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Model of UV flashes due to gigantic blue jets

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Abstract
Analysis of UV flashes observed by the UV detector on board the 'Tatiana' microsatellite suggests, based on their location, pulse width and energy of the source of the photons, that the flashes were generated by gigantic blue jets (GBJs). Presented in this paper is a numerical model of UV flashes due to a bunch of long streamers which form a leader, a prong such as that observed in a GBJ. Using a previously developed model of upward propagation of a long streamer in the exponential atmosphere the paper describes temporal evolution of the UV flux generated by a bunch of long streamers, in the given spectral range 300–400 nm used by the UV detector on board 'Tatiana'. The model is in agreement with the observations.

(Some figures in this article are in colour only in the electronic version)

The phenomenon termed gigantic blue jet (GBJ) was discovered by Pasko *et al* (2002) when observing a thunderstorm over the Atlantic Ocean. A number of GBJs were observed since from the ground (Su *et al* 2003) and from space by the ISUAL optical detector flying on board the FORMOSA-2 satellite. Similarly to ordinary blue jets which are beams of blue light propagating from the tops of thunderclouds up to 40–50 km (Wescott *et al* 1995, 1996, 1998, 2001) GBJs escape into the lower ionosphere. Like blue jets the GBJs have a pencil-like shape; however, a trunk of GBJ is crowned with a few prongs. Moreover the trunk grows slowly with a velocity of about 100 km s^{-1}, while the prongs propagate much faster; their velocity can reach 40 000 km s^{-1} (Pasko *et al* 2002). The total optical energy released by a GBJ is about 1 MJ (Su *et al* 2003).

Current models suggest that a blue jet consists of the bi-leader, whose top part is seen in photos as a 'trunk of a tree' and is capped at the top side of the leader by its streamer zone. The opposite polarity leaders grow in opposite directions and supply each other with the charge via the highly conductive channel. Evidently, if the bi-leader is initiated in the anvil, one of the leaders can extend beyond the cloud top (Raizer *et al* 2007). Furthermore, the upward leader transfers the potential from the leader origin upwards, thereby providing the long necessary voltage to form long streamers. Apparently the positive leader tip at 25–30 km emits streamers that can reach the ionosphere at rather moderate values of the cloud potential 40–60 MV (Raizer *et al* 2007). In the exponential atmosphere long streamers grow preferentially upwards, producing a narrow cone.

The UV instrument flying on board the microsatellite 'Tatiana' detected a number of intense flashes with duration 1–64 ms originated in the equatorial region of the Earth (Garipov *et al* 2005, 2006). The satellite, which belongs to the Moscow State University, was flying at a height 950 km along a circular orbit with an inclination of 82°. The detector operates in the wavelength range 300–400 nm. It should be emphasized that both GBJ and UV flashes were detected mainly over oceans and shores where the rate of lightning flashes is low. This is due to the fact that lightning activity is caused by thermodynamic and mechanical work performed by vertical air motion. Furthermore, the updraft strength in oceanic convection is usually much smaller than that over land, and as such it cannot support the production of robust mixed phase processes and lightning over ocean (Baker *et al* 1999).

This is illustrated by figure 1 which shows a global lightning map from a combined nine years of observations of the NASA OTD and LIS instruments (http://thunder.nsstc.nasa.gov/images/HRFC_AnnualFlashRate_cap.jpg) with superimposed locations of the UV flashes (squares) detected by 'Tatiana' and gigantic jets (stars) detected by the ISUAL instrument on board the Taiwanese satellite FORMOSAT-2.

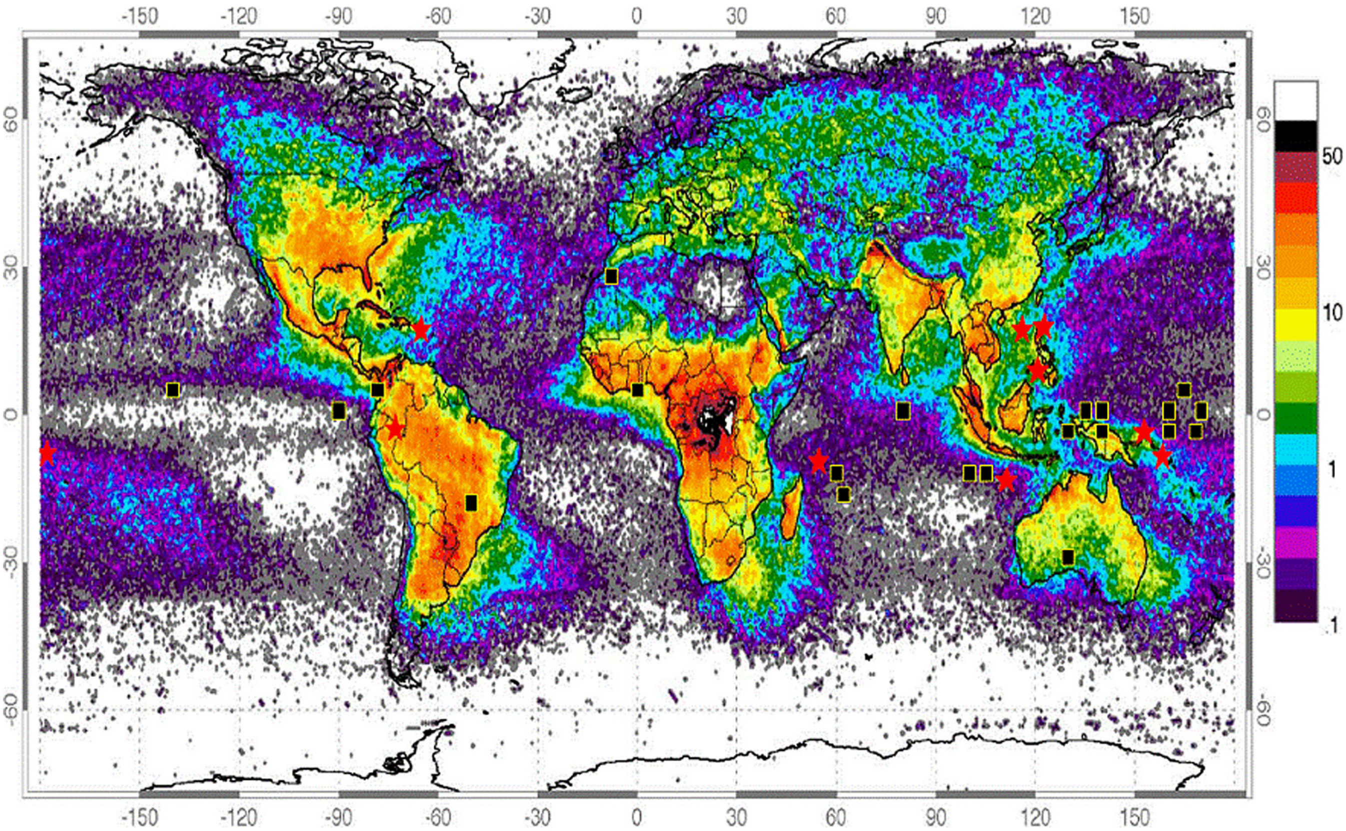

Figure 1. Global lightning map with superimposed locations of GBJ events (stars) and UV flashes (squares) detected by the 'Tatiana' microsatellite. The colour scale shows the rate of lightning appearance given in flashes $\mathrm{km}^{-2}\,\mathrm{year}^{-1}$. (Colour online.)

As apparent from this map the locations of UV flashes and gigantic jets coincide with the regions of low lightning activity over ocean or shores.

Garipov *et al* (2005) made energy estimates which took into account the geometric factor along with the quantum efficiency of the detector, as well as the atmospheric absorption. These estimates show that the detected flashes correspond to about 10^{22}–10^{23} radiated UV photons and in a few cases reach 10^{24} photons. The average energy of the radiated UV emission 10–10^3 kJ is in the range of the energy of gigantic blue jets as estimated by the Taiwanese group. Therefore, we suggest that the UV flashes detected by 'Tatiana' were generated by GBJs.

Finally, 'Tatiana' detected two scales of the flash duration, 1–4 ms and 10–64 ms. The first one corresponds to the lifetime of a long leader (prong) running towards the ionosphere, while the second corresponds to the lifetime of a slow moving leader or the streamer zone of a leader.

In this paper we present a model of UV flashes due to a bunch of long streamers which form a leader (prong). Using our earlier model of upward propagation of a long streamer in the exponential atmosphere we will describe the temporal evolution of the UV intensity generated by a bunch of such streamers in the given spectral range 300–400 nm and then check the model against the data obtained by the UV instrument on board the 'Tatiana' microsatellite.

In the next section we discuss the time dependent model of a long streamer propagating upwards in the exponential atmosphere. Then by using a Fokker–Planck code we obtain the excitation rates of the electronic levels of the air molecules which generate the UV emission of interest that occurs in the leader head. Finally, in the discussion section we will compare the model with existing observations.

1. Model of long ascending streamers in the exponential atmosphere

We first consider a single streamer moving in a self-consistent field $E_0(x)$ having a potential $U_0(x)$ as discussed by Raizer *et al* (2007). In the streamer zone of a leader a field most favourable for the streamer propagation is formed. Experiments show that under normal conditions this field is $E_{S0} \approx 500\,\mathrm{kV\,m^{-1}}$ (Petrov *et al* 1994). Despite significant progress in the studies of streamers and leaders (Petrov and Petrova 1999, Babaeva and Naidis 1996, Bazelyan and Raizer 2000, Pancheshnyi and Starikovskii 2003, Pancheshnyi *et al* 2005, Briels *et al* 2006, Ebert *et al* 2006) some problems are still awaiting their resolution. One of these problems is the formation of the self-consistent field in the streamer zone of a leader. Since the mechanism for this process has not been yet developed, we adopt the above-mentioned value E_{S0}. Furthermore based on the similarity law, which was justified in Raizer *et al* (2007), we assume that in an exponential atmosphere the self-consistent electric field also changes exponentially.

Figure 2 shows a schematic diagram of a streamer as well as a qualitative distribution of the electron density and electric

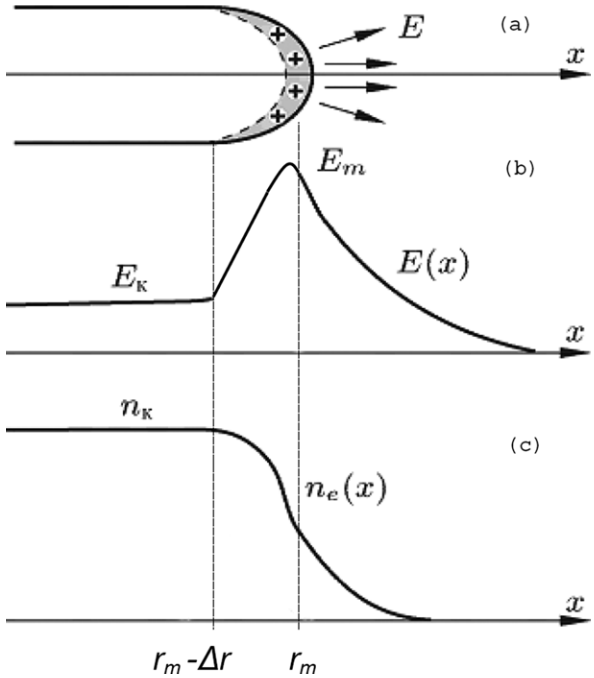

Figure 2. Schematic diagram of a streamer tip as well as the qualitative distribution of the electron density and electric field along the streamer axis.

field along the streamer axis. Notice that the electron impact ionization and excitation of the electronic states of the air molecules, which leads to UV emission, require high electric fields. Both occur in the streamer tip, in a thin region around the r_m point. The growth of the long streamer is computed based on the model by Bazelyan and Raizer (1998, 2000). In fact, a similar approach was used for simulation of the streamers in 'red sprites' descending from the ionosphere (Raizer *et al* 1998) and later for simulation of ascending streamers in blue jets. We present here only a qualitative description of the model while more details can be found in Raizer *et al* (2006, 2007). The set of engaging equations include: (i) the equation of motion of the streamer tip, $dx_t/dt = v_S$; (ii) relations between the velocity v_s, potential of the streamer tip U_t, its radius r_m, electron density n_{e0} and current at the tip I_t; (iii) equations describing electrical processes in the streamer channel; (iv) equations of the electron kinetics (attachment and recombination) to determine evolution of the channel conductivity.

The streamer velocity $v_S \approx \text{const} \times (U_t - U_0)$ does not depend on the air density. It sharply drops to zero at $U_t - U_0 < 5$ kV when v_S falls to the value of electron drift velocity such as that acquired at the field which exists near the streamer tip, $E_{max} \approx 1.5(N/N_0)$ MV m^{-1}; $v_{S\,min} \approx 10^5$ m s^{-1}. In fact, streamers with $v_S \leqslant 10^5$ m s^{-1} have never been observed in air. According to the similarity laws the radius of the streamer tip $r_m \sim 1/N$, with the electron density $n_{e0} \sim N^2$. The model considers a streamer channel as a long line with variable resistance and constant capacity per unit length, neglecting a small effect of self-induction. At the streamer tip $x = x_t$ the current I_t is spent charging newly created sections of the channel. The approximate scale of the charge separation region

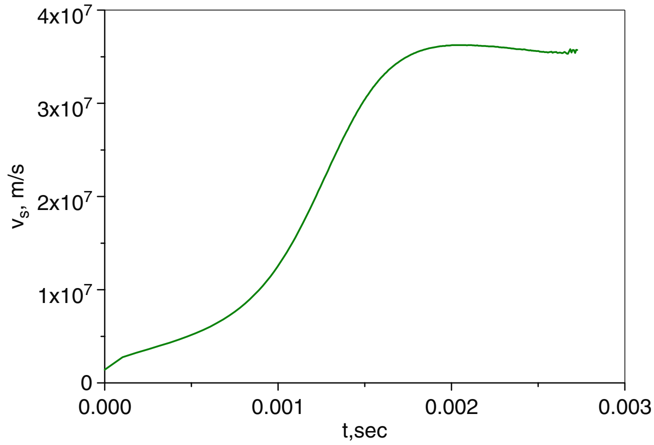

Figure 3. Streamer tip velocity in the averaged field.

in the streamer tip can be estimated as (Bazelyan and Raizer 2000)

$$\Delta r \approx v_s/\nu_i(E_m) \sim r_m/\ln(n_k/n_{e,0}), \qquad (1)$$

where n_k and $n_{e,0}$ are the electron number densities behind the ionization wave and the ambient electron density at altitude h, respectively; $\nu_i[E_m(h)]$ is the ionization frequency, corresponding to the maximal electric field near the streamer tip.

Following equation (1) we find that the corresponding approximate electron density distribution in the streamer tip (see figure 2) is

$$n_e(x) \approx (n_k - n_{e,0}) \exp[(r_m - \Delta r - x)/\Delta r] + n_{e,0}, \quad x \geqslant r_m - \Delta r. \qquad (2)$$

Since the electric field in the streamer channel is negligible with respect to the field E_m we use the following approximation to describe the field in the streamer (see figure 2):

$$E(x) \approx [1 - (r_m - x)/\Delta r]E_m, \quad r_m - \Delta r \leqslant x \leqslant r_m, \qquad (3)$$

$$E(x) \approx E_m r_m/(r_m + x), \quad x > r_m. \qquad (4)$$

Here, all values $n_k, n_{e,0}, \Delta r, r_m$ and E_m in (2)–(4) are at altitude h.

Shown in figure 3 is the streamer tip velocity in the averaged field as a function of time, computed by our model. The figure reveals that the streamer tip velocity gradually increases at the beginning of the process, followed by its steep increase and then the velocity reaches saturation. The process resembles that observed by Pasko *et al* (2002).

2. Excitation of UV emissions in the air

In the stratosphere the main optical atmospheric emission in the range 300–400 nm is due to two electronic states of nitrogen, the second positive N_2, $C\,^3\Pi_u - B\,^3\Pi_g$, and the first negative system of the ion N_2^+, $B\,^2\Sigma_u^+ - X\,^2\Sigma_g^+$. The wavelength of the corresponding optical emissions is 286–546 nm for 2P and 286–582 nm for 1N. The optical emission due to these bands is reduced due to collisional quenching described by the following quenching factor, $f_q = 1/(1 + \tau_R(n_{N_2}k_{qN_2} +$

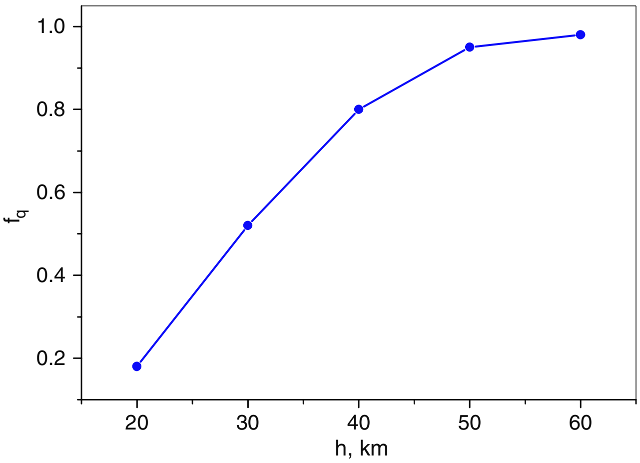

Figure 4. N_2(C) quenching coefficient f_q in the atmosphere versus altitude.

$n_{O_2}k_{qO_2}$)), where τ_R is the respective radiative lifetime, k_{qN_2} and k_{qO_2} are the rate constants for the quenching collisions with nitrogen and oxygen molecules and n_{N_2}, n_{O_2} are the number density of nitrogen and oxygen molecules. The quenching rate constants for N_2(C) are $k_{qN_2} = 1.1 \times 10^{-11}$ cm^{-3} s^{-1}, $k_{qO_2} = 2.8 \times 10^{-10}$ cm^{-3} s^{-1} (Kossyi *et al* 1992). In the stratosphere where $N > 3 \times 10^{17}$ cm^{-3} only the electronic levels having a lifetime shorter than 0.1 μs can survive collisional quenching. Figure 4 shows the height dependent quenching coefficient f_q of N_2(C) due to collisions with the atmospheric nitrogen and oxygen molecules.

The excitation rate coefficients for the above electronic layers were computed by a Fokker–Planck code which kinetically computes the modification of the electron distribution function by the applied electric field, along with the excitation of the molecular electronic levels by the energized electrons (Tsang *et al* 1991, Milikh *et al* 1998). The code includes both elastic and inelastic collisions with the air molecules. The excitation rate coefficients were obtained by using the excitation cross-sections of the retained nitrogen electronic levels C and B$^+$ by electron impact given by Cartwright *et al* (1977). The calculations reveal that in the E/N ratio range of interest, 100–650 Td, the dominant role is played by the excitation of the N_2(C) electronic level which radiates the first positive band. The first negative band plays a minor role at the moderate electric field and was neglected in the model.

The excitation rate coefficient of the N_2(C) electronic state was computed by the code as a function of the E/N ratio. The coefficient is in reasonable agreement with that given by Aleksandrov *et al* (1995). Besides, the temporal evolution of the UV fluxes generated by the GBJ, which is the main purpose of this paper, does not depend on the value of the excitation rate coefficient.

The rate of the excitation in the whole streamer tip region can be determined as

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

where N_{N_2} is the nitrogen number density at the given altitude h. The integration is taken from the beginning of the streamer tip to infinity.

A blue jet consists of a bunch of streamers, propagated in the self-formed averaged electric field E_S (Raizer *et al* 2007). Therefore, we consider the UV emission generated by a bunch of streamers forming a leader. According to observations of GBJs the prongs look like an expanding cone with some solid angle, θ, between 2.5° and 10°. Furthermore, we neglect the initial BJ radius (at $L = 0$) and obtain that the radius of the expanding cone of the length, L, is

$$R(L) \approx L \tan(\theta/2). \quad (6)$$

The total number of streamers in the BJ head at altitude, h, can be approximately estimated as

$$\xi \approx [R(L)/r_m(h)]^2 \times F_{pack}. \quad (7)$$

Here we introduce the packing factor ($F_{pack} \ll 1$) 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 streamer 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 bunch of the streamers is

$$\frac{dN^*}{dt} = \xi \frac{dN^*_{str}}{dt} = 2\pi R^2(L)\, F_{pack} \times \int_{r_m-\Delta r}^{\infty} k_{ex}[E(x)/N(h)] N_{N_2} n_e(x)\, dx. \quad (8)$$

Note that another way to compute the excitation rate of N_2(C) in the streamer head was proposed by Naidis (1997) who considered the dependence of the excitation rate and the electron drift velocity upon the electric field and then conducted integration by the field from its value in the streamer channel to that in the streamer head. However, in our case such an approach is not available since we consider not a single streamer but a bunch of streamers moving in the averaged field.

The qualitative temporal behaviour does not depend on the cone angle, θ, and on the packing factor, but the total number of excitations and thus the total number of emitted photons do; the latter can be estimated as

$$N^* = \int_0^{\infty} \frac{dN^*}{dt}\, dt. \quad (9)$$

3. Discussion and conclusions

The UV photon flux (in photons s^{-1}) due to the leader head can be presented as

$$I = f_q \frac{dN^*}{dt}, \quad (10)$$

where the quenching factor of the N_2(C) electronic state is revealed by figure 4.

The main result of our model is presented in figure 5 which shows temporal evolution of the flux of UV emission generated by a GBJ presented as a bunch of streamers. The intensity of the

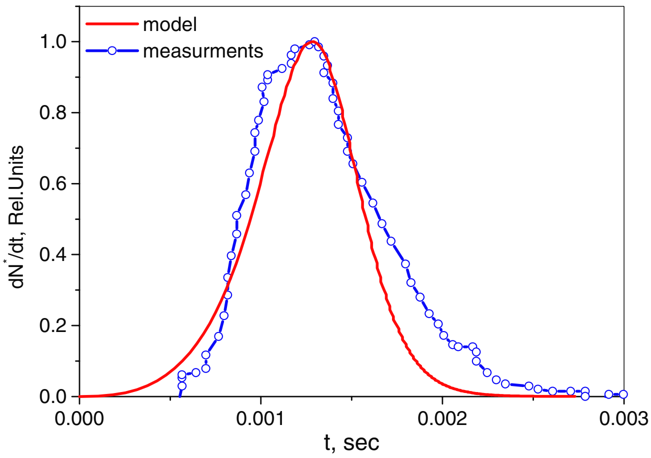

Figure 5. Flux of the UV flashes due to GBJ (solid traces) and that detected by the 'Tatiana' microsatellite (open circles).

Table 1. The number of photons radiated by a leader head computed for different cone angle.

Cone angle, θ (°)	Total number of photons: N_{ph}
2.5	0.66×10^{24}
5.0	2.64×10^{24}
10.0	1.06×10^{25}

UV emission which is normalized by its peak value is shown by a solid trace. Similarly normalized measurements by the 'Tatiana' microsatellite (Garipov *et al* 2005, 2006) are shown by open circles.

As we mentioned above the shape of the model curve $I(t)$ does not depend on the cone angle, although the total number of generated photons depends on this angle. Table 1 shows the computed number of photons radiated by a leader head as a function of the cone angle and assume that the packing factor $F_{pack} = 0.1$. We recall that based on 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 occasions even 10^{24} photons per flash. This is in agreement with our model.

In conclusion, the analysis of UV flashes observed by the UV detector on board the 'Tatiana' microsatellite based on their location, pulse width and energy of the source of the photons suggests that the flashes were generated by GBJ. The presented quantitative model of GBJ formed by a bunch of long streamers computes temporal evolution of the UV fluxes generated by the GBJ, which is in agreement with the observations. The total number of the radiated photons depends upon the conic angle on the GBJ and on the packing factor, and for the angles in the range 2.5°–10° such as were observed by Wescott *et al* (1998, 2001) and for the packing factor of the order of 0.1 it is in agreement with the 'Tatiana' observations.

Further theoretical work will focus on the model of the wavelength spectrum of the radiated photons; the photon spectrum will be convolved with the quantum efficiency curve of the detector. Besides, the photon losses in the stratosphere due to absorption and scattering will be considered along with the shape of the UV radiating source. The model will be combined with more detailed statistics of the UV flashes detected by 'Tatiana'.

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