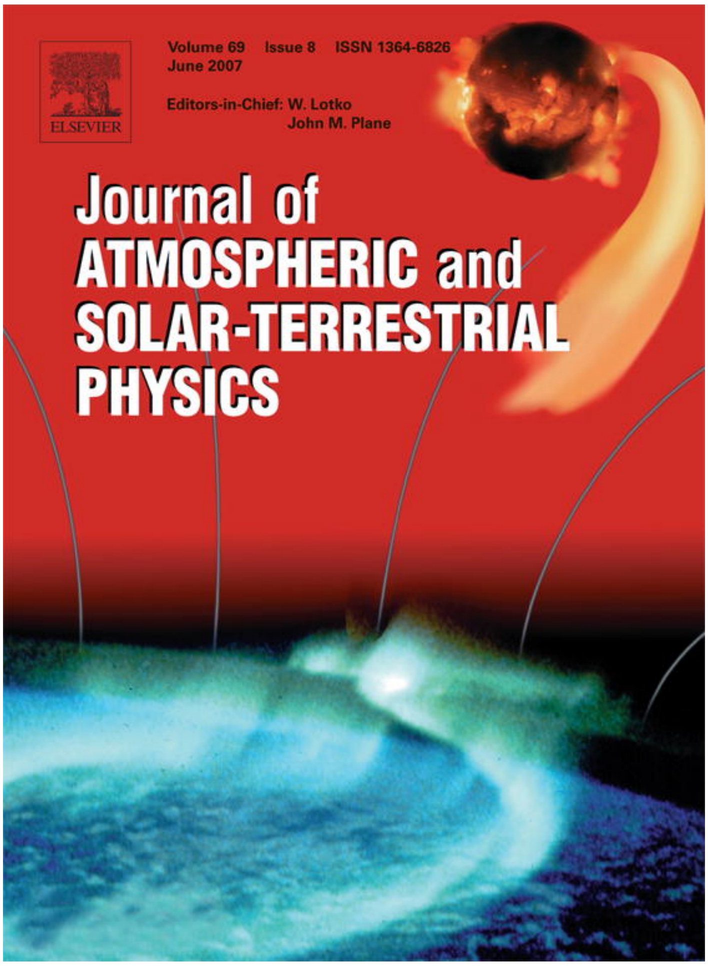
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# Leader–streamers nature of blue jets

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**Abstract**

A new model of blue jets as a lightning-related phenomenon is proposed. A blue jet consists of the bi-leader, whose top part is seen on photos as a "trunk of a tree", and is capped at the topside of the leader by its streamer zone. The latter is shown as tall and narrow branches of "the tree". It is shown that the time independent fractal blue jet model does not provide an adequate description of blue jets and streamer zone of a leader. It ignores an important fact of the fast loss of the streamer channel conductivity due to the electron attachment to the oxygen. The top streamer branches were born mostly prior to the bottom branches not as result of branching, but formed by the leader tip. It was shown that due to transfer of the high potential of the edge of the thundercloud by the leader, long streamers of blue jets can be sustained by moderate cloud charge.

The streamer length is estimated along with the height at which the streamers can reach the ionosphere. The propagation of a streamer in the atmosphere of exponentially falling density $N$ and in the self-consistent electric field of the streamer zone was computed. It was found that the critical external field $E_S$ required for unlimited streamer growth satisfies the similarity law $E_S/N \simeq$ const. The similarity law was numerically studied in a wide range of $N$.


*Keywords:* Meteorology and atmospheric dynamics; Lightning; Middle atmosphere dynamics; Atmospheric electricity

## 1. Introduction

The name of blue jets (Jets in what follows) is given to luminous bodies growing upward with a speed of about 100 km/s from the upper boundary of a thundercloud. Starting from a height $h_0 \simeq 18$ km they reach the height $h_f \simeq 30$–40 km (Wescott et al., 1995, 1996, 1998, 2001), although in a few exceptional cases they reached the ionosphere at 80–90 km (Pasko et al., 2002; Su et al., 2003). Photos of Jets resemble a tall tree with branches growing within a narrow angle ~15°.

The first published theoretical models suggested that Jets are either gigantic positive streamers (Pasko et al., 1996) or negative streamers (Sukhorukov et al., 1996) produced by lightning discharges. The runaway breakdown model (Roussel-Dupre and Gurevich, 1996) also assumes that Jet brings a negative charge. More rigorous analysis made by Petrov and Petrova (1999) and

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Pasko and George (2002) came to conclusion that Jets are similar to the streamer zone of a leader (streamer corona). In fact, Pasko and George (2002) presented a detailed model of a Jet as a ''fractal tree'' (see also Tong et al. (2005)). Using the earlier developed numerical algorithm (Niemeyer et al., 1989) the branching in the streamer corona was described as that originates from a point base. The growing of such ''streamer tree'' occurs in a self-consistent electric field generated by the cloud charge and the branches themselves. The branching is computed at each time-step by considering the electric field distribution around each free end of the branches. New branches are born in the direction of the maximal field. The field was taken from laboratory experiments, which reveal that positive streamers in the air at the normal conditions are sustained by the field $E_{S0} \backsimeq 500\,\mathrm{kV/m}$. In order to consider non-uniformity of the atmosphere the scaling law $E_S/N = \mathrm{const}$ was assumed, where $E_S$ is the electric field in a streamer channel, while $N$ is the molecular number density at the altitude $h$, $N \propto \exp(-h/\Delta)$, where the atmosphere scale height $\Delta \backsimeq 7\,\mathrm{km}$.

Although a similarity between Jets and a streamer zone of a leader looks as a constructive approach, some elements of the above computer model do not describe properly the physical processes happen both in a streamer zone of a leader and in Jets. Seems that only accidental resemblance between the fractal tree and the photographs of Jets occurs. A streamer branching that dominates the fractal model does not play an important role in the formation of the streamer zone of a leader. A very important mechanism missed in the above model is fast reduction of the electric conductivity of the streamer channel due to the electron sink caused by the attachment to $O_2$, and on some occasions by the electron–ion recombination. In a streamer zone of a leader having a length of a few meters, the individual channels of high conductivity formed behind the streamer tips are not longer than a few centimeters at $p \backsimeq 1\,\mathrm{atm}$ (Bazelyan and Raizer, 1998). For this reason, the top branches of the ''fractal tree'' cannot be supplied by the current (charge) from the bottom branches, not mention the supply from the base of the tree as it proposed in the fractal model. The streamers located higher up were born prior to those located near the bottom since the streamers are predominantly generated by the leader tip. When the streamers reach the top of the streamer tree they lose any link to the leader tip, and to the ''younger'' bottom streamers as well. Therefore, the tree that imitates a Jet grows mainly not by branching but by upward propagating independent branches that are born continuously near the tree base.

Below, we propose a mechanism of Jet origination and growing which also has a similarity with the streamer–leader process. Jet is kind of a lightning propagating upward from positively charged cloud top. We believe that a Jet carries positive charge although there are no experimental data on Jet's polarity. These are some considerations: firstly, the top part of a cloud is charged, as a rule, positively. Secondly, negative leader and streamers require essentially higher electric fields, i.e., the cloud's charges, than positive leader and streamer. Furthermore, Jet should consist of a leader (which is trunk of a tree seen on Jets photos) and its streamer zone (branches of the tree). Streamers can easily propagate in the rear atmosphere, since a weaker governing field is needed. Thus, when streamers of the streamer zone become longer than the pressure scale $\Delta$, they grow preferentially in the direction of the sharpest density drop, i.e. upward. They form much narrower beam than that in uniform gas.

Note that the Jet model by Pasko and George (2002) lacks a realistic mechanism of the current supply of the fractal three. In their mechanism, the charge is collected from the thundercloud to the base of the ''tree'' by charged particles of macroscopic size. However, such process takes much longer time than needed to develop a Jet propagating with the speed $v \sim 100\,\mathrm{km/s}$, i.e. $t \backsimeq (h_f - h_0)/v \backsimeq 0.3\,\mathrm{s}$. Similar problem of insufficient current supply for the fast developing leader ($\sim$0.01 s) exists in the theory of conventional lightning. A model which successfully resolved this problem proposes simultaneous formation of bi-leader, i.e., two leaders of opposite polarity, growing in two opposite directions (Kasemir, 1960; Mazur and Ruhnke, 1998; Bazelyan and Raizer, 2000). These leaders supply each other with the current and charge. We discuss this subject later on with respect to Jets.

## 2. Models of Jet formations and structure

### 2.1. *A thundercloud cannot supply blue jet with the electric charge*

Let us estimate charge of a Jet the same way as in Petrov and Petrova (1999). Assume that Jet is an inverted cone with an aperture of 15°, ranged between say, 20 and 40 km. The electric field at the top boundary is almost same as in the streamer channel $E_S \backsimeq 134$ V/m for the neutral density at 40 km $N = 6.7 \times 10^{16}\,\mathrm{cm}^{-3}$. According to the Gauss theorem the cone contains an electric charge $Q \backsimeq 0.25$ C (here we neglected the contribution from the field normal to the cone's side surface which reduces the value of $Q$). Furthermore, the cone has been developed during $t \backsimeq 0.2$ s, thus, the current is $i \backsimeq 1.25$ A. The mean charge density in a thundercloud $\rho \sim 10^{-9}\,\mathrm{C/m^3}$, such charge is attached to micrometeorites (droplets, ice particles, hail) (Marshall et al., 2001). Thus the macroscopic particles have to be collected from a volume $Q/\rho$ of about a cubic kilometer to a small leader (or streamer) channel, all within 0.2 s. A similar problem arises in a case of conventional lightning, which leader carries charge $Q \sim 1$ C for $10^{-2}$ s, thus possesses the current of ~100 A. The condition of fast charge collection cannot be fulfilled, which stimulated scientists to adopt the model of a bi-leader forms in the thundercloud as proposed by Kasemir (1960).

### 2.2. Bi-leader as a source for blue jet

Let us show first that the source of Jet current supply can be only a leader, not a streamer. According to the photographs (Wescott et al., 1995, 2001; Pasko et al., 2002) a Jet is born at altitude not higher than 18 km where $N = 2.5 \times 10^{18}\,\mathrm{cm}^{-3}$. The characteristic electron attachment time to $O_2$ due to three body collisions is given by

$$\tau_a \simeq 5 \times 10^{-5} \left(\frac{10^{18}}{N}\right)^2, s; \quad N[\mathrm{cm}^{-3}]. \tag{1}$$

It gives 8 µs at 18 km. This is by far shorter than the lifetime of Jets. Thus any cold source of Jet current supply loses the conductivity within tens µs and fades away. A high gas temperature $T > 5000$ K typical for a leader channel is required to supply the leader with a current for a long enough time (Bazelyan and Raizer, 1998). Therefore, only a leader tip can be a source of streamers for the Jet formation over a long-time (>0.1 s), as in (Petrov and Petrova, 1999; Pasko and George, 2002) and along our hypothesis.

A developed leader is a thin conductive plasma channel, heated up to $T > 5000$ K. It can propagate along kilometer-long distance, like a lightning. Stability and operation of such channel is provided by the high gas temperature that suppresses sink of the electrons, and by the cover of the space ion charge that surrounds the channel (see Fig. 1). The channel has high electric potential comparable with the potential of a high voltage source. Such source can be either an electrode from which the laboratory leaders start, or thundercloud in a case of lightning. Their potentials are in the range of about $U \sim 1$–100 MV (from laboratory studies up to the lightning).

In fact, if a thin channel of radius $r$ is surrounded by the uncharged dielectric such as cold air, a very strong field on the scale of $U/r$ will appear near its surface. The field will ionize the air, which leads to the channel expansion. However, the conducting channel has a limited energy resource $C_1 U^2/2$, where $C_1$ is the capacitance of its unit length. This energy is not enough to heat up the air column with the radius more than a few cm, to 5000 K in order to maintain its conductivity for a long time. However, a leader tip produces plenty of streamers propagating in fan-shaped manner. The streamers move along the distance $L_S \sim 1$–10 m, in a self-consistent field, before they die out. The charge carried away

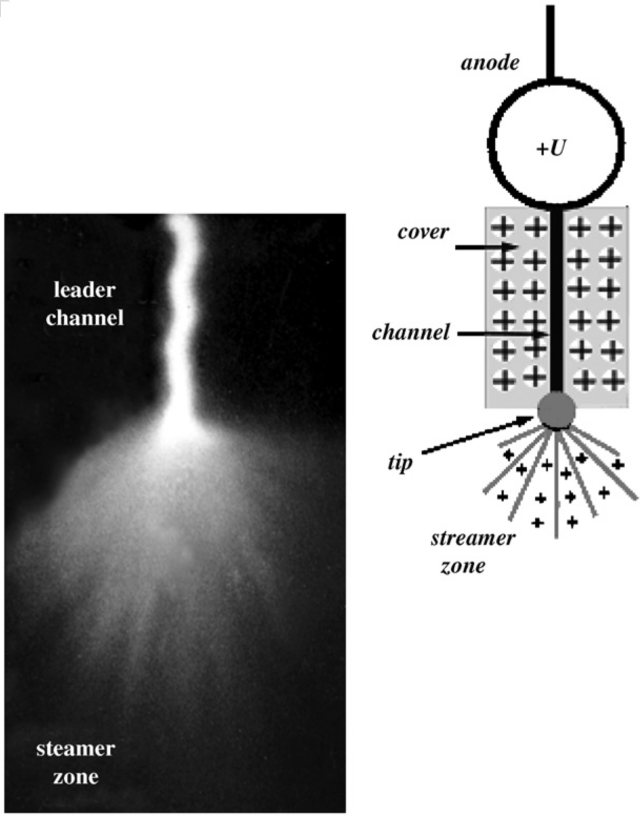


Fig. 1. Snapshot and schematics of a laboratory leader growing from an anode.

by the streamers is collected in a cylindrical volume with a radius of the order of $L_S$. This is how the cover of space charge around the leader channel is formed. The lateral field near a channel falls up by the scale of $U/L_S \ll U/r$, and thus cannot ionize. An outstanding problem in the modern theory of a leader formation is related to generation of self-consistent electric field in the streamer zone of a leader (Bazelyan and Raizer, 2000). This field is generated by the combine action of the exterior charges and the charges of a huge number of streamers, which are continuously appeared and disappeared. The resulting self-consistent electric field should maintain the streamers, i.e., be close to $E_S$. Although the qualitative picture is clear, the problem still awaits a comprehensive solution. Similar difficulty also exists in our model, however, since we deal with non-uniform atmosphere the complexity of the problem increases. Thus, we have to rely on the semi-empirical models of leader formation and propagation in the uniform atmosphere.

Another important reason exists for the leader to be a source of very long streamers, such as revealed by photos of Jets. Namely, the electric field in the region where streamers are formed cannot be weaker than $E_S$ at the given air density. But it is difficult to generate such strong field by the thundercloud charge alone. For this reason, the model by Pasko and George (2002) uses very high thundercloud charges $Q_C = 120$–130, much higher than usually observed (in a case of a negative Jet twice of that cloud charge is required). However, if the leader participates in the generation of the strong field $E_S$, a huge thundercloud charges are not needed. Highly conducting leader moves the high potential of a thundercloud upward from the place where the leader was born to the region of the lower $E_S \propto N$, and thus provides the voltage required to form streamers.

The mechanism of bi-leader initiation is similar to that of formation of a conventional lightning. In fact, a Jet can be considered as a lightning propagated upward from the top of thundercloud. Some hypothesis exist regarding the mechanism of leader initiation such as runaway electrons due to cosmic rays (Gurevich and Zybin, 2001), and occasional accumulation of large charge that produces a local ionizing field. But in any case, it is much easier to trigger a leader in the area where the electric field due to thundercloud reaches its maximum. With respect to Jets that appear on the height $h_0 \backsimeq 18$ km, the leader initiation should coincide with a bending point B of the cloud charge potential curve where the electric field is maximal (see Fig. 2). Plate a on Fig. 2 corresponds to the electro-neutral thundercloud, plate b corresponds to the case following the negative cloud-to-ground lightning discharge. Note that if a bi-leader is born in the vicinity of the point A it cannot move upward beyond the point B. The leader velocity is determined by the potential difference between the potential of the leader tip and the external (cloud) potential at the tip's location (Bazelyan and Raizer, 2000). The leader channel is rather a good conductor, and its potential slightly changes along the channel. If the leader is born near the point A and moves upward, i.e., towards the point B, the potential difference tends to zero when the leader reaches the upper branch of the potential curve (see Fig. 2b). The upward leader stops when the potential difference reduces to a value of about 400 kV at the sea level. Thus the point A cannot become a source of Jets since if been born near the point A they cannot propagate beyond the point B.

Contrary to it the upward component of a bi-leader born near the point B can move without obstacles. When two leaders grow, their potential changes such a way that the two dashed regions in Fig. 3 have equal areas (Bazelyan and Raizer, 2000). Actually they are proportional to charges of the positive and negative leader, while the total charge is zero, since it is not taken from the thundercloud. The negative downward propagating leader can not escape the cloud by crossing the left brunch of the curve $U_C(h)$ on Fig. 2 as it was explained in the previous paragraph. But the positive one can escape and becomes a Jet.

According to the lightning statistics 90% of cloud-to-ground lightning are negative, therefore, they are initiated in the point L in Fig. 2a. It also starts with formation of a bi-leader, but the negative leader reaches the ground while the positive stops in the negative part of the cloud without crossing the right branch of the $U_C(h)$ curve (Bazelyan and Raizer, 2000).

### 2.3. *Early stages of the development of leader and streamer sections of a Jet*

The tip of a positive leader growing upward from the initiation point B (Figs. 2 and 3) emits streamers at a high rate. In fact, at the laboratory conditions such rate is about $10^9$ 1/s. The streamers stop as

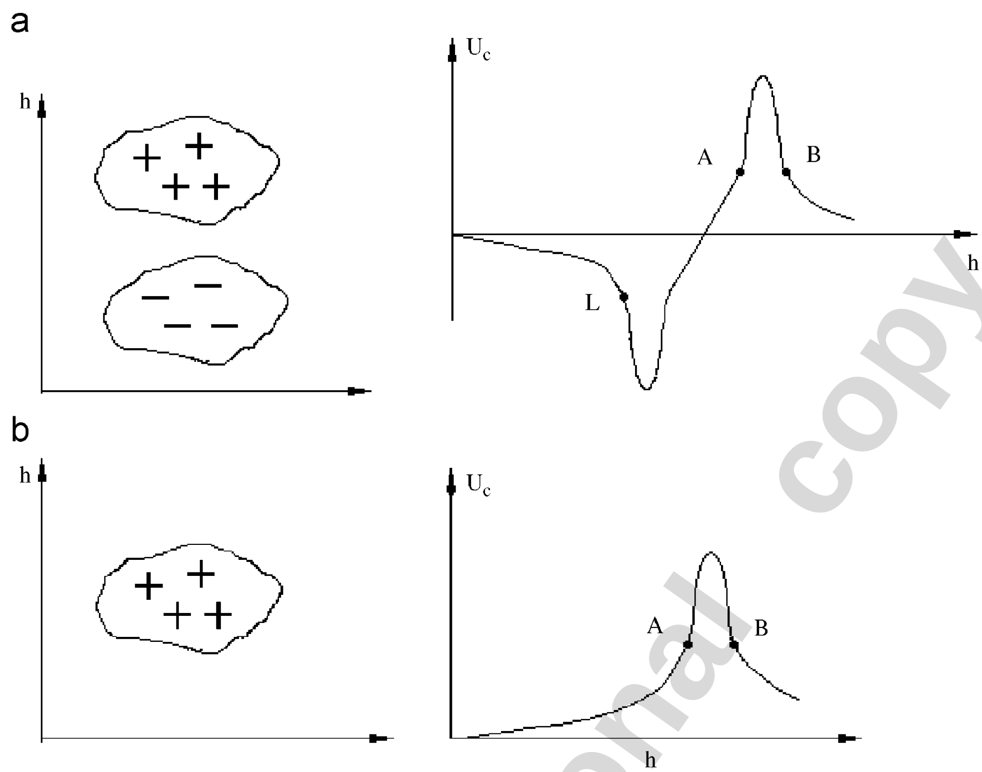


Fig. 2. Height distribution of the cloud charge potential: (a) the cloud is electro-neutral, (b) a single positively charged cloud appeares following the negative cloud-to-ground flash. B corresponds to the most probable initiation point of a Jet.

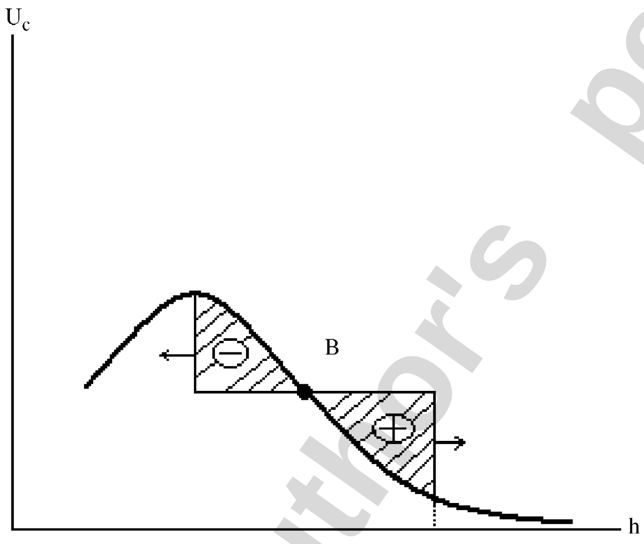


Fig. 3. The potential diagram illustrates the bi-leader initiation, and the potential transferred by it.

soon as the field drops below $E_S$, needed for their sustainment. This way a boundary of a streamer zone which on average moves with the leader speed is formed.

The length of the streamer zone can be estimated for the uniform atmosphere as the distance where the mean field between the streamer initiation and stoppage points is $E_S$. If $U_L$ is the leader tip potential located at the point $x_t$, and $U_0(x_t + L_S)$ is the potential on the leading edge of the streamer zone of length $L_S$, then the following equation has to be satisfied:

$$E_S L_S = U_L - U_0(x_t + L_S). \tag{2}$$

Let us make some estimates for an early stage of a Jet, when the streamer length $L_S$ is much smaller than the atmospheric pressure scale, $\Delta \backsimeq 7\,\text{km}$. Let us introduce the thundercloud field by a simplest way. We assume that it is formed by the charge $Q_C$ of the top positive cloud, which is uniformly distributed within the sphere of radius $R$. The electric field formed by the cloud charge has its maximum near the cloud edge; therefore Jet moves upward from the top cloud edge. If we consider the leader channel as a good conductor and neglect the contribution to the potential by the charges in the leader cover and streamer zone compared to the potential of the thundercloud, we get

$$U_L = U_R = \frac{Q_C}{4\pi\varepsilon_o R}, \; U_0(x_t + L_S) = U_R \frac{R}{R + x_t + L_S}. \tag{3}$$

Here $U_R$ is the potential at the edge of the thundercloud at which the potential coincides with that of the tip of the leader. The distance is counted upward from the cloud edge. For example, if $Q_C = 50\,C$ and $R = 3\,km$, we have $U_R = 150\,MV$ (the potential of the cloud center is $3/2U_R$).

If the cloud center is located at 12 km, while the leader tip moves $x_t = 3\,km$ from the edge of the cloud from 15 up to 18 km where Jets are usually observed, the field required to sustain streamers at 18 km is $E_S = 50\,kV/m$. By substituting Eq. (3) into Eq. (2) one can obtain an algebraic equation, and its solution gives that $L_S = 1.85\,km$, which is much smaller than $\Delta = 7\,km$. Thus the assumption of the uniform atmosphere holds.

The early stage of Jet development may therefore be depicted as a positive leader of 3 km length with a streamer zone of about 2 km length. Although a Jet is seen at about 18 km, it does not mean that it is born at this height. The initial part of a leader can be hidden inside a cloud, as it usually happens in a conventional lightning. Furthermore, in the above case of 18 km height the electric field due to the cloud $E_C(x_t) = 12.5\,kV/m$, is four times weaker than $E_S = 50\,kV/m$ needed for streamer formation. However, a required voltage can be formed along the streamer zone since the leader delivers the potential of the cloud edge $U_R = 150\,MV$ to the point $x_t$. Such a potential is two times higher than the cloud potential at this location $U_C(x_t) = 75\,MV$.

### 2.4. Ascending long streamers in the non-uniform atmosphere

As demonstrated in Section 2.3, the streamers that were born by a source located at $h = 18\,km$, where Jets are initiated, according to the photographs (Pasko et al., 2002), can move upward only for 2 km. Let us show that the streamer source should be located at least 10–15 km above that height in order for the streamers to escape to the ionosphere, as observed by Pasko et al. (2002) and Su et al. (2003) (Fig. 4). Therefore, it will be shown that observed by Pasko et al. (2002) two "tree trunks", those tops develop the branches are not streamers, but the two leaders. They are in turn branched out from a single leader, which is typical for a conventional lightning.

Assume that the leader tip is located at the altitude $h_L$ where $N(h_L) = N_L$, and the field required to maintain streamers $E_S(h_L) = E_{SL}$. Let the ionosphere has zero potential while the leader tip's

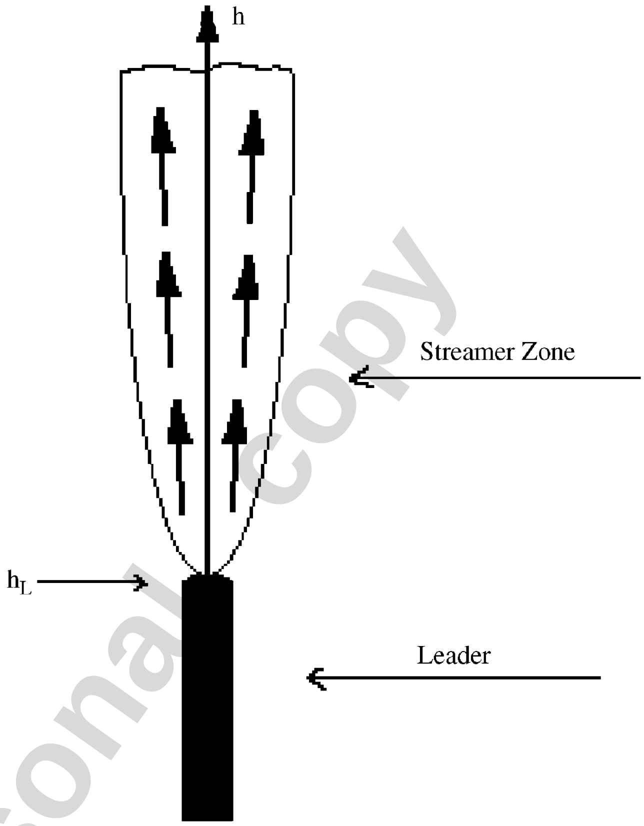


Fig. 4. Schematic of blue jet with long streamers.

potential $U_L$ is close to that at the edge of the thundercloud. Actually, it is obtained from the equality of the areas in Fig. 3, and if we consider possible voltage fall along the leader channel and branching of the leader, the value of $U_L$ can be a few times smaller than the cloud potential.

Let us make a fundamental assumption that the field $E_S(x)$ needed for the streamer propagation in each point $x$ of its channel in the non-uniform atmosphere where $N \propto e^{-x/\Delta}$ satisfies the similarity law $E_S(x)/N(x) = \text{const}$. Such non-obvious assumption will be justified later on by the numerical modeling of long streamers propagating in the uniform atmosphere with different $N$, as well as in the non-uniform atmosphere.

Notice that existing experimental and model data that belongs to the density range from the normal $N_0$ to 0.3 $N_0$ show some deviations from the similarity law. In fact, in the above range of the air density the value $E_S/N$ drops by the factor 1.4 (Bazelyan and Raizer, 1998), thus $E_S/N \propto N^{1/3}$, while the similarity law $E_S(x)/N(x) = \text{const}$ fulfills at the low air density which corresponds to the height in excess of 18 km, as shown below in Section 4.1.

Based on the above assumption, we generalize the relation (2) that determines the streamer length, to the case of exponential atmosphere by replacing $E_S L_S$ by the following integral:

$$\int_0^{L_S} E_{SL} e^{-x/\Delta}\, dx = E_{SL}\Delta(1 - e^{-L_S/\Delta}) = U_L - U_{ext}. \tag{4}$$

Here $U_{ext}$ is the potential drop from the front of the streamer zone to the ionosphere with zero potential. The potential $U_{ext}$ is formed on the height $h_L + L_S$ by the combined effect of the charges of the thundercloud, the leader (or rather leader cover) and its streamer zone along with their mirror images in the ionosphere.

Let us focus on the late stage of a Jet when the streamers of streamer zone travel a few tens of kilometers, and the front of the streamer zone is located only at a distance $\leqslant L_S$ from the ionosphere. In this case, $U_{ext}$ is small compared to the potential drop along the streamer zone, i.e., $U_{ext} \ll U_L$. In fact, the charges due to the thundercloud and leader are located too far from this point, while the effect of the charge due to the streamer zone is compensated by its mirror image. Besides, in the exponential atmosphere charge density in the streamer zone drops exponentially.

Therefore, by neglecting $U_{ext}$ in Eq. (4) we find the length of the streamer zone of a leader with the tip located at the height $h_L$ and having potential $U_L$:

$$L_S = \Delta \times \ell n\left[(1 - U_L/E_{SL}\Delta)^{-1}\right]. \tag{5}$$

This equation also shows at what minimum height $h_{L\infty}$ streamers emitted by the leader tip can escape to the ionosphere. The height $h_{L\infty}$ is determined by the condition $E_{SL} = U_L/\Delta$ which brings $L_S$ to infinity.

As will be shown in Section 4.1 for the altitudes of a few tens of kilometers the value of $E_S/N$ is of about $1.28 \times 10^{-23}\,\mathrm{kV\,m^2}$. Hence we obtain

$$h_{L\infty} \approx \Delta \ell n \frac{E_{S0ext}\Delta}{U_L} \approx 7.2 \ell n \frac{2400}{U_L\,[\mathrm{MV}]}\ \mathrm{km}, \tag{6}$$

where $E_{S0ext} = 326\,\mathrm{kV/m}$ is the value of $E_S$ extrapolated to the normal atmospheric conditions with the density $N_0$, is smaller than the measured $E_{S0} \backsimeq 500\,\mathrm{kV/m}$. Here, the deviation from the similarity law at high densities is revealed.

Thus, if the leader tip at the height $h_L$ has a potential $U_L \backsimeq 100\,\mathrm{MV}$, the height $h_{L\infty}$ is equal to 23 km. If $U_L = 50\,\mathrm{MV}$ $h_{L\infty} = 28\,\mathrm{km}$, and if $U_L = 30\,\mathrm{MV}$ $h_{L\infty} = 32\,\mathrm{km}$. Therefore, starting from 10 to 15 km above the observed origination altitude of Jets, the streamers, which form branches of the "tree" and spreading from the trunk at the height $h_{L,\infty}$ can propagate upward for a long distance. Such streamer behavior resembles the observations by Pasko et al. (2002) in which the brunches (streamers) run out of two trunks (leaders). The smallest among the above values of $U_L$ seems to be more realistic due to the potential drop along the leader channel and the leader branching. The smallest potential is close to that is carried be a conventional lightning.

## 3. Growth of an individual streamer in the exponential atmosphere. Formulation of the problem

We consider a model of Jets illustrated by Fig. 4, and study evolution of a single streamer, which starts at the leader tip and moves upward along the $x$-axis. The coordinate $x$ is counted from the place where the streamer was born while neglects small displacement due to a slow motion of the leader tip.

### 3.1. *Characteristics of streamer tip*

The growth rate of a streamer $v_s$ and the number density $n_{e0}$ of the electrons formed by the streamer are determined by the processes in the streamer tip. The local value of $v_s$ is determined by the potential difference $\Delta U_t = U_t - U_0$ between the tip potential $U_t$ and the local potential of the external field, $U_0$.

The equations written below are based on the model by Raizer et al. (1998). Here, we present them in the most appropriate form using numerical coefficients and the similarity law. The maximum electric field near the tip $E_m$ weakly depends upon the intensity of the streamer, which is characterized by the voltage $\Delta U_t$. It has the following form:

$$E_m \simeq 1.5 \times 10^4 (N/N_0)\,\mathrm{kV/m}, \tag{7}$$

where $N_0 = 2.5 \times 10^{25}\,\mathrm{m^{-3}}$ is the air density at the sea level. The radius of the tip is described by the following electrostatic relation:

$$r_m \simeq \frac{\Delta U_t}{\xi E_m} = 3.3 \times 10^{-5} \Delta U_t (N_0/N)\mathrm{m}; \quad \Delta U\,[\mathrm{kV}]. \tag{8}$$

Here the coefficient $\xi$ ranged between 1 and 2 considers input to the tip potential of the charge located in the channel next to the semispherical streamer tip. For a sphere $\xi = 1$, while for a long conductor $\xi$ tends to 2, the latter value was assumed in Eq. (8).

The velocity of a positive streamer is approximately

$$v_s \simeq 5.3 \times 10^4\, \Delta U_t\, \mathrm{m/s}, \quad \text{if } \Delta U_t \geqslant 5\,\mathrm{kV}. \tag{9}$$

It sharply drops to zero at $\Delta U_t < 5\,\mathrm{kV}$. In fact, streamers slower than having $v_s \backsimeq 10^5\,\mathrm{m/s}$ have never been observed in the air (Bazelyan and Raizer, 1998; Briels et al., 2006; Ebert et al., 2006). Due to the air ionization by a strong field of the streamer tip plasma is formed with the electron density:

$$n_{e0} \simeq 10^{20} (N/N_0)^2\,\mathrm{m}^{-3}. \tag{10}$$

The model relations (7)–(10) are in a reasonable agreement with results of the 2D numerical simulations of the positive streamers (of 1–10 cm length) at atmospheric and close pressures (Babaeva and Naidis,1996; Pancheshnyi et al., 2005; Pancheshnyi and Starikovskii, 2003). They are also in line with the recent measurements of streamers radii and velocities (Briels et al., 2006).

### 3.2. Mathematical description of the long streamer growth

The streamer length is described by the following equation:

$$\mathrm{d}x_s/\mathrm{d}t = v_s[U_t(x_s)]. \tag{11}$$

Here $U_t$ is the potential of the streamer tip, which is defined by the processes occur in the entire channel. These processes can be described by the equations of the long line with distributed characteristics. By neglecting self-induction as justified in Bazelyan and Raizer (1998), we get

$$\frac{\partial q}{\partial t} + \frac{\partial I}{\partial x} = 0, \quad \frac{\partial U}{\partial x} = -IR_1, \quad q = C_1(U - U_0), \tag{12}$$

where $U$ and $I$ are the potential and current, while $q$, $C_1$, and $R_1$ are the charge, capacity and Ohmic resistance per unit length of the channel, respectively. All the above functions depend on $x$ and $t$. Remind that $U_0$ is the potential of the exterior field. The capacity

$$C_1 \simeq \frac{2\pi\varepsilon_o}{\ln(\ell/r)} \simeq 7.9\,\mathrm{pF/m} \tag{13}$$

can be assumed constant since it only logarithmically depends upon the streamer length $\ell$ and the mean radius $r$ (for example at the normal conditions $\ell = 1\,\mathrm{m}$ and $r = 1\,\mathrm{mm}$). In fact, in Eq. (13) we assume that $\ell/r = 1000$. The channel resistance is equal to

$$R_1(x,t) = \left[\pi r_m^2(x)\ e\mu_e(x) n_e(x,t)\right]^{-1}. \tag{14}$$

Here the radius of the channel can be assumed to be equal to the radius of the streamer tip in the point $x$, since after passing this point by the streamer its radius stays unchanged. The electron mobility is taken as

$$\mu_e \simeq 2.7 \times 10^{-2}\, N_0/N(x)\,\mathrm{m^2/V\,s}. \tag{15}$$

The electric field in the channel is relatively weak, and plasma decays there. Thus the electron density $n_e$ along with the density of positive ions $n_+$ reduces from the initial value $n_{e0}(x)$ due to recombination and electron attachment. This is described by the following equations:

$$\frac{\mathrm{d}n_e}{\mathrm{d}t} = -\frac{n_e}{\tau_a} - \beta n_e n_+, \quad \frac{\mathrm{d}n_+}{\mathrm{d}t} = -\beta n_e n_+. \tag{16}$$

Moreover, we consider in accordance with Eq. (1) that

$$\tau_a = 7.7 \times 10^{-8} (N_0/N)^2\,\mathrm{s}, \quad \beta = 2.8 \times 10^{-13}\,\mathrm{m^3/s}. \tag{17}$$

The kinetic equations can be simplified. If the initial electron density is high, at first the plasma decay is dominated by the recombination, then the attachment takes over. At the beginning of the decay $n_+ \backsimeq n_e$, while at the later time the ions do not affect the electron sink, since at moderate $n_{e0}$ the electrons are lost due to the attachment only. In both the cases, we can assume that $n_+ \backsimeq n_e$ and then integrate Eq. (16). The value of $n_e(x,t)$ is presented in the form:

$$n_e = \frac{n_{e0}\,\mathrm{e}^{-t'/\tau_a}}{1 + \beta n_{e0}\tau_a (1 - \mathrm{e}^{-t'/\tau_a})}, \quad t' = t - t_s(x), \tag{18}$$

where $t_s(x)$ is the moment when a streamer tip passes the point $x$, and $\beta n_{e0}\tau_a = \mathrm{const} = 2.16$ (according to Eqs. (10) and (17)).

The boundary condition on the growing end of the streamer is based on the fact that the current was spent to charge the newly formed part of the channel, thus

$$I = qv_s = C_1(U_t - U_0)v_s \quad \text{when } x = x_s. \tag{19}$$

Note that $I$ is invariant with respect to $N$, as well as to $v_s$. The second boundary condition at the base of the channel is

$$U = U_0(0) = U_L. \quad (20)$$

Formally, there is no streamer in the initial moment. However, the given equations cannot describe how a streamer is born. Thus an artificial short streamer with $U(x) = \text{const} = U_L$ and such length $x_0$ that $U_L - U_0(x_0) > 5\,\text{kV}$, is used as the initial condition. In this case, $v_s > 0$ and the streamer grows.

In order to get a numerical solution, it is convenient to convert two equations (12) for $U$ and $I$ into a single equation for $U$

$$\frac{\partial U}{\partial t} = \frac{\partial}{\partial x}\chi\frac{\partial U}{\partial x}, \quad \chi = \frac{1}{R_1 C_1},$$

$$\chi(x,t) = 190\frac{N_0}{N(x)}\frac{n_e(x,t)}{n_{e0}(x)}[U_t(x) - U_0(x)]^2\,\text{m}^2/\text{s}, \quad (21)$$

where $U$ is given in kV. The boundary conditions to Eq. (21) are provided by Eq. (20) along with the following equation:

$$\left(\frac{\partial U}{\partial x}\right)_{x=x_t} = -280\left(\frac{N}{N_o}\right)\,\text{kV/m} \quad (22)$$

which is reduced from Eq. (19) and the second of Eq. (12). According to Eq. (22), the field in the channel near the tip is close to $E_S$, although it does not necessarily coincides with $E_S$, the latter is the mean field value along the channel. Note that Eq. (21) is of a type of the equation of non-linear thermal conductivity. It describes non-linear diffusion of the potential along a streamer path.

## 4. Modeling results and discussion

### 4.1. Checking the similarity law for $E_S$

Streamer propagation in the uniform atmosphere in the $N/N_0$ range of 0.01–1.0 was computed using equations described in Section 3. The electric field $E$ was assumed uniform, while $U_0(x) = -Ex + \text{const}$. It was found that the streamer fades away if the field falls below the critical value $E_S(N)$, while for $E > E_S$ the streamer has unlimited grows. The found value of $E_S/N$ required for stable streamer growth is shown in Fig. 5. For $1.0 \geqslant N/N_0 \geqslant 0.3$ the value of $E_S/N$ reduces when $N$ drops, in a good agreement with the previous calculations (see Section 2.4) but it reduces much weaker with the smaller $N$. Thus the similarity law $E_S/N = \text{const}$ holds with a good accuracy in the atmosphere above 15 km ($N/N_0 < 0.1$) (see also Liu and Pasko, 2006). This is based on the following physical consideration. The similarity law is violated due to electron losses in the channel. But at low air density, the losses are weaker since the electron attachment rate $\tau_a^{-1} \propto N^2$ becomes small along with the recombination rate $\beta n_{e0} \propto N^2$. Meanwhile, in the absence of electron losses the field required to sustain the electric current in the channel fulfills the similarity law.

Another way to check the similarity law at high altitudes is related to modeling streamer propagation in the non-uniform atmosphere with $N = N_L e^{-x/\Delta}$ (in what follows $x$ is counted from the

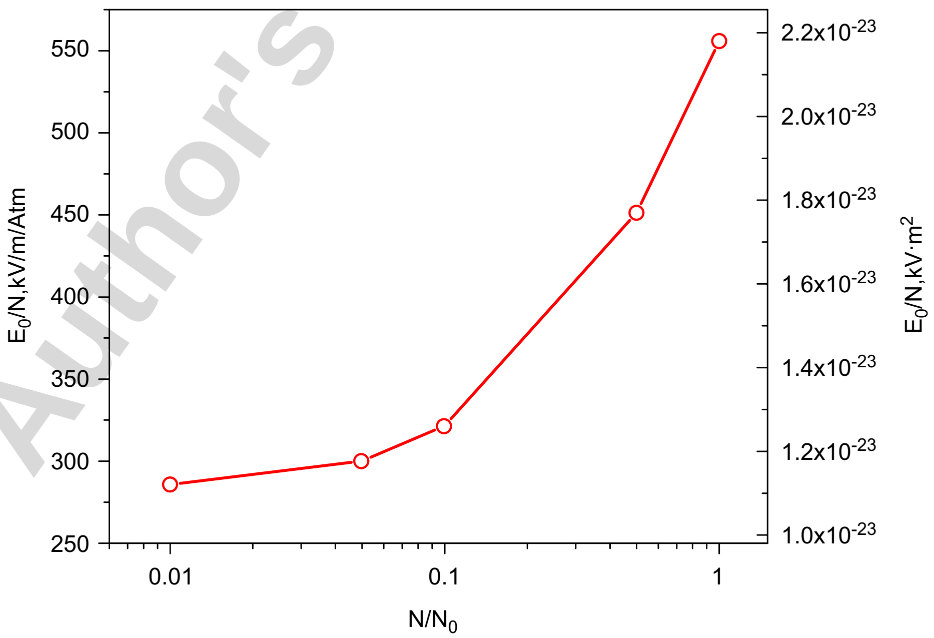


Fig. 5. Values $E_0/N$ required for unlimited streamer growth vs. the air density normalized by its normal value.

streamer initiation point where $N = N_L$). Here a question arises how to choose the external field, i.e., $U_0(x)$. Seems that in the streamer zone of a leader, where the air density is varying, such self-consistent electric field is formed that becomes the most favorable for the streamers propagation. In fact, the laboratory experiments conducted at the atmospheric pressure show that the constant field $E_{S0}$ is formed in the streamer zone (Petrov et al., 1994). However, a proper theoretical model has not been developed yet, since the process in which a huge number of streamers born at different time is too cumbersome. We assume that in the exponential atmosphere the self-consistent field also changes exponentially, i.e.

$$E_0(x) = E_{SL}e^{-x/\Delta}, \quad U_0(x) = U_L e^{-x/\Delta},$$
$$U_L = E_{SL}\Delta. \tag{23}$$

We define the absolute value of $E_{SL}$, i.e., the similarity invariant $E_{SL}/N_L$ the same way as for the uniform atmosphere, based on a condition of unlimited growth of the streamer. The computations have been conducted for the case when the streamer source (the leader tip) is located at the height $h_L = 18 + \Delta = 25.2$ km, where $N_L = 8.3 \times 10^{23}\,\mathrm{m}^{-3}$ ($N/N_0 = 0.0325$). In this case, the length of the Jet leader above the cloud edge is 7.2 km. The critical field at the leader tip needed for the unlimited streamer growth is $E_{SL} = 10.6$ kV/m; the leader tip potential $U_L = 76.5$ MV. The corresponding value of the similarity invariant is $E_{SL}/N_{SL} = 1.28 \times 10^{-23}\,\mathrm{kV\,m^2}$, which is just 10% higher than that leading to the unlimited streamer growth in the uniform atmosphere with $N = N_L$ (see Fig. 5).

### 4.2. *Escaping streamer in the non-uniform atmosphere*

Fig. 6 shows results of the calculations of the growth of a single streamer in the non-uniform atmosphere under the external (self-consistent) electric field, which drops exponentially. The streamer rises from the height $h_L = 25.2$ km while the field amplitude here $E_{SL} = 11.0$ kV/m, is slightly higher than the critical field 10.6 kV/m, required for the streamer growth.

At any moment, i.e., at any streamer length the channel potential and field amplitude are close to the external values but near the streamer tip the channel potential $U$ exceeds the external potential $U_0$ that sustains the streamer growth, since $v_s \propto U_t - U_0$. During the whole process the electron density peaks at a distance 10–12 km from the streamer source. Close to the source the value $n_e$ drops due to electron losses, since these electrons were born at earlier times. While close to the streamer tip the value of $n_e$ drops, since the air density is smaller and the density of electrons born in the tip is proportional to $N^2$. The current reduces continuously from the streamer's tip to its igniting point due to electron losses, increasing the resistance of unit length of the channel.

The most typical, but not obvious, peculiarity of the processes is the polarization of the channel. Although the streamer is positive, charge of the channel is positive only in the region close to the tip. The region near the ignition point is charged negatively. A similar effect occurs when the streamer grows in the uniform media under the constant field $E > E_S$ (Bazelyan and Raizer, 1998, 2000). It is due to the fact that the external field that exceeds the critical one $E_S$, moves charge towards the streamer tip (this charge is positive for a positive streamer). Till the streamer is short, and the plasma in the channel has not been decayed, this charge is provided by the external source. The charge is transferred by the current flying from the initiation point of the streamer. As the plasma decays over time, the channel resistance increases, and the current at the ignition point of the streamer decreases. In such case, the positive charge that provides streamer growth is fed by parts of the channel remote from the tip, charging those parts negatively. The net charge of the entire channel provided by the external source is always positive, but the net charge is smaller than the magnitudes of its positive and negative components.

The existence of extended negatively charged zone of individual streamers does not contradict to the fact that the space charge in the streamer zone is positive on the average, even if the averaging occurs along rather small volumes. Otherwise, regions of discontinuity or even reverse direction of the self-consistent field could appear. This could disrupt the streamer zone development.

The streamer zone is formed by a huge amount of streamers having different initiation time and length. Negatively charged bottom parts of the long "old" streamers overlap on the average with positively charged parts of "younger" shorter streamers. The total neutralization of all negative charges (on average in the space) is facilitated by the fact that the youngest streamers which have not lost

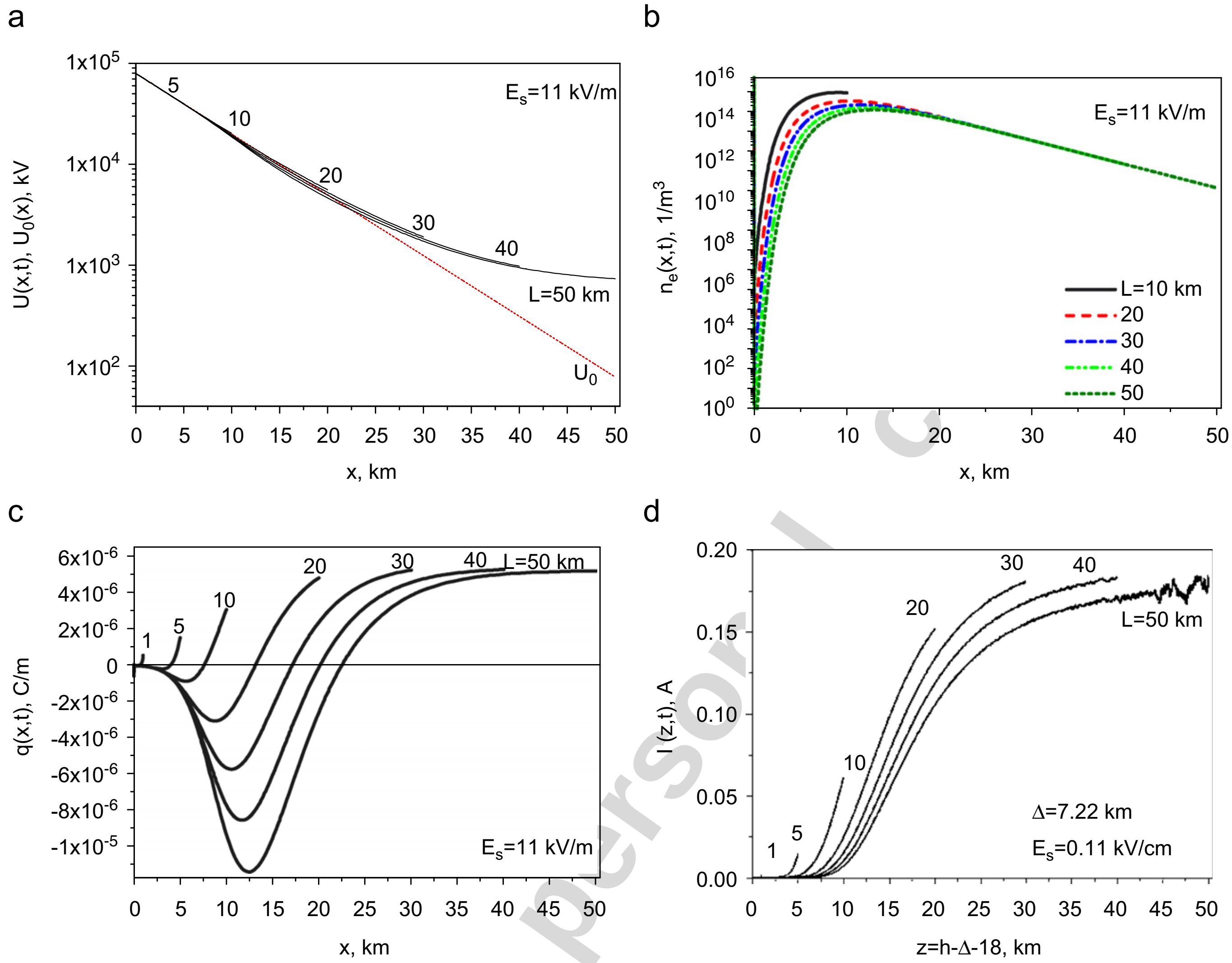


Fig. 6. Results of numerical computations of a long streamer growing in the exponential atmosphere $N = N_L e^{-x/\Delta}$ ($\Delta = 7.22$ km), and in the exponential external field $E = E_{SL} e^{-x/\Delta}$. The streamer is initiated at $x = 0$ which corresponds to the height of the leader tip $h_L = 18 + \Delta = 25.2$ km, $N_L(h_L) = 9.2 \times 10^{24}\,\text{m}^{-3}$, $E_{SL} = 11$ kV/m: (a) The potential distribution along the streamer channel computed at different times when the streamer's length is 5, 10, 20, 30, 40 or 50 km; (b) respective distribution of the electron density; (c) current distribution; (d) charge per unit channel.



their conductivity, does not have negatively charged region at all. These streamers are fed by a current directly from the leader tip. In order to justify such imaginative picture of the streamer zone one has to solve problem related to the formation of the self-consistent governing field. Such problem has not been solved even for a simplest case of the positive leader under the normal atmospheric conditions.

### *4.3. How important is the assumption of exponential self-consistent field?*

The assumption has been made similarly to the case of a streamer zone of the conventional positive leader. In the latter case, streamer needs the constant average field along the zone $E_{S0} \backsimeq 5$ kV/m. Such field forms self-consistently. In the non-uniform atmosphere if assuming that the similarity law $E_S/N = \text{const}$ holds, the governing streamer field should vary exponentially. Such field has to be formed self-consistently as mentioned above. And since these arguments are not too convincing, let us check what will change if the self-consistent field will not vary exponentially with height.

When the length of the streamer zone exceeds $\Delta$ the most part of the overall charge of streamers moving upward from the leader tip concentrates in the region of the size $\Delta$. Actually, the density of the space charge $e\ (n_+ - n_e)$, as well as the electron and ion densities is proportional to $n_{e0} \propto N^2$, i.e., they decrease with altitude exponentially with the scale $\sim\Delta$. Therefore, the characteristic length along which the self-consistent field drops should also be $\Delta$. For example, if the external field corresponds to the field of the charge concentrated inside a sphere having radius $\Delta$, we have

$$U_0 = U_L \Delta/(\Delta + x), \quad E_0 = E'_{SL} \frac{\Delta^2}{(\Delta + x)^2},$$
$$E'_{SL}\Delta = U_L. \tag{24}$$

Calculations based on Eq. (24) and for $N = N_L e^{-x/\Delta}$ reveal that the critical field $E'_{SL}$ exists at the point where the streamer was initiated. If the field is lower than $E'_{SL}$ the streamer fades away, for $E > E'_{SL}$ the streamer grows unlimited. The value of $E'_{SL} = 140\,\mathrm{kV/m}$ is only 30% higher than $E_{SL}$ for the exponential field when computed at the same air density $N_L$ in the initiation point. Weak sensitivity of the computational results to the exact form of the $U_0(x)$ dependence allows us to adopt a convenient and physically sufficient exponential behavior which corresponds to the similarity law.

### 4.4. *Remarks about the length and velocity of blue jets*

As followed from Eq. (5) the limiting length of the streamers producing branches of Jets depends upon the potential of the leader tip. The latter is determined by the thundercloud charge and location of the leader initiation point. The variation of these two factors can explain why the observed Jets are of different length and intensity.

The computed velocity of the escaping streamer is by one to two orders of magnitude higher than the velocity of Jets observed. However, the velocity of a Jet of limited length should not coincide with the velocity of an escaping streamer, which accelerates in a pertinent electric field stretched to infinity. For example, in a streamer zone of positive laboratory leader, the electric field, which governs streamers drops below the required value $E_{S0} \simeq 500\,\mathrm{kV/m}$ at a distance of a few meters from the leader tip. The front boundary of the streamer zone coincides with the above location and it moves on the average with the velocity of the leader, which is much slower than the streamer velocity.

The observed Jet velocities of 100–200 km/s is close to the detected lower limit of the streamer velocity (Briels et al., 2006), which according to the similarity law does not depend on $N$. We may assume that the front edge of this a Jet coincides with the front of the streamers. These streamers enter the region where the field becomes too weak for their continuous development. Analysis of such problems is related to the formation of self-consistent field, and how it falls below the streamer sustainment limit. Note that the fractal models (Pasko and George, 2002; Tong et al., 2005) are time independent and do not deal with the velocity of streamers and Jets.

## 5. Summary

A new model of blue jets is presented. Qualitative analysis and some quantitative substantiation are given as follows:

1. It was shown that apparently the leader tip is the source for most streamers, which form the upper part of a Jet, which in turn consists of spreading branches. Such leader is evidently seen in the Jet photographs as the long "trunk" from which branches of the jet tree" grow.
2. The necessity of the leader's existence in Jets is caused by two reasons:
   - 2.1. At the altitude of about 18 km where Jets were observed, any cold plasma, as well as streamer's plasma, decays in 10 μs. Such short-lived electrons cannot supply the Jet streamers with the current during 0.3 s, which is the Jet lifetime.
   - 2.2. In the absence of a leader, unrealistically high charges from a thundercloud are required to generate the field $E_S$ sustaining the streamers. In fact, the fractal model (Pasko and George, 2002) relies on such high charge since it does not assume the leader mechanism. The leader carries away the potential of the thundercloud of a moderate charge to 10–15 km above its edge. At such height the air density reduces, as well as the sustaining field for the streamers, thus the cloud potential becomes sufficient to govern the streamers.
3. It was shown that the non-conducting thundercloud cannot serve as a source for the charge required for Jets. The charge source is the leader moving upward, formed simultaneously with the leader of the opposite polarity moving downward. These leaders feed each other with the

charge and current without any involvement of the cloud charge. Similarly, the bi-leaders are formed in the ordinary lightning.

4. An estimate of the Jet length is provided depending on the potential of the leader tip that emits streamers, and the altitude of the tip. The potential and altitude at which the streamers can escape to the ionosphere are estimated.
5. Based on a simple streamer model the motion and characteristics of a streamer that grows unlimited in the exponential atmosphere, and in the exponential self-consistent external field, are computed. It is found from the numerical calculations that the critical external field $E_S$ required for unlimited streamer growth satisfies the similarity law $E_S/N = \text{const}$.
6. An assumption is formulated, that the observed Jet velocity of about 100–200 km/s is the lower limit of the streamer velocity. The latter was obtained experimentally, and it does not depend upon the air density as comes from the similarity law.
7. It was shown that the time independent fractal model of blue jets does not provide a sufficient description of the streamer zone of a leader and of the Jets. Such a model ignores the fundamental fact of the fast conductivity loss by the streamer channel due to electron attachment to the oxygen.

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