, $r_m$, 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]

$$\Delta r \approx v_s/\nu(E_m) \sim r_m/\ln(n_{k,0}/n_{c,0}), \quad (4)$$

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

We assume that, at sea level, $n_{c,0} = 10^2$ cm$^{-3}$ and $n_{c,0}(h) \sim n_{c,0}(0)N(h)/N_0$. 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 $n_{k,0} \gg n_{c,0}$, results of the calculations are almost independent of the assumed value of $n_{c,0}$.

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.

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

$$\frac{dN^*_w}{dt} = 2\pi \int_{r_m-\Delta r}^{\infty} k_{ex}[E(x)/N(h)]N_e(n_e(x)r_m^2(h))\ dx. \quad (5)$$

where $N^*_w(t)$ 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.

It follows from observations that BJ looks like an expanding spherical cone with some solid angle, $\theta$, between $2^\circ$ and $15^\circ$. $L$ 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 $R(L) = L \tan(\theta/2)$. 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 Schneider [2008], we introduce the packing factor ($F_{pack} < 1$), 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

$$\frac{dN^*}{dt} = \xi F_{pack} \int_{r_m-\Delta r}^{\infty} k_{ex}[E(x)/N(h)]N_e(n_e(x)r_m^2(h))\ dx. \quad (6)$$
As mentioned by Milikh and Shneider [2008], the temporal behavior of the intensity of the UV flashes does not depend on the cone angle, $\theta$, but the total number of excitations (total number of emitted photons) does depend on the assumed cone angle. This can be estimated as

$$N^* = \int_0^\infty \frac{dN^*}{dt} dt.$$  \hspace{1cm} (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: $h_i = h_{\text{cloud}} + D_L$. 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 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.

**Figure 3.** Normalized UV pulse shapes generated by the blue jet computed for $h_{\text{cloud}} = 18$ km, the leader length $\Delta_L = 7.2$ 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 $h_{\text{cloud}} = 18$ km, leader length $\Delta_L = 7.2$ km, cone angle $\Theta = 10^\circ$, and packing factor $F_{\text{pack}} = 0.1$: (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.

Figure 5 shows a sequence of the ISUAL images of GBJ adapted onboard FORMOSAT satellite [Kuo et al., 2008]. Figure 5a shows a sequence of the ISUAL images of GBJ recorded 28 May 2007 by an ISUAL instrument onboard FORMOSAT satellite [Kuo et al., 2008]. Figure 5b shows a sequence of the ISUAL images 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

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

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

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.
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).

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 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.

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]).
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 micro-satellite.

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.

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References


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