Analysis of UV flashes measured by Universitetsky–Tatiana-2 satellite as significant factor of TUS detector operation

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Abstract: Ultra high energy cosmic rays (UHECR) orbital detector TUS will operate in various UV night atmosphere background. This background slowly varies due to variation of scattered moon light intensity, of atmosphere airglow, of cloud cover. Important part of background are fast UV flashes (lightning, transient luminous events). These transient events will effect operation of trigger system and decrease duty cycle of UHECR detectors especially above thunderstorm regions where frequency of lightning could be very high. New measurements of transient events were performed by UV detector on-board Universitetsky-Tatiana-2 satellite. Based on those data estimation of TUS trigger rate was made. Influence of transient events on operation of UHECR detector TUS is discussed.

Keywords: ultra high energy cosmic rays, GZK cut-off, orbital fluorescent detector

1 Introduction

On October 20th, 2009 microsatellite Universitetcky–Tatiana-2 was launched on the solar synchronous orbit with inclination of 98 degrees and altitude of 850 km. The main goal of the scientific program of this satellite was study of space near the Earth by measuring charge particle fluxes at the orbit and radiation from the atmosphere. Radiation from the atmosphere was measured by detectors in two ranges of wavelengths: 240 – 400 nm (UV) and 610 – 800 nm (red-IR) [1][2]. Both detectors were photomultiplier tubes R1463 of Hamamatsu with multialcathode. Detectors were oriented to nadir and covered the atmosphere area of effective diameter 300 km (effective area 7·10⁹ km²).

2 Results of Universitetsky-Tatiana-2 satellite mission

Every minute UV detector selects the event with maximal 1 ms signal. During the operation time from October 2009 to January 2010 detectors of UV and red-IR radiation, installed on board Universitetcky–Tatiana-2 satellite (Tatiana-2 in short) have registered more than 2000 transient events in the atmosphere with duration 1-128 ms (average rate ~ 5·10⁻⁵ hr⁻¹km⁻²) with different temporal profiles and photon numbers in the atmosphere.

All events were characterized by photon number \( Q_a \) radiated in the atmosphere which was calculated from photon number in the detector. Selected transient events are distributed in wide range of photon numbers \( (10^{70} - 10^{25}) \).

Position of every transient event is determined in geographical coordinates by Universal Time (UT) of the event. The global distribution of all detected by Universitetcky–Tatiana-2 events has an evident component concentrated above continents in equatorial region (America, Africa, Indo-China). There are some regions which transients avoid-deserts of Sahara and Australia.

In the most active areas (south America, Africa, Indonesia, Australia) the transient rate is of about \( 6 \cdot 10^{-4} \) events/km²/hr.

Measured ratio of number of photons radiated in red-IR range to number of photons radiated in UV related to excitation of molecular nitrogen indicates a high altitude (> 50 km) of the measured events [3][4].

A lot of transients were detected out of thunderstorm areas, in cloudless region thousands km away of thunderstorms. This fact allowed us to assume that transient events are not only consequences of lightning in event-by-event way; some of them are result of “long distance” influence of thunderstorm electric activity causing break-downs in the upper atmosphere (at altitudes > 50 km), [2].

There is strong correlation of transient event temporal profile with number of photons \( Q_a \): events with \( Q_a < 5 \cdot 10^{21} \) are mostly short single pulse (< 5 ms); events with the large photon numbers \( Q_a > 10^{23} \) are mostly longer in time, with duration of tens – hundred ms.

Differential distribution of transients over photon numbers \( Q_a \) shows two ranges with a changing exponent of power law approximating the differential distribution: “-1” for \( 10^{21} < Q_a < 10^{23} \) and “-2” for \( Q_a > 10^{23} \). Cause of the exponent change could be a possible difference in origin of “small” and “large” flashes. Events with larger photon numbers may be related to Transient Luminous Events (TLE) recently measured by space video cameras and spectrometers (for example see [3]). Events with small photon numbers may be related to one of TLE kind events: “elves” rings but detected far away of lightning initiated the event [2]. This hypothesis is confirmed by difference in geographical distribution of detected events: transients with \( Q_a > 10^{23} \) are concentrated in equatorial regions above continents as lightning do (figure [1]), transients with \( Q_a < 10^{23} \) are distributed more uniformly (figure [2]).
3 Modeling of UV flashes

Transient events in the atmosphere measured by Tatiana-2 detectors are very different from fluorescence radiating by extensive air shower (EAS) initiated by UHECR. EAS fluorescence is much shorter in time (tens of microseconds against milliseconds of atmospheric transients) and image of EAS fluorescent source looks like a point of 1 km size moving through the atmosphere with velocity of light. Measured transients are much longer in time and larger in space scale (from tens to hundreds km) with development velocity much lower than light velocity. Nevertheless the rate of atmospheric transients (order of $10^{-4}$ events/km$^2$ hr) is so high to compare with UHECR rate $10^{-6}$ events/km$^2$ hr that triggering by atmospheric flashes may be dominant for TUS trigger system. Registered atmospheric UV flashes may imitate the EAS image if random fluctuations of signals are taken into account. In this way “small” flashes could be more dangerous for imitation as they are closer to EAS events in photon number. EAS fluorescence photon number at primary UHECR energy $10^{20}$ eV is $10^{16}$ while TLE have $>10^{23}$ photons and “small” transients have $10^{20} - 10^{22}$ photons.

At present origin of “small” transients is not clear: more data are needed. Early stage of transients is of special interest as at early stage its signal being close to EAS size and duration may imitate EAS. For analysis of possible EAS imitation by transients a model of UV flash in the atmosphere was developed with characteristics (duration, number of photons, temporal profile) measured in experiment. The model is close to TLE model of “elves”.

The developed model is based on emission of nitrogen molecules excited by an electromagnetic pulse (EMP) with a radial front propagating up in the ionosphere from parent lightning.

It is known that in the ionosphere there are enough free electrons. They can be accelerated under the electromag-
Atmospheric UV flashes

**Figure 3**: EMP propagation through the ionosphere layer. R is EMP radius at the lower border of chosen layer of the ionosphere, D is ionosphere layer thickness, d is radius of visible glow ring, L is EMP radius at the higher border.

Glow emerges in a layer of the ionosphere, when the front of spherical electromagnetic pulse passes the ionosphere (Figure 3). Layer borders are defined by level of electron density. In the model a high enough electron density was suggested at altitudes 80 – 100 km.

EMP sphere expands with speed of light \( R(t) = c \cdot t \), where \( c = 3 \cdot 10^8 \) km/s). The time is counted in microseconds from the start of EMP in the lower atmosphere. When the sphere points are inside of a given layer of the ionosphere (D), they radiate isotropic UV photons. Fluorescence yield \( q(Q) \) depends on \( R \) as \( 1/R \) (such dependence on \( R \) is expected if the radiation intensity is proportional to the EMP electric field). The total number of photons \( Q \), emitted by such flash is defined as the integral of the glow over all coordinates in the ionosphere layer in total glow time. Transient glow begins when the EMP reached lower layer of the ionosphere. Then spherical EMP propagates and makes a “visible ring” with radius \( d \) spreading far away of lightning.

In our simulation we are interested in glow expected in a field of view (FOV) of the detector. In this case the ending of the glow is over when the area of intersection of the EMP sphere and the ionosphere layer will go out of the detector FOV.

The temporal profile of the transient glow in the detector is determined by velocity of EMP sphere expansion, position of the ionosphere layer, ready to produce glow, and position of the center of the flash in the detector’s FOV.

It is important to note that described model was adjusted to experimental data on temporal characteristics of small short flashes (signal rise time \~200 \( \mu \)s, signal fall time \~750 \( \mu \)s) [6].

In figure 4 example of a flash calculated by described above model is presented. The figure shows spatial distribution of photons number in TUS detector pixels with time resolution \~25 \( \mu \)s. In this example the center of the discharge is located at the corner of the detector’s field of view. The flash ring develops through all detector FOV. In contrast to expected EAS image an atmospheric flash appears simultaneously at large number of pixels. The flash image changes much slower than “point-like” EAS image moves through the detector.

**Figure 4**: Development of the model flash image in TUS detector.

4 Conclusion

Data on atmospheric flashes obtained in Universitetsky-Tatiana-2 satellite mission have shown existence of UV flashes less intensive than TLE (transient luminous events). Their geographical distribution is wider than distribution of TLE concentrated in equatorial regions above continents. Their rate is much higher than the rate of UHECR events. Those small in photon number events may present important background in measurements of UHECR from space. Experimental study of this new background gave a base for developing a model of those flashes and look for simulated flash events in TUS detector. The first approximation the analyzed events could be distinguished from UHECR events. Analysis of the flash background in TUS detector will be continued.

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**References**