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Formation and Propagation of Streamers in Lower Ionosphere above Active Thunderstorms

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ABSTRACT

The newly discovered transient luminous events (TLE) in the strato/mesosphere above active thunderstorms are important phenomena which can influence the global atmospheric electric circuit, the chemical processes in the middle atmosphere, and can play a role in realization of the solar-terrestrial relationships. This explains the active investigations of TLE, and particularly, of red sprites. Sprites occur in the height interval ~45 - ~90 km up to tens ms after strong lightning discharges; usually these are positive cloud-to-ground (CG+) discharges above mesoscale convective systems at nighttime. Observations demonstrate that the sprites are composed, particularly in their lower part, of filaments formed by streamers, which are produced by strong quasi-electrostatic fields (QESF). These fields are a result of lightning discharges. The realization of streamers in the mesosphere needs an investigation of the conditions needed for their production. These conditions are examined here theoretically with respect to the parameters of the causative lightning discharges and of the atmospheric conductivity. First, in order to evaluate the streamer producing post-lightning QESF, an analytical approximation is proposed for the peak value of the QESF intensity with respect to its modification self-consistently with the variations of the atmospheric conductivity above 60 km where heating of free electrons occurs. Conditions are revealed by which positive streamers are formed and propagated downward, and their characteristics are estimated. Our calculations help us show why the lightning discharges with continuing currents produce streamers much more often than the ordinary lightning discharges.

❖ Red sprites and streamers

Sprites and their causative lightning discharges

The transient luminous events (blue jet, red sprite and elf) are shown schematically in Fig.1. A sprite appears up to tens (rarely more) ms after a CG+ lightning discharge at night [1], usually above mesoscale convective systems (MCS). The reason can be that MCS's often generate lightning discharges followed by continuing currents (i.e. they has a long tail), as opposed to the ordinary (short-time) CG+ discharges [1, 5]. While ordinary lightning removes to ground only the local cloud charge, the following continuing currents transport larger distributed charge in longer time period.

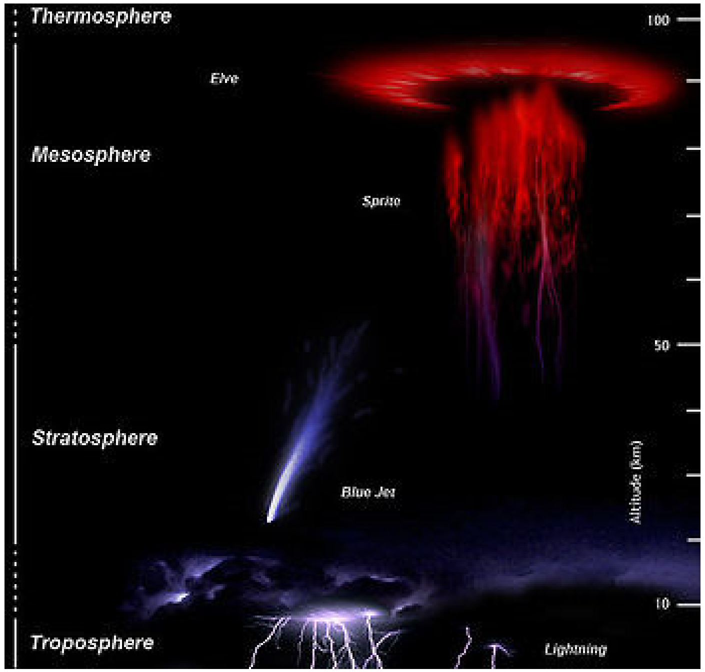

Fig.1. Main Transient Luminous Events: **Blue Jet**, **Red sprite [3]**, and **Elf** (a schematic view).

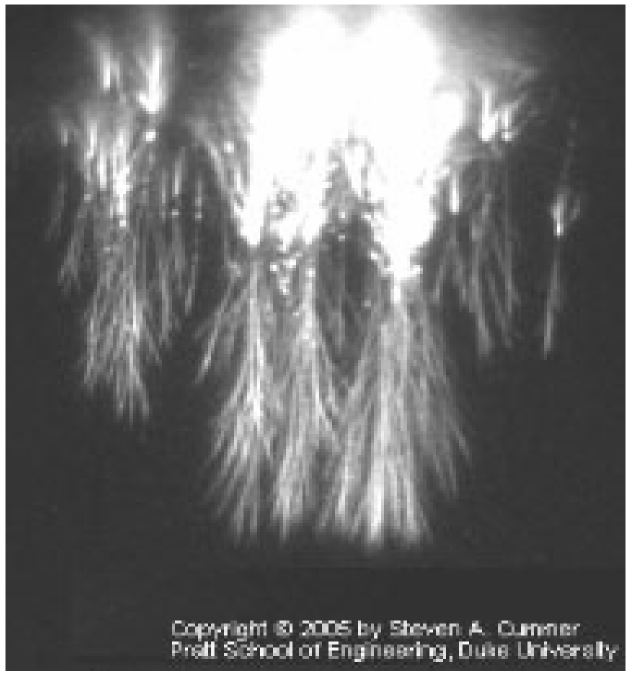

Fig.2. A red sprite with filamentary structure, well seen in the lower section. The filaments are streamers of positive or negative polarity.

A sprite consists of three regions [2] determined by the interplay of the dissociative attachment time τ_a, the charge relaxation time τ_R, and the time t_s for the development of an electron avalanche into a streamer: 1) **Diffuse region** (85-90 km); 2) **Intermediate region** (75-85 km); 3) **Streamer region** (~45-75 km) [2]. The upper boundary of the streamer region is at the altitude where $\tau_R = t_s$.

The problem: to determine conditions needed for development of streamers in lower ionosphere

The occurrence of the sprite has been studied in relation with the charge moment change (CMC) of the causative lightning [5]. Most of sprites occur after lightning with CMC >1000 C×km; however, sometimes sprites appear after much weaker ones, while strongest discharges do not cause sprites. We consider additional factors: the discharge time parameters and the atmospheric conductivity σ.

Causative CG+ lightning discharge and quasi-electrostatic field generated

The caused CG+ lightning discharge is accompanied, in general, by continuing currents. The locally situated and the distributed charges are removed from altitude Z_C according to time dependences:

Local: $Q_1(t) = Q_L \exp(-t/\tau_L)$, (1a) Distributed: $Q_2(t) = Q_D \exp[-t/\tau_{CC})$. (1b)

The common charge remained at Z_C is represented by time function $Q(t) = Q_1(t) + Q_2(t)$ with local and distributed charges Q_L and $Q_D > Q_L$ removed in characteristic times τ_L and $\tau_{CC} > \tau_L$, respectively. An ordinary CG+ discharge (with no continuing currents) is represented by time function $Q(t) = Q_1(t)$.

Quasi-electrostatic fields by CG+ lightning discharge

The time-space distribution of the QESF **E** is determined under assumption that **E** is a potential field, $\mathbf{E} = -\nabla U$. It is based on the continuity equation for the Maxwell's current with density $\mathbf{j}_M$ [6,7]:

$$\nabla \cdot \mathbf{j}_M = 0, \quad \text{where} \quad \mathbf{j}_M = \sigma \mathbf{E} + \varepsilon_0 \partial \mathbf{E}/\partial t \qquad (2)$$

Here σ is the atmospheric conductivity, ε_0 is the dielectric constant, t is the time from the beginning of the discharge. Eq.(2) is solved in cylindrical coordinates (r, φ, z) with vertically oriented axis z (z=0 corresponds to the surface) and radial component r (r=0 corresponds to the lightning discharge position). In order to analyze the streamer production by QESF below 75 km, the model domain is 0 - 90 km. The initial and boundary conditions are similar to these in [6].

An example of the time distribution of QESF $E(z,t)=\|\mathbf{E}(r=0, z,t)\|$ at different altitudes z above a sample CG+ lightning discharge without continuing currents is shown in Fig.3 [6]. At a fixed altitude z E reaches its time peak E_P at time $t_P(z)$. At altitudes, where $\tau_R>\tau_L$, we have $\tau_L<t_P<\tau_R$ [7], and the time dependence of E forms a 'plateau' around the peak: at times t, $\tau_L<t<\tau_R$ the QESF intensity E is close to E_P ($E>e^{-1}E_P$) [6, 7].

Atmospheric conductivity

The conductivity σ has two components: electron σ_e, and ion σ_i ones. σ_e depends self-consistently on the electric field applied $\mathbf{E}$ when $|\mathbf{E}|>E_0$, E_0= 1620 $N(z)/N_0$ V/m [4], while σ_i=const. When the QESF causes initiation/propagation of streamers (i.e. $|\mathbf{E}|>>E_0$), σ_e is reduced 25-30 times. This leads to an additional self-consistent increase of the electric field. σ_e is negligible below 60 km, and σ_i becomes small above 85 km. We accept that the ratio σ_e/σ increases exponentially in the interval 60-85 km. Although the undisturbed conductivity is anisotropic above 70 km, by large QESF the anisotropy of the conductivity below ~85 km can be neglected [4].

Initiation and propagation of streamers

A streamer is initiated at altitude z from an individual electron avalanche when the electric field intensity $E=|\mathbf{E}|$ is larger than the conventional breakdown threshold $E_k=3.2\times10^6 N(z)/N_0$ V/m for at least

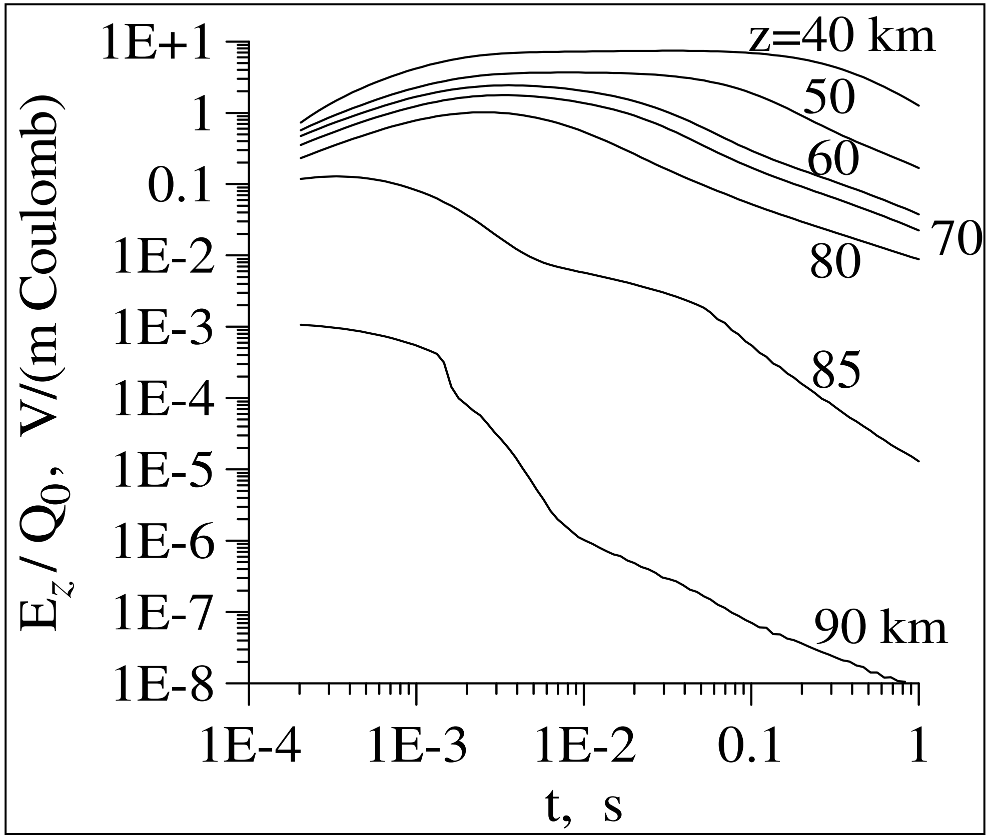

Fig.3. The normalized QESF above ordinary CG+ lightning discharge (no continuing currents) with parameters Z_C=10 km, τ_L=1 ms at altitudes 40, 50, 60, 70, 80, 85 and 90 km, as function of time. A nighttime conductivity profile [9] is used; its modifications due to QESF and the anisotropy are not taken into account.

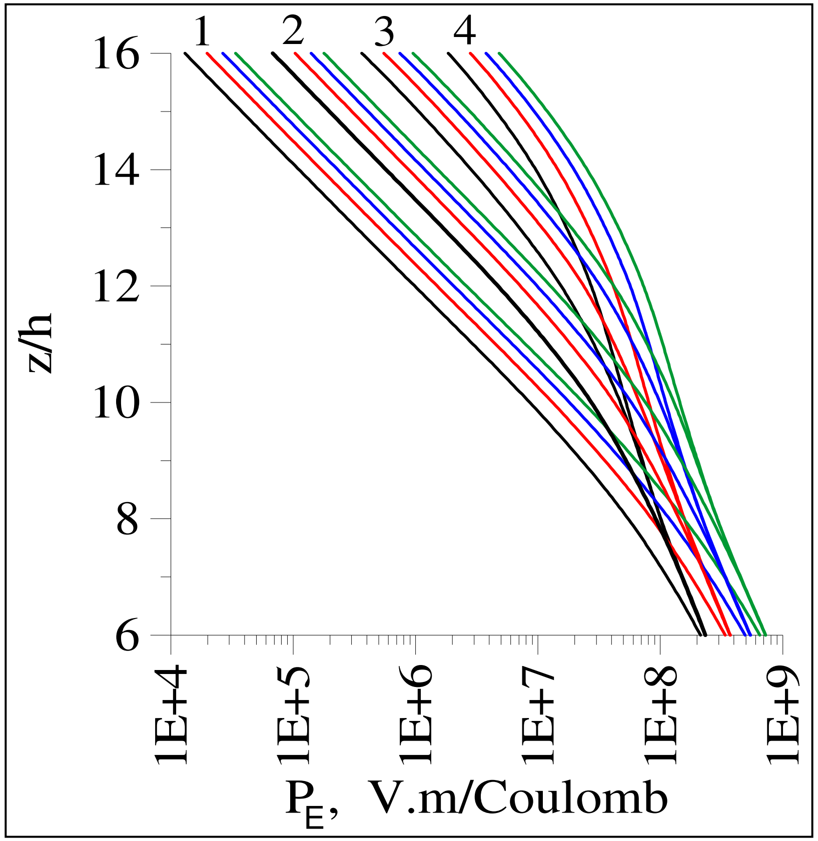

Fig.4. The normalized QESF peak P_E as function of ζ by different ζ_Q and ζ_L. Groups of curves 1-4 correspond to: ζ_L= 8, 10, 12, 14. Curves in each group correspond to: ζ_Q = 1 (black), 1.5 (red), 2 (blue), and 2.5 (green curve).

time t_S [2]. Here N_0 and $N(z)$ are the atmospheric neutral densities at the sea level and at altitude z, respectively. For the propagation of an initiated streamer the applied electric field have to exceed the threshold E_{cr} which is substantially lower than E_k: $E_{cr+}=4.4\times10^5 N(z)/N_0$ V/m for positive streamers, and $E_{cr-}=1.25\times10^6 N(z)/N_0$ V/m for negative ones [2]. The velocity v_S of a streamer newly created is estimated to be up to $v_S = 10$ km per ms [8]. According to recent investigations, v_S can decrease during streamer propagation down to 10 km per ms [12].

❖ Determination of conditions needed for development of streamers

We study the possibility for development of a streamer in the streamer region of a sprite (75-45 km) by a CG+ causative lightning discharge, depending on: (*i*) discharge parameters Z_C, Q_L, Q_{CC}, τ_L and τ_{CC}; (*ii*) conductivity profile $\sigma(r=0, z)$ which depends self-consistently on $E(z)$.

Analytical expression for the QESF peak intensity E_P

We obtain an approximate analytical expression for the peak intensity $E_P(z)$ of QESF at an arbitrary altitude z. It is based on our computational results [6] obtained by us under idealized assumption for an exponential conductivity profile $\sigma_E=\sigma_{E0}\exp(z/H_E)$ (H_E=const is the conductivity scale height) which does not depend on the QESF applied. We assumed that the QESF was a result of an ordinary lightning (with no continuing currents) with a time function of the remaining charge $Q_1(t)$ described by Eq.(1a). We showed in [6] that the value of the QESF peak intensity $E_{P\sigma}(z)$ at a fixed altitude z by a realistic (non-exponential) conductivity profile σ, is approximately equal to the peak $E_P(z)$ computed by an exponential conductivity profile with a scale height $H_E=H=(z-Z_C)/[\ln\sigma(z)-\ln\sigma(Z_C)]$. Here H is the mean conductivity scale height between the altitudes Z_C of the removed charge and z.

In [6] computations were made for the normalized peak $P_E = H^2E_P/Q_L$ as function of the dimensionless parameters $\zeta = z/H$, $\zeta_Q = Z_C/H$, and $\zeta_L = z_L/H$, where z_L is the altitude at which the relaxation time $\tau_R = \varepsilon_0/\sigma$ is $\tau_R = \tau_L$. ζ and ζ_Q characterize the altitudes of observation and of the removed charge, ζ_L characterizes the discharge time τ_L. The computational results were obtained for the full set of combinations of the following parameter values: ζ_L=8, 10, 12, 14; ζ_Q=1, 1.5, 2, 2.5, when ζ varies from 6 to 16 by a step $\Delta\zeta$=1 [6]. These calculated dependencies are illustrated here in Fig.7. Due to their regularity by each argument, we obtain here an analytical presentation of P_E as an approximate function of three arguments: ζ, ζ_L and ζ_Q. This presentation is given below:

$$\ln(P_E) = -k_1(\zeta-6) + f(\zeta_Q) + d \qquad \text{by } \zeta < \zeta_L-2;$$

(3)

$$\ln(P_E) = R_1(s)[f(\zeta_Q)+d-k_1(\zeta_L-8)] + R_2(s)[g-k_2(\zeta_L-14)] - k_1Q_1(s) - k_2Q_2(s) \qquad \text{by } \zeta_L-2 \le \zeta \le \zeta_L+2;$$

$$\ln(P_E) = g - k_2(\zeta-16) \qquad \text{by } \zeta > \zeta_L+2.$$

Here

$$f(\zeta_Q) = -0.1564\zeta_Q^2 + 1.304\zeta_Q - 1.147; \qquad g = b(\zeta_L-8) + f(\zeta_Q) + 9.475;$$

$$k_1 = 0.0213\zeta_Q + 0.402; \quad k_2 = 1.076; \quad b = 0.829, \quad d = 19.27.$$

$R_{1,2}$, $Q_{1,2}$ are the following polynomials of 3-rd order:

$$R_1(s) = 2s^3-3s^2+1; \quad R_2(s) = -2s^3+3s^2; \quad Q_1(s) = s^3-2s^2+s; \quad Q_2(s) = s^3-s^2,$$

where $s = 0.25(\zeta-\zeta_L+2)$.

Eq.(3) is an analytical estimation of the peak intensity of QESF by an ordinary lightning discharge described by Eq.(1a). In a case when continuing currents are also present, the total QESF is a sum of the quasi-electrostatic fields independently generated by the removals of the local and the distributed charges, respectively. We consider the particular situation when the time periods of peak intensities E_{P1}, E_{P2} of the QESF by both sources almost coincide, i.e. the peak intensity E_P of the total QESF is a sum of both separate peaks intensities, i.e. $E_P= E_{P1}+ E_{P2}$. It was shown that this situation takes place by nighttime conductivity profiles proposed by different authors [9-11] with respect to their modification.

It follows from Eq.(3) that at altitudes with a relaxation time τ_R much larger than the characteristic discharge time τ_D of the local or distributed charge, the QESF peak intensity E_P is determined by the condition $\zeta < \zeta_D-2$, where $\zeta_D=z_D/H$ (z_D being altitude with $\tau_R=\tau_D$), and E_P does not depend on τ_D. In this case the QESF time dependence has a form of a 'plateau' in the time interval $[t_1 \approx \tau_D,\ t_2 \approx \tau_R]$ [7]. Hence, at altitudes $\zeta<\zeta_L-2$ E_P is almost proportional to the amount of the charge removed, irrespectively to whether the QESF is generated due to the removal of the local Q_1 or the distributed charge $Q_2>Q_1$. We have in mind that the horizontal dimension of the removed charge has a relatively small influence on QESF at sprite altitudes [6]. Therefore, in the streamer region (where $\tau_R>\tau_{CC}$) the removal of the distributed charge has larger contribution to QESF than the removal of the local charge Q_1. E is close to its peak value E_P within a time period with length $t_P \approx \tau_R$, since $\tau_R>\tau_{CC}$ [6, 7]. Since the time of the streamer formation is $t_s=\tau_R$ at the upper boundary of the streamer region Z_U=75 km, the creation of an initial streamer at Z_U occurs at the end of the 'plateau' period of the QESF. Therefore, the condition for a streamer generation is $E_P(z=75\text{ km}) \geq eE_k$.

By an assumptions that the streamer velocity is $v_S=10^7$ m×s^{-1} [12], the streamer reaches any altitude $z<75$ km before the end of the 'plateau' period at the altitude z. Indeed, this is valid when the mean conductivity scale height $H(z)$ of the conductivity profile in the height interval [Z_C, $z\leq75$ km] satisfies the condition $|d\tau_R/dz|>1/v_S$, which is true for actual conductivity profiles. Because of this feature, a positive streamer, once created, propagates downward to an altitude close to Z_D at which $E_P(Z_D)=E_{cr+}(Z_D)$. It has to be noted that the QESF peak intensity E_P above 60 km is determined by us self-consistently with the modification of the conductivity just before the streamer generation.

Computational results

Calculations are made in sample cases of CG+ lightning discharges at night by conductivity profile [9]. In the streamer region ($z\leq 75$ km) the relaxation time is $\tau_R\geq 3$ ms under undisturbed conditions; under QESF large enough to generated streamers $\tau_R>\tau_{CC}$. Therefore, the peak of the total QESF intensity in the streamer region above a CG+ discharge with continuing currents is $E_P=E_{P1}+E_{P2}$, where E_{P1} and E_{P2} are the peaks of the QESF by the removal of the local and of the distributed discharges, respectively. Fig.1 demonstrates the altitudinal dependence of the QESF peak intensity for two CG+ lightning discharges of different type when a cloud charge is removed from altitude Z_C=10 km. Curve 1 relates to a CG+ ordinary lightning discharge with Q_L=100 C, τ_L=1 ms. Curve 2 is for a discharge with continuing currents whose additional parameters are Q_{CC}=200 C, τ_{CC}=7 ms. Three threshold electric fields are also presented: the conventional breakdown field E_k, and the thresholds E_{cr+} and E_{cr-} of propagation of a streamer of both polarities. Fig.2 demonstrates the ability of creation of a streamer and the height interval of its propagation due to CG+ lightning discharge of two types: an ordinary lightning (curve 1) and one with continuing currents (curves 2-4), characterized by the same parameters Z_C, τ_L, and τ_{CC}, as in Fig.1. Curves 1-4 show the lower boundary Z_L of a positive streamer, if initiated at Z_U=75 km, as a function of the amount Q_L for curve 1, or Q_{CC} for curves 2-4, when Q_L=50, 100, and 150 C, respectively. The left end of each curve shows the minimum charge removed which allows the creation of a streamer.

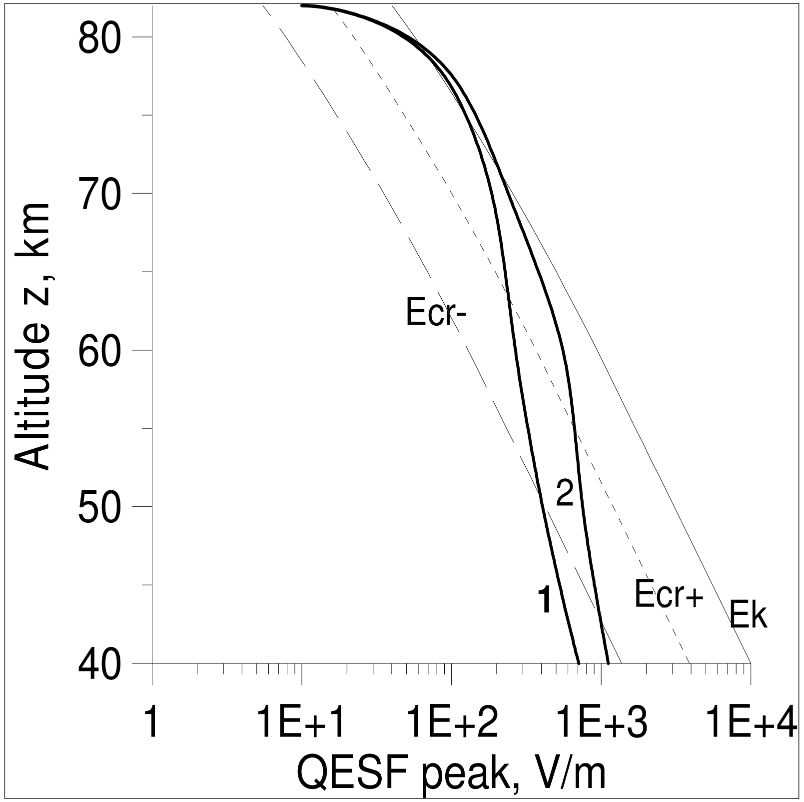

Fig.5. QESF peak intensity (curves 1 and 2) as a function of altitude by a single-phase (ordinary) and by a double-phase (accompanied with continuing currents) CG+ lightning discharge, respectively. The discharge parameters are Z_C=10 km, Q_L= 100 C, τ_L=1 ms; Q_{CC}=200 C, τ_{CC}=7 ms. Nighttime conductivity profile [13] is adopted. The thin lines show the conventional breakdown field E_k, and the thresholds E_{cr+} and E_{cr-} of propagation of positive and negative streamers.

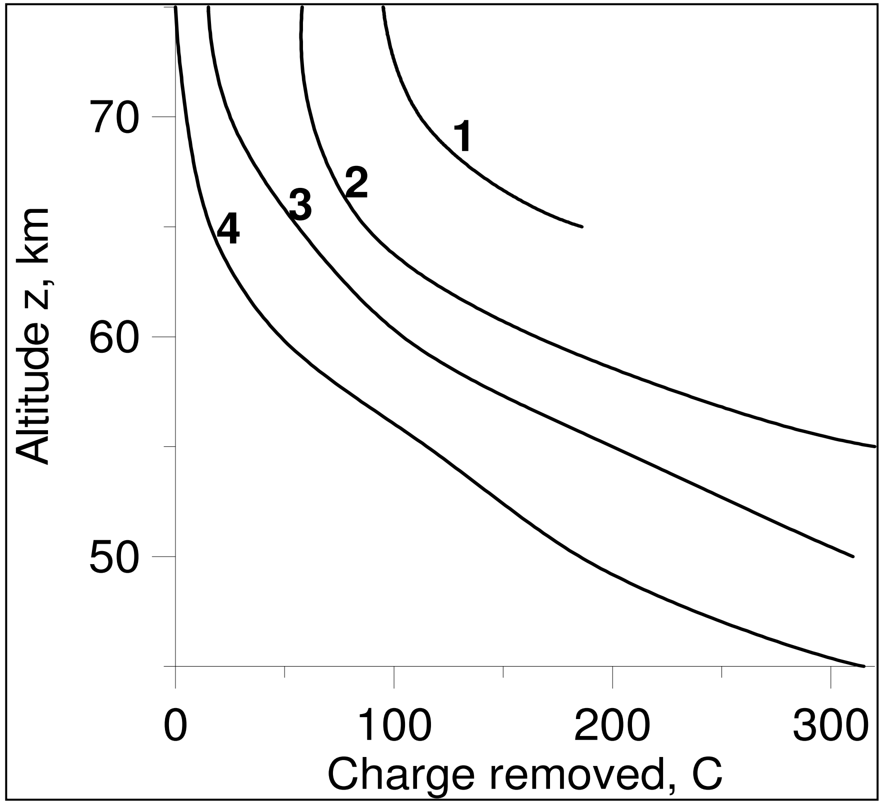

Fig.6. The lower boundary Z_L of propagation of a positive streamer due to both types of CG+ lightning discharge considered in Fig.1 with the same parameters. Curve 1 (ordinary lightning discharge) shows Z_L as function of the removed local charge Q_L. Curves 2-4 (for discharges with continuing currents) show Z_L as function of the distributed charge Q_{CC}, when Q_L=50, 100, 150 C, resp. The left ends of the curves correspond to the minimum charge removed needed to produce a streamer.

❖ Conclusions

- An analytical expression is obtained for the peak intensity of the quasi-electrostatic field in the lower ionosphere above a CG+ lightning discharge as a function of the parameters describing the causative lightning discharge and the conductivity self-consistently with its modification.
- Conditions, concerning the values of these parameters, are derived for realistic nighttime conductivity profiles, by which streamers can be developed.
- Altitudinal interval of the streamers initiated is estimated.
- It is shown that CG+ lightning discharges with continuing currents generate QESF with much larger peak intensity in the streamer region of a sprite, than the ordinary type of lightning.

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