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SIMULATION OF ASCENDING ATMOSPHERIC DISCHARGE AND ITS EMISSIONS IN OPTICAL AND GAMMA - RANGES

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Introduction

High-altitude transient luminous events (TLEs) Blue Jets, Red Sprites etc. [1, 2] and terrestrial γ-ray flashes (TGFs) detected aboard CGRO [3] and RHESSI [4] satellites are believed to be connected with upward atmospheric discharges (UADs) driven by avalanches of relativistic runaway electron (REs) [5]. Configurations have been simulated with large variations of thundercloud dipole moment $\Delta M = \Delta Q_{\rm cl} \cdot l_{\rm Q}$ caused by lightning, permitting TLFs and TGFs correlation. Here $\Delta Q_{\rm cl}$ is the charge variation (let to be equal to cloud charges $Q_{\rm cl}$ placed at high altitudes) and $l_{\rm Q}$ is the vertical component of the dipole arm. But representative set of observations analyzed in [6, 7] contradicts both TGF correlation with large ΔM and Sprite and TGF correlation. It was proved that TGF sources are localized rather low, TGFs are correlated in average with $\Delta M \sim 49$ C·km and are connected with globally prevalent intracloud lightning discharges annihilating positive upper and negative lower cloud charges [6,7]. Results of simulations of configurations satisfying these conclusions are discussed below.

Technique of computations

Simulations of the UAD were executed using 2D fluid model with the multigroup description of the RE kinetics [8] in self-consistent electric field [9] and cosmic ray source of seed REs [10]. The kinetics of low energy secondary and background electrons, positive and negative ions was simulated by drift equations allowing for impact ionization, recombination and electron attachment. The air fluorescence was calculated as in the paper [11]. The configurations satisfying the following conditions were simulated. (1) The field strength $E \leq$ 300-400 kV/m. (2) Ascending lightning discharge annihilating the upper charge $+Q_{\rm cl}$ at the altitude $H_{\rm cl}$ and $-Q_{\rm cl}$ at $H_{\rm down}$. (3) Relatively small $Q_{\rm cl}$ and, accordingly, small $\Delta M = Q_{\rm cl} \cdot l_{\rm Q}$. (4) The γ-flash duration is limited to the TGF duration Δt_γ = 1-3 ms [3, 4]. (5) The photon numbers N_γ reaching the satellites should fit N_γ measured in the range 20 - 1000 keV (the detector area $S_{\rm det}$ = 2000 cm^2) [3] and 20 keV - 20 MeV ($S_{\rm det}$ = 250 cm^2) [4].

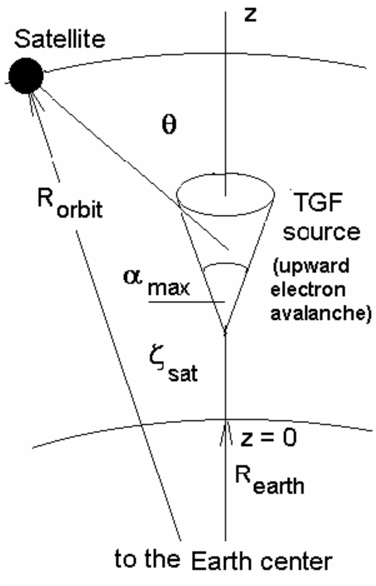

Fig. 1.

A transport of the RE Bremsstrahlung to the near space was simulated by Monte Carlo code ELIZA allowing for all elementary interactions of photons, electrons and positrons with matter (cf. [12, 13]). It was accepted that the ascending RE flux is propagated symmetrically to the axes $\vec{z}$ passing through the Earth's center (fig. 1). REs started at the altitude z relative to the Earth's surface (z = 0). Available in [12, 13] dependencies were used for RE and Bremsstrahlung angular and energy distributions and for the photon emission rates on the "overvoltage" $\delta = eE/(F_{min} \cdot P)$, where F_{min} = 218 keV/(m·atm.) and P(atm.) is the local pressure. The photon trajectories were traced up to a hemisphere symmetrical relative to $\vec{z}$ with a radius $R_{orbit} = R_{earth} + H_{sat}$, where R_{earth} is the Earth's radius and $H_{sat} >> z$ is the orbit altitude (500 km [3, 4]). The hemisphere was divided onto 32 sections for different intervals of the angle ζ between $\vec{z}$ and a line from the Earth's center to the middle of a particular zone. The satellite orientation relative to the source is characterized by the angle θ. The dependencies on the source altitude z of the photon specific current $C(z)$ (1/(s·electron)) and normalized per unit angular distribution $I(z,\zeta)$ (1/ster.) were calculated at the hemisphere. If $z \leq 35$ km the scattered photons dominate in $C(z)$ over the "line-of-sight" ones.

Results

The RE concentration $n_{run}(z,r,t)$ was the primary result of the UAD simulations. The domain where UAD develops was limited to vertical H_{max} = 74 km and horizontal r_{max} = 30 km sizes. The simulation duration t_{max} = 3.5 ms in accordance with the TGF duration 1-3 ms.

Maxima of the RE concentration $n_{run}(z,t)$ and the air fluorescence brightness $< J >$ averaged over the TV frame duration [1] appear at the altitudes of $H_{run} \approx$ 11km.

Table. Fluorescence brightness above thundercloud <J> and γ-photon numbers N_γ "detected" aboard satellites CGRO and RHESSI.

Q_{cl}, C	H_{cl}, km	H_{down}, km	ΔM, C·km	H_{run}, km	E_{max} kV/m	<J>, rayleigh	N_γ	
							CGRO	RHESSI
30	10	8	60	11.2	322	28 000	69	108
35	10	8	70	11.3	313	50 600	172	264
Experiment [3, 4]							~50-800	~30-100

The $< J >$ values in the table are comparable to the star brightness and less than the Blue Jet maximal brightness [1, 2]. At the altitudes of 50-70 km, common for the Red Sprites [1, 2], the calculated brightness does not exceed 50 rayleigh.

The gamma-photon numbers at the detector aboard the satellites were calculated as [9]

$$N_\gamma(\zeta_{\rm sat}) = \Delta\Omega_{\rm det}\int_{H_{\rm cl}}^{H_{\rm max}} C(z)I(z,\zeta_{\rm sat})dz\int_0^{r_{\rm max}} rdr\int_0^{t_{\rm max}} n_{\rm run}(z,r,t)dt,$$

where $\Delta\Omega_{\rm det} = 2\pi\sin\zeta_{\rm sat}\cdot\Delta\zeta_{\rm det} = S_{\rm det}/R^2_{\rm orbit}$. The N_γ numbers in the table were calculated in the range of the detector sensitivity for the case $\zeta_{sat} = \theta = 0$ in fig. 1. In this case N_γ are maximal for a given configuration (Q_{cl}, H_{cl}, H_{down}). The calculated N_γ are close to the observational data [3, 4]. Some overestimation, most likely, is connected with adopted $\zeta_{sat} = \theta = 0$. The numbers N_γ approach the observational data with increasing ζ_{sat} and θ.

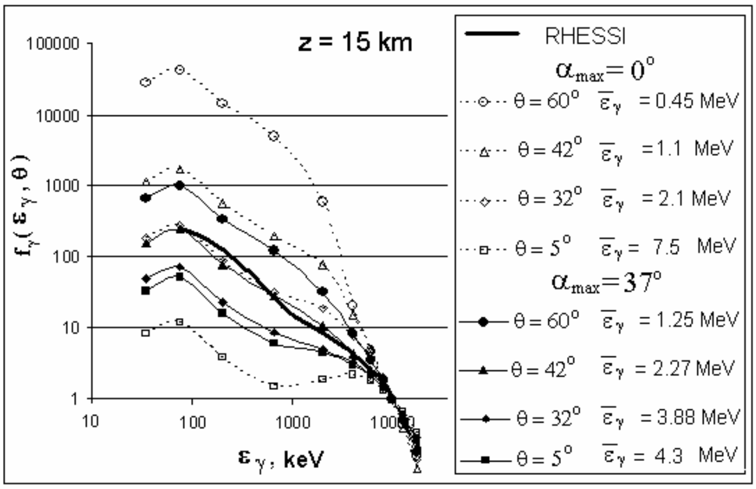

Fig. 2.

The γ-photon angular and energy distributions at the hemisphere $f_\gamma(\varepsilon_\gamma,\theta,z)$ were calculated as functions of the source altitude z and the angular aperture $\alpha_{\rm max}$ of the ascending RE flux (fig. 1). The distributions in the ranges z = 10-20 km and z = 30-60 km are close. For z = 10-20 km the calculated distributions fit the RHESSI data [4] best of all if θ = 32°-42°. The mean photon energy $\bar{\varepsilon}_\gamma(z,\theta)$ for these z and θ is in the range 1.1-2.2 MeV in agreement with the RHESSI data [4]. For z = 30-60 km the best agreement is achieved if θ = 6°-34°, namely, $\bar{\varepsilon}_\gamma(z,\theta)$ = 0.88-2.7 MeV. Fig. 2 illustrates the distributions for z = 15. More details of calculations and obtained results will be published elsewhere [14, 15].

Discussion and conclusions

The configurations allowing the ΔM variations typical for intracloud discharges [6, 7] were simulated. The simulations confirm the analysis [6, 7] that rather common cloud configurations and lightning discharges causing small variations of the cloud dipole moment ΔM

are responsible for TGFs. The TGFs are not correlated with Red Sprites, which are connected with large ΔM. The calculated maxima of the RE concentration are located at the altitudes of $H_{run} \approx 11$ km. Therefore the TGF sources are also located at rather low altitudes.

The calculations were carried out supposing the vertical lightning discharge. In the case of the tilted dipole the lower charge affects less the development of the ascending RE avalanches. The avalanches can amplify up to a level capable to account for the generation of the observed TGFs at the same (smaller) Q_{cl} values as in the case of vertical arrangement of the arm l_Q, but at smaller (greater) differences of the altitudes H_{cl} - H_{down}.

The assumption that the leaders of ascending intracloud discharges could be the TGF sources [7] requires an additional argumentation. As noted in the article [9], this idea does not agree with the observed cutoff of X-ray generation inside thunderclouds by lightning [16]. Besides the duration of the X-ray pulses in thunderclouds before lightning stroke is of seconds [16] and even tens seconds [17], while the TGF duration is of Δt_γ = 1-3 ms [3, 4].

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