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CONDITIONS FOR DEVELOPMENT OF RED SPRITES IN STRATO-MESOSPHERE BY DIFFERENT LEVELS OF SOLAR ACTIVITY

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Abstract: *Red spites are transient luminous events at night above thunderstorms whose lower part is occupies the region from 75-85 km down to 40-50 km. In this region they consist of downward propagating and branching positive streamers driven by a post-lightning quasi-static electric field **E**. The problem studied is: do the spatial characteristics of sprites (esp., their lower boundary) show sensitivity to the solar activity realized by 11-year variations of strato-mesospheric conductivity, and thus, of **E**. We estimate by modeling the lower boundary reached by a streamer by different level of solar activity and show that the propagation of positive streamers is sensitive to the presumable 11-year conductivity changes. During solar maximum the sprite length is larger than during solar minimum, due to larger post-lightning electric fields determined by smaller conductivity.*

УСЛОВИЯ ЗА РАЗВИТИЕТО НА ЧЕРВЕНИ СПРАЙТОВЕ В СТРАТО-МЕЗОСФЕРАТА ПРИ РАЗЛИЧНИ НИВА НА СЛЪНЧЕВА АКТИВНОСТ

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Резюме: *Червените спрайтове са явление на преходно светене през нощта над гръмотевични бури, чиято долна част обхваща областта от 75-85 km до to 40-50 km. В тази област те се състоят от разпространяващи се надолу и разклоняващи се положителни стримери, които се поддържат от квази-статични електрически полета **E** след мълния. Решаваният проблем е дали пространствените характеристики на спрайтовете имат чувсвителност към нивото на слънчева активност чрез 11-годишни вариации на атмосферната проводимост, водещи до вариациии в електрическото поле **E**. Чрез модел се оценява долната граница достигана от стример при различна слънчева активност. Показана е чувствителността на тази граница към 11-годишните изменения на проводимостта през слънчевия цикъл. През слънчев максимум вертикалните размери на спрайт са по-големи от тези през слънчев минимум поради по-големите електрически полета след мълния, дължащи се на по-ниска проводимост.*

Relationships between solar activity and strato-mesospheric conductivity influenced by galactic cosmic ray modulation

The conductivity in the region where streamers of the red sprites [1-3] are propagated downwards (from ~75-85 down to ~40-50 km) varies with the solar activity (SA) by few tens of percent (up to 50%) at high middle and polar latitudes, due to latitudinal dependence of the galactic cosmic ray (GCR) flux cut-off rigidity (close to the equator this influence is negligible). We consider middle and high-middle latitudes where sprites occur frequently [1]. 11-year variations of conductivity between 40 and 75 km are considered: conductivity is accepted to be smaller by 10% - 50% during solar maximum, than during solar minimum, due to the modulation of GCR flux by SA. We adopt conductivity profile for the middle atmosphere [4] for moderate solar activity and consider also two profiles of modified conductivity by solar activity maximum and minimum, respectively.

Conductivity in strato-mesosphere and sprite-producing quasi-electrostatic fields

We study the quasi-electrostatic (QS) fields **E** after a positive cloud-ground (+CG) lightning discharge at nighttime possible to cause a sprite as an inception of a single positive streamer which propagates downwards and initialize a net of positive streamers by branching. The actual picture of sprites as composed by streamers was discovered by observations in the last decade [3]. The development of a sprite in time is shown in Fig.1a [7]. Fig.1b demonstrates the initial streamer velocity as function of its altitude.

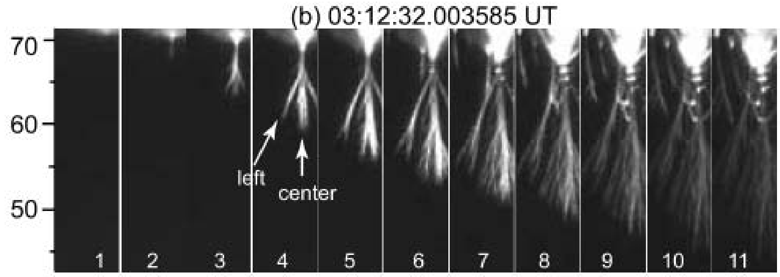

Fig.1a. - Succeeding pictures of development in time of a bright sprite taken by high-speed high-sensitive camera [7]. The structure of the sprite is formed by positive streamers which propagate downwards and branch.

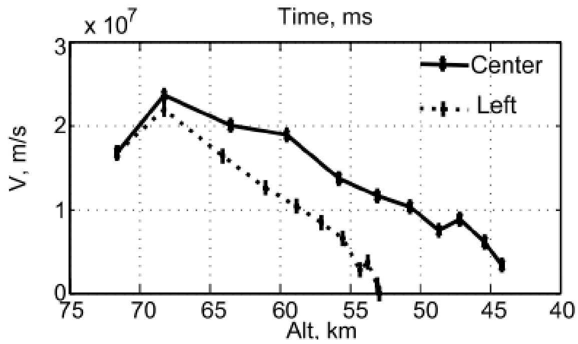

Fig.1b. - Velocity of propagation of fast positive streamers (the main and the secondary ones) in the bright sprite shown in Fig.1a as function of altitude [7] (faster streamers are branching more intensively).

The mechanism of the inception of an initial streamer at ~80-85 km is complex and not understood completely yet [3]. We assume that this mechanism is not sensitive to the solar activity variations (the nighttime conductivity at these altitudes does not depend significantly on SA). The propagation of downward streamers is realized by an applied electric field E when $E > E_{cr+}$. Here E_{cr+} is the electric breakdown threshold of a streamer type: this is the minimum electric field which allows further existence and propagation of a streamer. The height profile of E_{cr+} is shown in Fig.1. A streamer passes few tens of kilometers from its birth (at ~75-85 km, or at a lower altitude, after branching) to its end in time period of few milliseconds (with propagation velocity up to 10% of the speed of light). Hence, for continuous downward propagation of a streamer in the sprite body, the relation $E > E_{cr+}$ has to be fulfilled anywhere at the streamer position, at the proper time of its arrival.

Modeling the quasi-electrostatic fields E after lightning [5,6]

We study the quasi-electrostatic (QS) field **E** after +CG lightning discharge from the equation:

(1) $\nabla\cdot \mathbf{j}_M = 0,$ where $\mathbf{j}_M = [\sigma]\mathbf{E} + \varepsilon_0\, d\mathbf{E}/\underline{dt}$.

for the Maxwell current $\mathbf{j}_M$. Computations are made in a sample case of a +CG lightning discharge which removes a normalized charge Q = 1 C located at altitude 10 km by an exponential decay in time τ_L=1 ms. The results for the vertical field E above the discharge are presented in Fig.2. The features of spatial and temporal distribution of E (slow decrease with the altitude increase, slow decay with time after reaching of its peak value) allow initiating of streamers and sprites [5].

We evaluate by (1) the electric field E applied to the initial streamer of a sprite. According to the observations, the inception of this streamer is at time t_I = 2.5 - 3 ms after the beginning of lightning at time t = 0 [2] (we accept t_I=3 ms). The profiles of the vertical electric field E computed from Eq. (1) at the time moments of arrival of the initial streamer at a given altitude are presented in Fig.3. The curves 1, 2, and 3 show the electric field profiles for minimum, moderate, and maximum solar activity. The explanation is as follows: during solar minimum the conductivity is larger with respect to the conductivity during solar maximum, because of the more intense GRC flux in the first case. On the other hand, bigger conductivity leads to smaller electric fields. Fig.3 shows that significant long-term variations of the electric field with the solar activity variations take place.

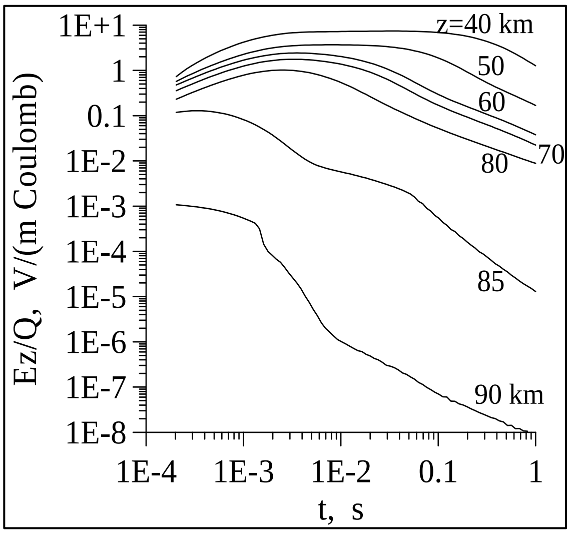

Fig. 2. - Normalized vertical component of the QS electric field |E /Q| at altitudes z= 40, 50, 60, 70, 80, 85, and 90 km computed by modeling in a case of a +CG lightning discharge which removes the electric charge Q from Z_Q=10 km in characteristic time τ_L=1 ms.

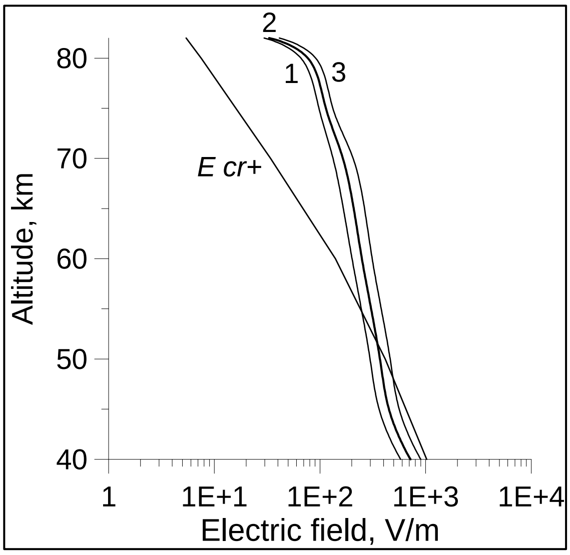

Fig. 3. - Electric fields as a function of altitude by minimum (curve 1), moderate (2) and maximum (3) solar activity generated by +CG lightning discharges from height 10 km. with removal of 100 C in 1 ms. The thin line E_{cr+} shows the threshold field of positive streamer propagation.

The comparison of the electric field **E** applied to the initial steamer with the threshold field E_{cr+} which supports streamer propagation shows the altitude where the streamer stops: it corresponds to the lower sprite boundary. Fig.3 shows that this boundary significantly depends on the solar activity level: it is located at 48, 52 and 55 km for maximum, moderate, and minimum SA, respectively. Thus, much stronger (due to the bigger electric field applied) and larger (extending to lower heights) streamers will take part by solar maximum with respect to solar.minimum.

Results in Fig.3 demonstrate that even small variations in conductivity provoked by solar activity changes (and thus in the post-lightning QS electric fields) lead to considerable changes in vertical dimension of sprites. These differences are most significant in cases of stronger +CG lightning discharges.

Actually, the velocity of a streamer propagation is not constant in time: there is an initial phase of acceleration of a streamer (typically, down to 70-65 km), followed by deceleration, as shown in Fig.1b. Actual functional dependences of the streamer speed *v* are not completely studied yet. To make estimations of streamer propagation with account of its varying velocity *v*, we accept here, according to observations, that the sample streamer accelerate down to z=68 km (as in Fig.1b) from a half (at z = 80 km) to full of its maximal speed v_{max}, and then it decelerate to 1/3 of v_{max}. at z=40 km. We adopt for the maximum speed v_{max}= 5% of the speed of light. The respective results are given in the Table with account to time of arrival of the streamer at the altitude of estimation. These results also show that during maximum solar activity the driving electric field is significantly larger than that during moderate and minimum SA. More than that, the streamer under these conditions propagates to the stratosphere slower than in the former case. Since the applied QS electric field at altitudes below ~60 km are larger in this case, the streamers stop at relatively lower altitude (the sprites are larger).

Table. QS electric fields applied to a streamer compared with E_{cr+} by same conditions as in Fig.3, but with a variable streamer velocity for minimum, moderate, and maximum SA. The time of streamer arrival is also shown. Shadowed rows are for the lowest boundary reached by the streamer for minimum (~ 54 km), moderate (~ 50 km), and maximum (~ 48 km) SA.

Altitude, km	Applied QS electric field *E*, V/m			E_{cr+}, V/m	$t_{arrival}$, ms Constant	$t_{arrival}$, ms Variable
	minimum SA	moderate SA	maximum SA			
80	66.1	77.0	91.2	7.5	3.00	3.00
75	76.6	105	111	16	3.33	3.55
70	120	157	196	34	3.67	3.96
65	147	183	229	69	4.00	4.31
60	191	238	296	140	4.33	4.71
55	252	313	391	241	4.67	5.19
54	274	332	397	279	4.74	5.31
50	322	405	434	415	5.00	5.79
48	360	429	486	510	5.13	6.01
45	417	517	564	652	5.33	6.61
40	697	864	1080	1025	5.67	7.94

Conclusions

Following main conclusions can be derived from the obtained results:

1. Solar activity has a significant long-term effect on the vertical size of red sprites provided by the 11-year changes of conductivities in the strato/mesosphere due to modulation of GCR flux. During maximum solar activity the sprites extend to lower heights than by minimum SA.
2. The account of the actual streamer velocity variations (the streamer initially accelerates, then decelerates) leads to slight lowering of its lower boundary.

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