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# Conditions for initiation and propagation of electric streamers in lower ionosphere above thunderstorms at night

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## Electric streamers and sprites in the middle atmosphere

The electric streamers are thin filaments of plasma created in gases by application of strong electric fields as a part of the process of electrical breakdown [5]. Here the phenomenon of streamers in the middle atmosphere is considered in the case when they are a part of red sprites. The accent of this report is on solving the problem of generation of a positive streamer during initiation of a sprite itself (after creation of halo). Although much studied, the problem of the mechanism of initiation of streamers during sprite onset is not fully solved yet. Since this problem is closely related to the role of sprites in global atmospheric electrical circuit and in atmospheric processes, it is thus important.

Red sprites [10] are transient luminous events above thunderstorms caused by strong quasi-electrostatic fields (QSF) $E$ which are generated in middle atmosphere after cloud-ground lightning discharges. Sprites are discovered ~ two decades ago and are subject of intense investigations. In the recent decade it has been shown that the sprite body is ‘build up’ by thousands of streamers, as demonstrated in Fig.1. The physics of sprites is described shortly in the poster [14]. A single sprite comprises a large volume in the middle atmosphere - thousands of cubic of kilometers [12] and presumably can cause significant physical and chemical effects [14]. Possibly a link between solar activity and the chemical status of meso- and stratosphere is realized by sprites [14]. Here the typical case of sprites due to a positive cloud-ground (+CG) lightning discharge at night is considered only.

The set of positive and negative streamers which constitutes a sprite originate by a single positive streamer created at 80 - 85 km [12] which gives rise to a network of positive and negative streamers by hierarchical branching. The filamentary (streamer) structure of a sprite was first observed a decade ago [2] (Fig.1).

The global frequency of sprites on Earth is estimated between 1 per minute [Chen] (Fig.2) and 3 per minute [14]. Therefore, they may have significance upon global scale chemical processes in meso- and stratosphere [14]. Being elements of the global atmospheric electric circuit, sprites also can influence this circuit. The presumable role of sprites and their effects can depend essentially on the details and conditions of streamer formation and propagation. This exaggerates the need of respective studies.

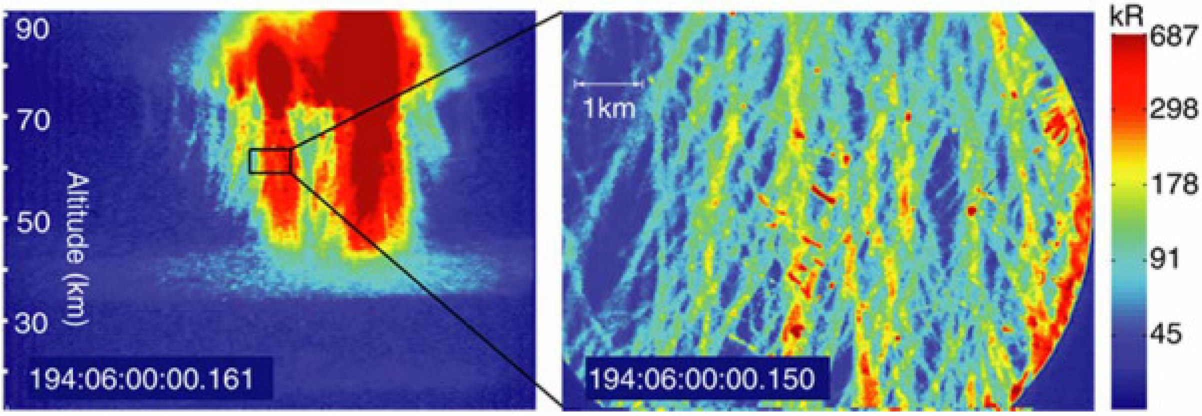



Fig.1. Photo of a sprite (left) and of its part where its streamer structure is observed in smaller scale (right) [2]

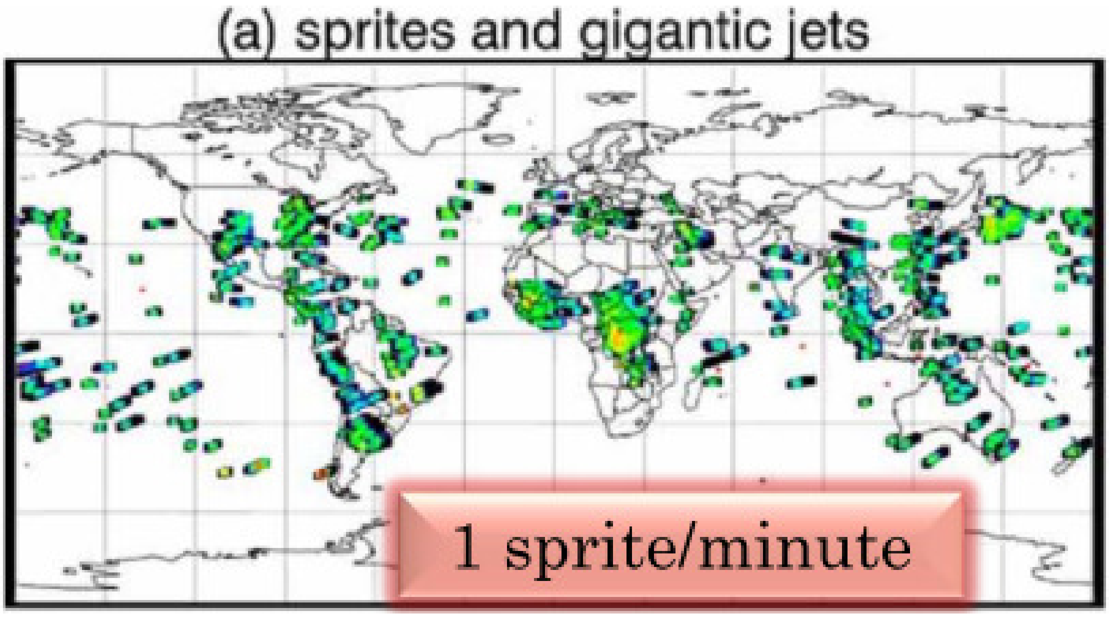



Fig.2. Distribution of red sprites on Earth by data of instrumental ISUAL for observation of sprites onboard of FORMOSAT-2 satellite in period July 2004 - June 2008 [1]. The global sprite rate is estimated by these data to **~1 sprite per minute**.

Almost all observed sprites occur after a positive cloud-to-ground (+CG) lightning discharge at nighttime; quite a little are sprites after -CG lightning or by daytime.

It should be mentioned that not all streamers, resp. sprites, as well as halos, can be observable [14]. Thus, the actual rate of occurrence of sprites (and streamers) may be significantly higher.

## Streamers in atmospheric regions, breakdown theory [5]

Streamers considered here are created in atmosphere by quasi-electrostatic fields generated after a +CG lightning discharge at night. There is similarity between streamers which occur in atmospheric pressure and those born in lower ionosphere. A streamer is a filament of polarized plasma; it is positive when its head contains positive charge (Fig.3) and vice versa. Streamers are described in details in poster [14].

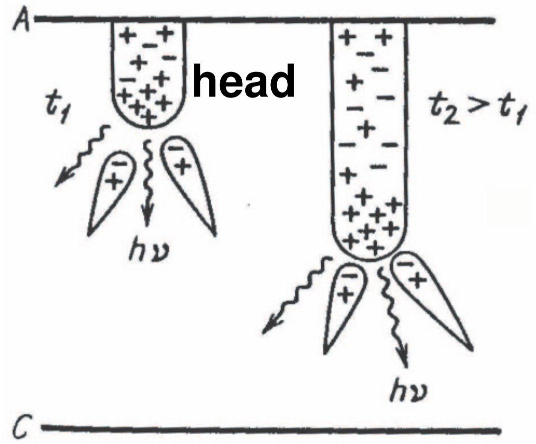
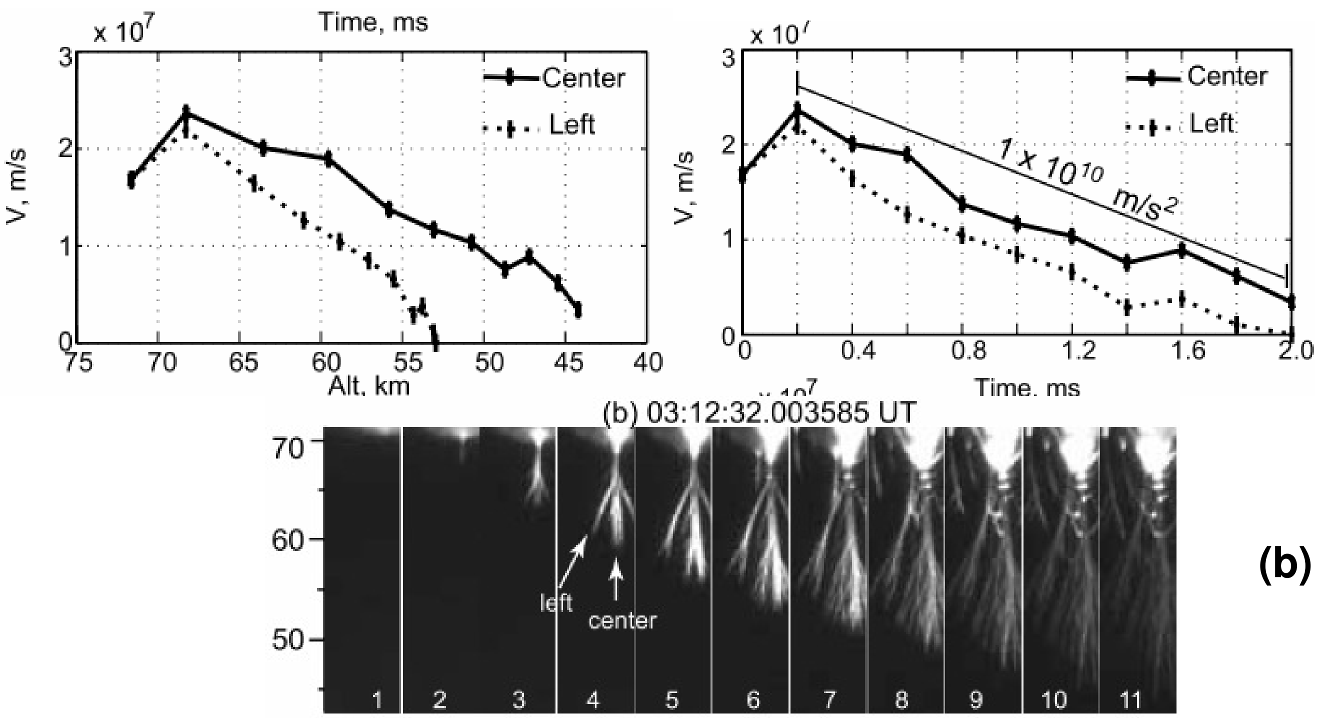



Fig.3. Development of a positive streamer in strong external electric field $E$ (oriented downward) at two time moments $t_1$ and $t_2 > t_1$. There is a positive charge of high density in its head whose local electric field $E_S$ in front of its head is comparable to $E$. Upward electron avalanches are created in front of the head by ionization and photo-ionization (above 26 km). After escape of the newborn electrons in front of it driven by el.field $E$, a net positive charge remains and becomes a new part of the head (streamer propagates downward).

A threshold electric field $E_{cr}$ is required for the propagation of streamers ($E_{cr+}$ for a positive and $E_{cr-}$ for a negative streamer). At see level $E_{cr+}$=440 kV/m, $E_{cr-}$=1250 kV/m. At higher altitudes $E_{cr}$ decreases as $E_{cr} \propto N$ where $N$ is the atmosphere density (Fig.4). Since $E_{cr}$ decreases with height faster than the peak value of the QSF E, there is an altitude in the lower ionosphere above which the QSF by lightning exceeds the streamer threshold (Fig.5). The condition $E > E_{cr+}$, however, is not sufficient for creation of a positive streamer, nor its mechanism well understood.

# Propagation and branching of streamers [3]




(

a)

(b)

(c)

Fig.4. Photo frames of sprite developing by time with branching positive streamers (a). Variations of velocity *V* of propagation of two main streamers by altitude (b) and by time (c). In bright sprites *V* is high (2 - $3\times10^{7}$ m/s, up to ~10% of the speed of light. The fast streamers are bright and they branch. Initially they accelerate (down to 70-65 km) with $0.5\text{-}1\times10^{10}$ $m.s^{-2}$, then decelerate. Here the streamer is unobserved above 72 km.

Slow streamers (*V* is smaller by one order) are dim and do not branch. They become observable at lower altitudes where already slow down.

Combination of streamer characteristics depends on its history. Streamers are unobservable by their initiation. They may remain obscured [4].

***Streamer characteristics:*** Dimensions (transverse size and length); luminosity (depends on transverse size), velocity and acceleration; electron & ion density distributions; electric characteristics; branching parameters; residual luminosity.

## Quasi-electrostatic fields generated in middle atmosphere after +CG lightning as drivers of sprites and streamers

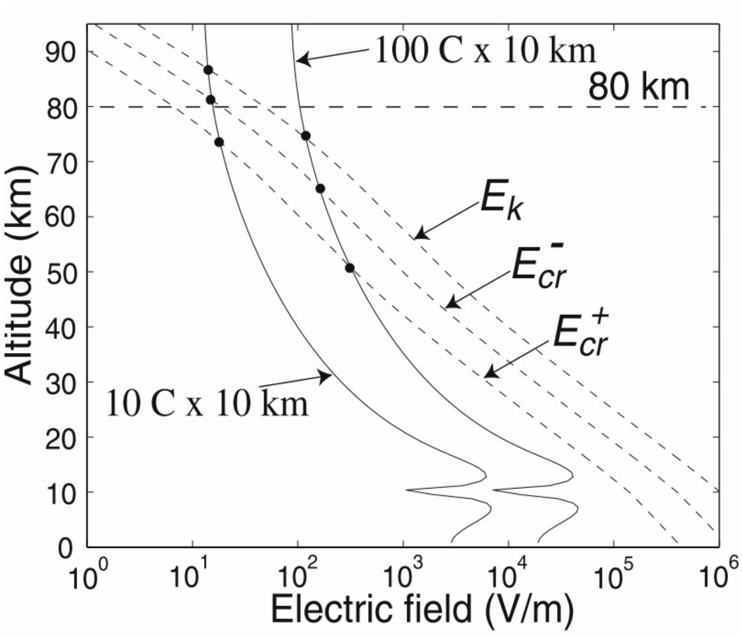



Fig.5a. Threshold electric fields as functions of altitude. Dashed curves are for minimum electric fields $E_{cr+}$, $E_{cr-}$, $E_k$ necessary for propagation of positive and negative streamers, and of an runaway avalanche, respectively. They are proportional to atmospheric number density $N$.

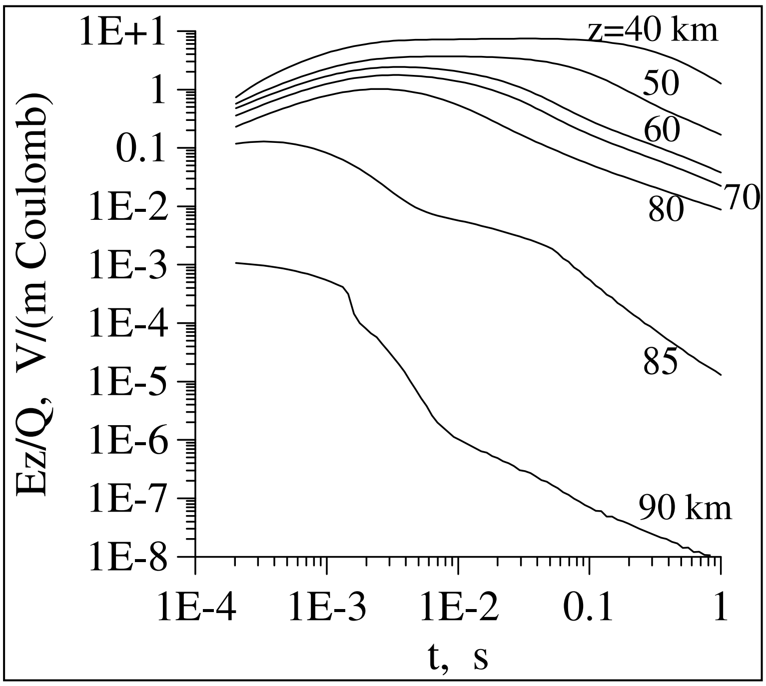



Fig.5b. Time variation of the vertical electric field at altitudes 40 - 90 km above thunderstorm after a +CG lightning discharge for time 1 ms [13]. Results are normalized to 1 C removed charge.

# Behavior of spatial charges (linear approximation)

Realization of streamers is closely related to the dynamics of the spatial charges after the causative +CG lightning discharge. The time variations of the charge's density $\rho$ after the beginning of the +CG lightning discharge are demonstrated in Fig.3. The results are derived from the solution of Eq. (1) and div $\mathbf{E} = \rho/\varepsilon_0$, where $\mathbf{E}$ is the electric field vector.

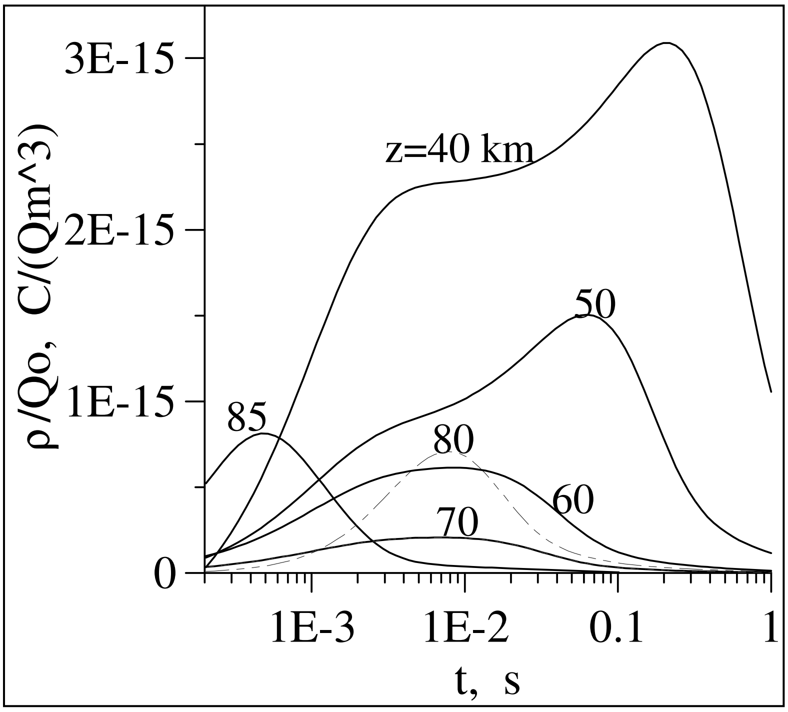



Fig.6. Temporal variations of spatial positive charges density $\rho$ at altitudes 40 - 85 km after the beginning of the causative +CG lightning discharge. The density $\rho$ is normalized to a charge removed by lightning of 1 C.

**Peculiarities:**

1) The spatial charge $\rho$ at an altitude $z$ reaches maximum $\rho_{max}$ long after the maximum $E_{max}$ of QSF $E$ reached at this altitude.

2) The proportionality between $\rho_{max}$ and $E_{max}$ is strongly impaired. For example, values of $\rho_{max}$ at 85 and 80 km are much larger than at 70 km, although $E_{max}$(70 km) >> $E_{max}$(80, 85 km); also, $\rho_{max}$(85 km) is ~25% of $\rho_{max}$(40 km), while $E_{max}$(85 km) is ~20 times less than $E_{max}$(40 km).

These features show that positive electric charge of very large density (which will further create a 'head' of a streamer) can be formed at a very thin layer where conductivity has an abrupt jump with big change.

## Studies related to initiation of a positive streamer in lower ionosphere after a +CG discharge (qualitative description)

Different mechanisms have been proposed for the positive streamer initiation after +CG lightning, for example:

1. A streamer is created from a big enough irregularity with larger ion density than around it, and by QSF $E_0$~$E_k$, where $E_k$ is electric field necessary for conventional breakdown [8]. Vertically oriented and long irregularities are better candidates.

2. Formation of a streamer occurs due to continuous increase of the 'ionization wave' gradient with entering to denser atmospheric regions (no electron avalanche is required) [6].

Modeling of processes in middle atmosphere after +CG lightning discharge was developed in a series of works [4]. Three convection-diffusion equations for dynamics of densities of electrons, and positive and negative have been included:

$$\frac{\partial n_e}{\partial t} + \nabla \cdot n_e \vec{v}_e - D_e \nabla^2 n_e = (\nu_i - \nu_{a2} - \nu_{a3}) n_e - \beta_{ep} n_e n_p + S_{ph}$$

(1)

$$\frac{\partial n_p}{\partial t} = \nu_i n_e - \beta_{ep} n_e n_p - \beta_{np} n_n n_p + S_{ph} \; ; \qquad \frac{\partial n_n}{\partial t} = (\nu_{a2} + \nu_{a3}) n_e - \beta_{np} n_n n_p$$

for densities of electrons $n_e$, positive ions $n_p$, and negative ions $n_n$, respectively, together with Poisson equation for the electric potential $\Phi$:

(2) $$\nabla^2 \Phi = -\frac{e}{\varepsilon_0}(n_p - n_e - n_n)$$

$\mathbf{v}_e$ is drift velocity for each specy, $\mathbf{v}_e = -\mu_e \mathbf{E}$ ($\mu_e$ is the electron mobility: it is proportional to conductivity); $\nu_i$ is the ionization coefficient; $\nu_{a2}$, $\nu_{a3}$ are attachment coefficients by reactions with 2 and 3 particles; $\beta$ and $D_e$ – recombination and electron diffusion coefficients; $S_{ph}$ – photo-ionization rate. In Eq. (2) F is the electric potential, $e$ - the electron charge, $\varepsilon_0$ – the permittivity. The system of equations (1-2) is highly non-linear, and thus is difficult to be solved correctly [12]. This system accents on dynamics of the negative charges (electrons) and neglects that of the positive charges, which appear in much larger time scale.

Here a scenario of a positive streamer initiation is presented which on which a model will be developed further. This scenario stresses on the dynamics of positive charges since it is basic in positive streamer formation.

## *Scenario:*

**First, a narrow layer of positive charge of relatively high density is created at altitude ~85 km because of realization of a) a halo; b) an avalanche of runaway electrons.**

**A halo** occurs at altitudes 85-90 km at time *t* ~1 millisecond after the causative +CG lightning discharge, for a time period of ~1 ms. In it the free multiplication of electrons is realized [5] driven by QSF *E* whose maximum by time agrees with the halo occurrence. Halo always occurs in sprites (although sometimes it is not observable) before creation of streamers [12].

The free electrons drift upward by QSF **E**; the positive ions drift downward but much slower. A net positive charge is formed before their relaxation.

**An avalanches of runaway electrons** of energy up to 50 MeV is initiated in the thunderstorm by a seed electron of energy > 1 MeV born by GCR particle of energy ~100 MeV [9]. The friction force *F* of an electron depends on its energy as shown in Fig.7 - *F* has a minimum at 1.4 MeV. The seed electron can be thus accelerated to relative energies by the post lightning electric field **E**. It then generates a cascade of electrons of energy > 1 MeV which also become relative, etc.

In the lower ionosphere the runaway avalanche causes also a cascade of electrons of thermal energies [9] which form narrow upward beams. The fast escape of the runaway and thermalized electrons at altitudes 85-90 km also contributes to the population of positive ions. The positive charge density $\rho$ is large in a compact sub-region *R* of the halo depending on the avalanche spatial distribution. This agrees with recent observations [7].

A descending front is formed at altitude $z_F$ of gradually enhancing positive charge of density $\rho$ in the sub-region *R*. At its lower edge an abrupt jump of the conductivity $\sigma$ and the density $\rho$ is gradually formed due to positive feedback. Before lightning the profile of conductivity $\sigma$ has a 'knee' at 75-80 km (well demonstrated in Fig.8) which plays an important role further: above 80 km the relative height gradient $\nabla_z\sigma/\sigma$ is relatively large. This gradient becomes even larger at halo's heights before the lightning discharge due to Joule heating by electric fields generated by thunderstorm in quiet conditions [11]. Due to heating, the conductivity $\sigma$ between 70 and 85 km decreases by several times - this is demonstrated in Fig.8.

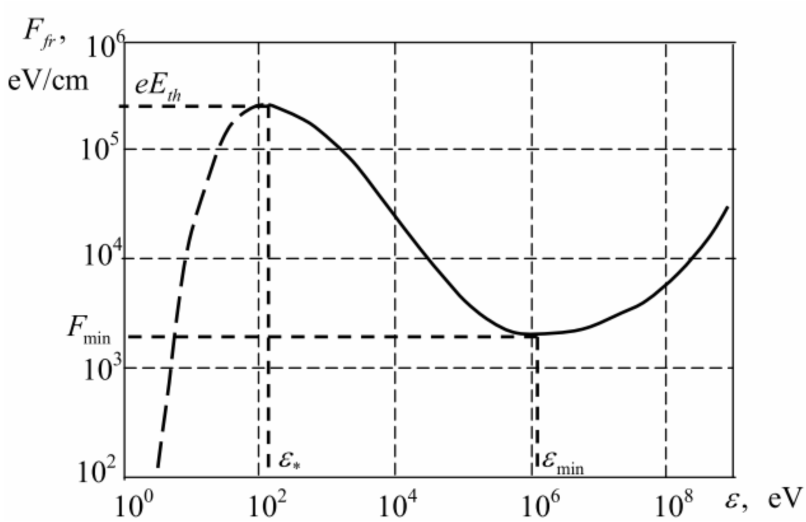



Fig.7. A schematic plot of dynamical friction force of electrons in the air versus electron kinetic energy [12].

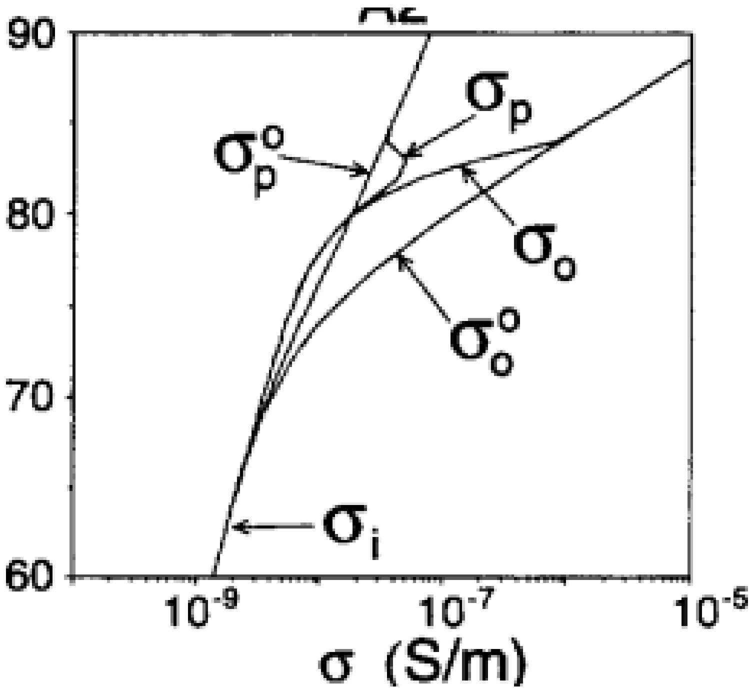



Fig.8. Profiles of ambient (with o) and modified above a quiet thunderstorm field-aligned and Pedersen conductivities [11].

Much more abrupt slope in $\sigma$ profile is formed locally at $t$ ~ 1 ms at a lower edge $z_F$ of the descending sub-region $R$. It is due to the increase of ion density $\rho$, and to the decrease of conductivity just below $z_F$ by descending. The increase of $\nabla_z\sigma/\sigma$ with time leads to a further dramatic increase of positive charge density $\rho$ and, hence, of conductivity $\sigma$, as schematically shown in Fig.8. Thus, a positive feedback is realized. It is driven by a superposition of the QSF $E$ generated due to +CG lightning, and electric field $E_e$ created by free electrons situated above $R$. Another two factors of fast increase of the positive charge density $\rho$ are: *i*) the upward flow of free electrons from below driven by the QSF $E$ which enhance ionization at the front; *ii*) the increase of the atmospheric density $N$ before the descending front line; *iii*) ionization by the local electric field generated by positive charges. With the increase of $\rho$ the density $n_X$ of excited molecules also enhances. The edge at lowering altitude $z_F$ of the region of positive ionization becomes abrupt by time $t$ ~ 3 ms. Irregularities in horizontal distribution of charge $\rho$ at altitude $z_C$ are possible due to non-linearity.

These processes will lead to large enough density $\rho$ at some locations and to large electric fields $E_S$ near these locations. Eventually, the strictly localized electric fields $E_S$ will be large enough for sufficient ionization close below their source in order to initialize a positive streamer. But a formation of a streamer with typical transverse dimensions of tens or hundreds of meters is possibly not guaranteed.

Possible additional contribution in this process can have galactic cosmic rays. A GCR particle could play a role to impair the smoothness of the front line and thus trigger a streamer initiation. It is required that this particle passes through a local maximum of positive charge density ρ, and is in the same direction as the applied electric field $E$, and is possible to create a long ionization path above and below this point. A specific irregularity will be then created in the front line able to develop further to a streamer of typical transverse dimension by large enough density $\rho$.

It is worth to note the results of the most recent observations (Qin et al., May 2014, abstract) of the process of generation of a positive streamer of a sprite. The scenario proposed here shows agreement with them.

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