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Streamer- and leader-like processes in the upper atmosphere: Models of red sprites and blue jets

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[1] Models of red sprites and blue jets based on the concept of the streamer-leader mechanism of the air breakdown are presented. Red sprites are interpreted as the downward streamers of varying cross sections launched from plasma patches in the lower ionosphere, which are caused by the electric field generated by the lightning discharge. Results of this streamer model are in good agreement with the observations of sprites. Blue jets are interpreted as produced by a bileader, whose top part is seen on photos of blue jets as a "trunk of a tree." The upward leader is capped by its streamer zone seen as the tall and narrow "branches" of "the tree." It is shown that the long upward streamers of blue jets can be sustained by the moderate cloud charge due to transfer of the high potential of the thundercloud edge by the upward leader tip. It is revealed that the critical external field E_S required for an unlimited streamer growth satisfies the similarity law $E_S/N \sim$ constant for a wide range of the molecular number density N. In addition, the streamer length is estimated along with the height from which the streamers can reach the ionosphere. The main unresolved problems in the field are discussed.

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1. Introduction

[2] Following the discovery of sprites [*Franz et al.*, 1990; *Sentman and Wescott*, 1993; *Lyons*, 1994; *Sentman et al.*, 1995], a continuous effort was made to improve the temporal and spatial resolution of their measurements. Indeed, such improvements revealed new features and improved our understanding of the physics of sprites. In fact, the first high-speed images obtained by *Stanley et al.* [1999] showed the streamer structure of sprites, including streamer branching. Later on, *Stenbaek-Nielsen et al.* [2000], *Stenbaek-Nielsen and McHarg* [2008], and *Moudry et al.* [2003] used high-speed cameras, while *Gerken et al.* [2000] and *Marshall and Inan* [2005] developed a telescope-based technique that dramatically improved both temporal and spatial resolution of the observed sprites.

[3] The streamer structures observed in red sprites are the same phenomenon as streamers observed in laboratory experiments conducted at high pressure, although the streamers in the red sprites are scaled by reduced air density in the upper atmosphere [*Pasko et al.*, 1998; *Raizer et al.*, 1998]. Furthermore, a blue jet (BJ) has its own structure which is similar to a laboratory leader with a streamer corona on the top.

[4] It is the objective of this paper to discuss several models describing the streamer-like structure of red sprites, along with the streamer- and leader-like structure of blue jets. In section 2 we briefly describe basic physics of the laboratory streamers and leaders. This is followed by section 3, which is devoted to studies of the red sprite streamer-like structure. The leader-like structure of blue jets is discussed in section 4.

2. Basics of Streamer and Leader Discharges

[5] We outline below some basic features of the streamer and leader types of transient discharges in the air relevant to our topic [*Bazelyan and Raizer*, 1998, 2000; *Ebert et al.*, 2006]. Positive or negative streamers/leaders are initiated near the anode or cathode, respectively, transporting positive or negative charge toward the opposite electrode. An example of positive streamer patterns growing from an anode is shown in Figure 1a.

[6] Streamers represent cold, low-conductive plasma filaments growing in a relatively weak external field. The total electric field increases in front of the streamer tip due to the space charge and drives electron avalanche. In negative streamers, electrons drift upstream, so seed electrons are not needed. In laboratory positive streamers, the seed electrons are mainly due to photo ionization by UV radiation from the streamer front. In the lower ionosphere a positive streamer develops in the preionized media. Note that to initiate a streamer an initial plasma patch is required [*Raizer et al.*, 1998]. Figure 2 shows a schematic of the positive streamer

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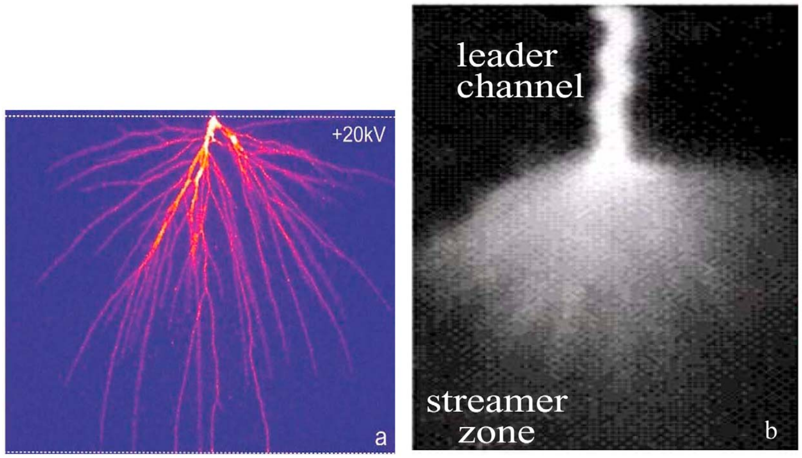

Figure 1. (a) A photograph of a positive streamer in a 40 mm gap in air at 1 bar (adapted from *Briels et al.* [2008] with permission). (b) A photograph of a positive laboratory leader (adapted from *Raizer et al.* [2007] with permission from Elsevier).

tip and the leading part of the streamer channel (Figure 2a) and the spatial distribution of the electric field, space charge, and the electron density (Figure 2b). A variety of laboratory studies of streamers of negative and positive polarity were conducted [*Ebert et al.*, 2006; *Briels et al.*, 2005, 2006, 2008] along with a number of 2-D and even 3-D simulations [*Luque et al.*, 2008; *Ebert et al.*, 2006; *Babaeva and Naidis*, 1996; *Pancheshnyi and Starikovskii*, 2003; *Pancheshnyi et al.*, 2005].

[7] Analysis by *Raizer et al.* [1998] based on the similarity theory and the model of a streamer tip shows that initial plasma patch and streamer tip radii, R_{st}^{min} and R_{st}, minimum number of electrons in the initial plasma patch N_e^{min}, electron densities in the patch n_e^{min} and behind the streamer tip n_e scale with the air density N as

$$R_{st}^{min}, R_{st} \propto 1/N, \quad N_e^{min} \propto 1/N, \quad n_e^{min}, n_e \propto N^2.$$

In dense air a streamer rapidly loses its conductivities due to electron attachment to the atmosphere oxygen in triple collisions. Thus, it takes the leader mechanism to develop a long spark or lightning.

[8] Contrary to streamers, a positive leader (such as shown in Figure 1b) represents a hot conductive plasma channel, quasi-continuously emitting a fan of streamers, termed the streamer zone or corona. The tip moves at a speed much slower than that of individual streamers. Gas in the leader channel is heated up to a few thousand K by the current. A huge number of short-lived streamers in the corona generate the space-charge field, which on average is close to governing field E_s. As streamers move along some distance until termination, their charge covers the leader channel and prevents its expansion and cooling, since the charge shields the radial electric field of the leader and thus stops its transverse expansion. The overall phenomena are not fully understood yet, and no rigorous solution is found.

3. Streamer-Like Structure of Red Sprites

[9] As mentioned above the recent progress in the observation technique of red sprites found a few meter size

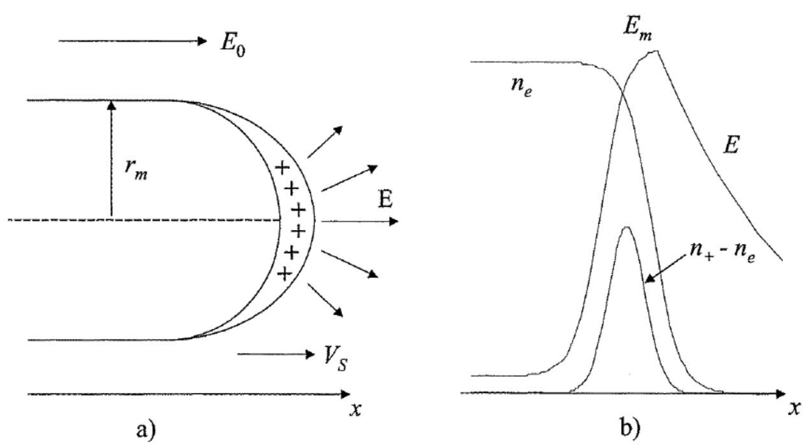

Figure 2. (a) Schematic diagram of a streamer tip and the leading part of the streamer channel. (b) The qualitative distribution of the electron density n_e, field E, and the difference between the densities of positive ions and electrons which defines the space charge density, along the streamer axis.

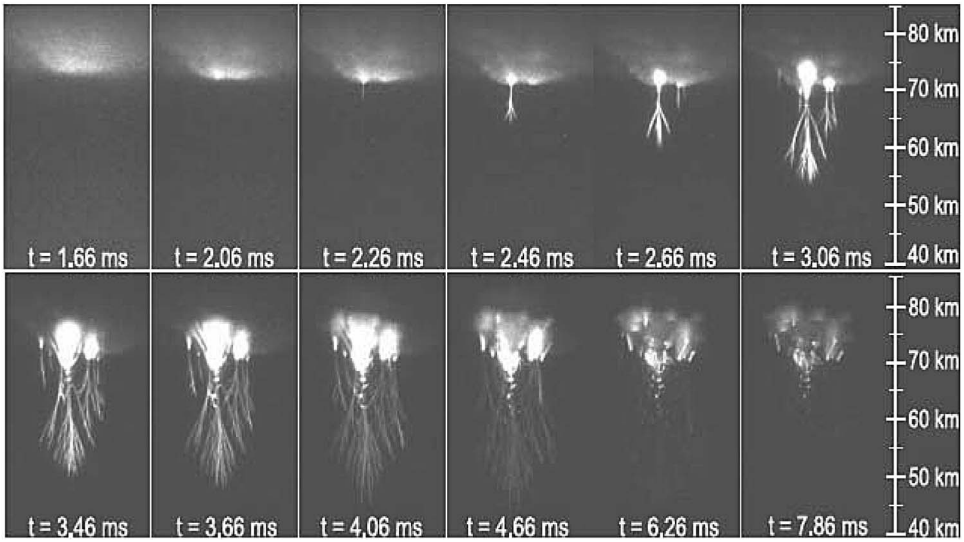

Figure 3. High-speed images of red sprites (adapted from *Cummer et al.* [2006]).

streamer-like filaments which propagate downward from the diffusive upper part of sprites [*Pasko*, 2007]. Those findings can be best illustrated by Figure 3, which shows the sequence of images of halo and sprite captured by *Cummer et al.* [2006] with a high-speed camera. The images reveal initiation and propagation of streamers in red sprites. The streamers start from a bright nucleolus at about 73 km, propagates downward as a thin filament, becomes longer and thicker, branches, and then disappears at about 50 km. They exist for more than 8 ms and give the sprite its jellyfish-like structure. While the *Cummer et al.* [2006] images are an excellent example of a diffuse halo causing streamer formation (via increased fields at the edges of the halo) this breakdown sequence is not universally observed in high speed images. As discussed below, preexisting localized ionization or plasma patches are another possible way to initiate streamers.

[10] It should be mentioned that the images by *Cummer et al.* [2006] are smoothed over many frames due to low temporal resolution. As a result, those images give a false impression of continuing emissions in the channel behind the descending streamer tips. As shown later by *McHarg et al.* [2007], who applied high-resolution detectors, the sprite images reveal that it is bright streamer heads that are the principle source of the optical emissions and as they descend they do so as compact glowing balls.

[11] The model of streamer formation in sprites is illustrated by Figure 4. A quasi-static electric field is generated in the upper atmosphere above the thundercloud followed by positive cloud-to-ground (CG) discharge which left the unbalanced cloud charge. The quasi-static field endures for a time equal to the local relaxation time $\tau_r = \varepsilon_o/\sigma$ (where σ is the ionospheric conductivity and ε_o is the permittivity of free space), which is of about 1 ms at 80 km. Here we consider the process following +CG discharge, since these are much more often associated with sprites than −CG discharges, and since a positive streamer requires the governing field two times smaller than a negative one. However, as mentioned by *Lyons et al.* [2008], it is not a strict requirement that the parent CG be of positive polarity. Indeed, at least 10% of all CG lightning which exceeds sprite breakdown is associated with negative CGs. Furthermore, since positive streamers need the governing field two times less than negative streamers, the sprites caused by −CGs should have a much less pronounced tentacle-like streamer structure.

[12] The positive streamer is launched from a plasma patch which serves as streamer nuclear. In fact, using the above similarity relations, one can find that for altitude 80 km triggering conditions for a streamer require that $R_s^{min} \approx 60$ m, $n_e^{min} \approx 150$ cm^{-3} [*Raizer et al.*, 1998]. The streamer then propagates downward till it stops when entering the dense atmosphere where much stronger electric field is required to sustain the streamer. A few mechanisms were suggested to form the plasma patches, among them the electromagnetic pulses from intracloud "fractal" lightning

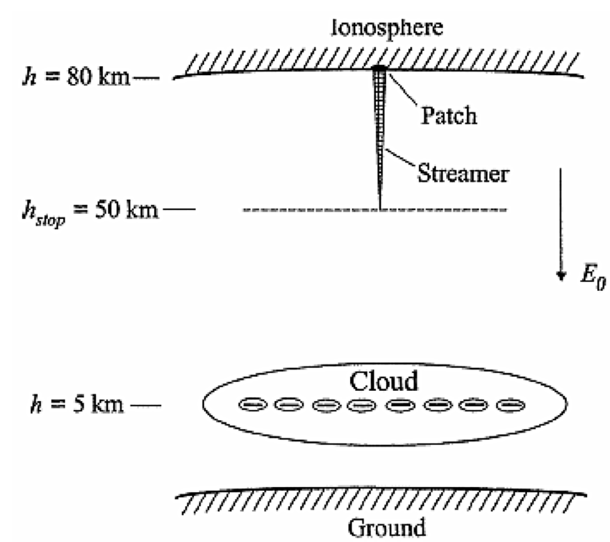

Figure 4. Schematic of a streamer development in red sprites.

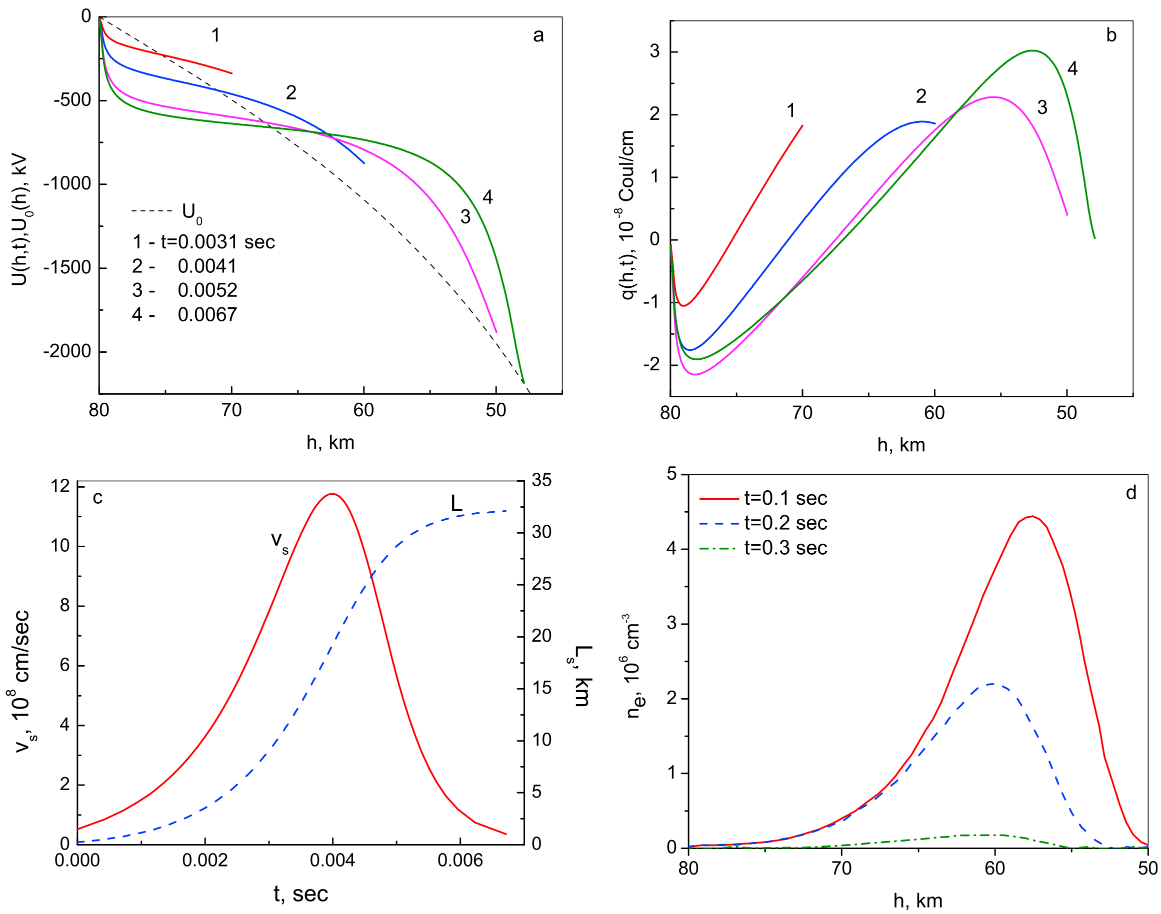

Figure 5. (a) Distribution of the streamer tip potential along the streamer channel computed for a few consecutive times. The dashed line shows the external potential. (b) Distribution of the linear streamer charge along the streamer channel. (c) The streamer velocity is shown by the solid line, and its length is shown by the dashed line. (d) Electron density in the streamer channel computed for the different times.

[*Valdivia et al.*, 1998], ionized meteorite traces [*Suszcynsky et al.*, 1999], broken down gravity waves [*Snively and Pasko*, 2003], previous sprite breakdowns, and energetic particles. However, a comprehensive model of the patch formation still does not exist. Notice that such patches can manifest themselves by bright optical spots detectable by sensitive optical imagers. In fact, high-resolution photography data [*McHarg et al.*, 2007] show a number of bright spots in the sprite tendrils. Future analysis of such spots could provide some useful details of the streamer dynamics, which thus will help us to understand the relevant physics, including the mechanism leading to the patch formation.

[13] Thus, the positive streamer of varying cross section is formed, starting from a plasma patch with a maximum diameter of about 120 m at 80 km, and converging when propagating downward while experiencing increase in its electron density.

[14] Despite significant progress in computer simulations of streamers [*Luque et al.*, 2008; *Ebert et al.*, 2006], modeling of streamers which propagate a distances that exceed the atmospheric pressure scale (H) nowadays is beyond reach. Therefore, *Raizer et al.* [1998] introduced a numerical model of a long streamer which propagates downward in the nonuniform atmosphere. This is kind of a hybrid description, where the streamer tip is modeled according to laboratory observations to satisfy the similarity laws. The streamer channel is modeled as a long line with the distributed electrical characteristics (capacitance, inductance, resistance). The boundary condition which coupled the two models required that the field behind the tip should maintain the current in the channel. As the initial condition a streamer having a small length was considered. This is the equivalent of a needle used to initiate streamers in laboratory experiments.

[15] Figure 5 shows results of numerical computations using the above model. Here the positive streamer starts from a plasma patch at 80 km and propagates downward in the static electric field due to unbalanced thunderstorm charge. The potential distribution at four different instants is shown by curves 1–4 in Figure 5a; the dashed curve shows the external potential. The role of driving force is played by the difference between the electric potential at the tip and the local external potential. The driver increases with time until it reaches the peak, and then drops. Accordingly, the streamer first accelerates, then slows down, and finally stops, as illustrated by Figure 5b.

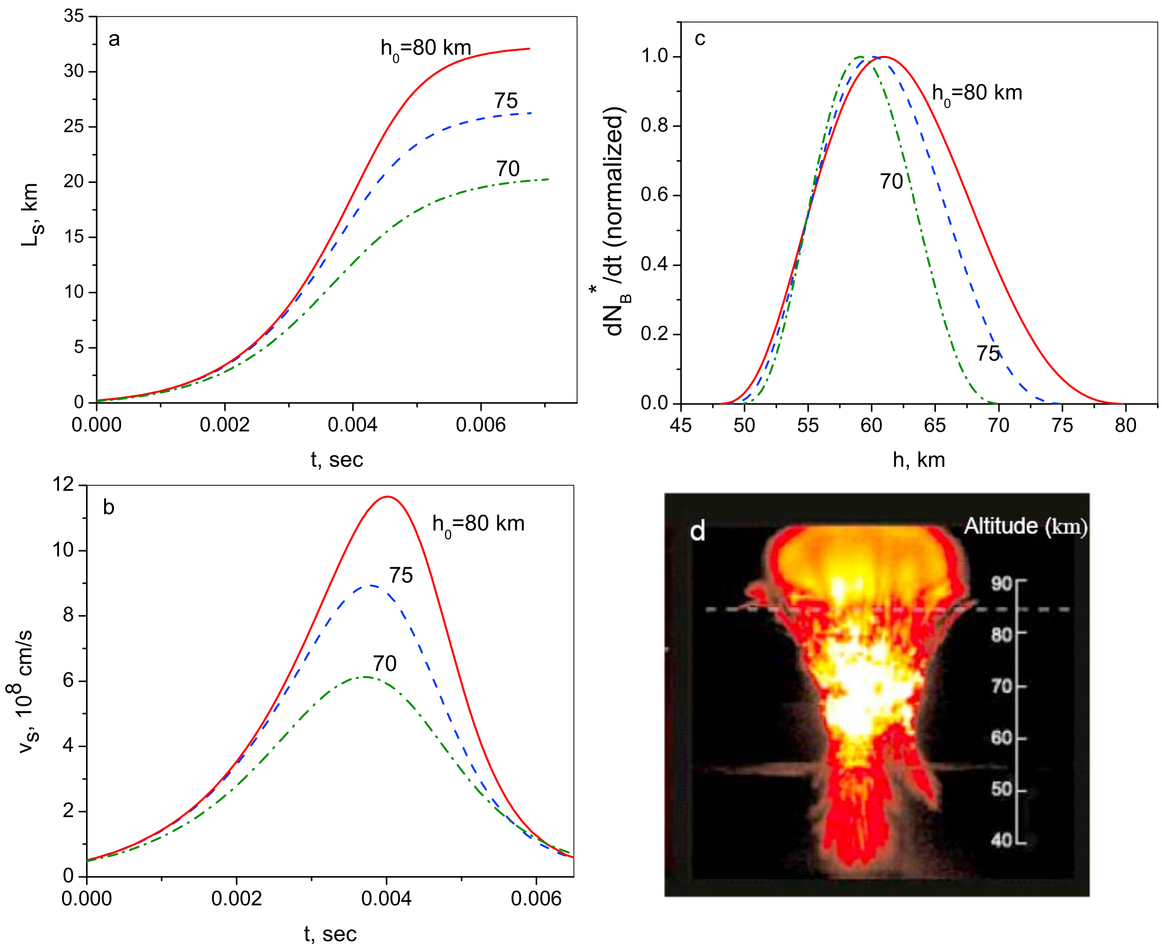

Figure 6. (a) The length of the streamers versus the propagation time. Here the streamers were launched from the different altitudes. (b) Same for the streamer velocity. (c) The excitation rate of N_2(1P) emission normalized by its peak value, generated by the streamers launched from the different altitudes. (d) Photo of red sprites (adapted from *Stenbaek-Nielsen and McHarg* [2008] with permission).

[16] Figure 6 shows the model of downward propagating streamers launched from various heights. It reveals that streamer lifetime is insensitive to the initiation altitude although the peak velocity does depend on the initiation height. The bottom altitude is always about the same altitude, which depends on the fact that the terminal altitude, as well as the streamer lifetime, is determined by the slowdown that occurs when the streamer enters the dense atmosphere.

[17] We also computed the pumping rate of B electronic level of molecular nitrogen which is responsible for emission of N_2(1P) band which plays a dominant role in sprites. Similarly to our earlier work [*Milikh and Shneider*, 2008], we assume that the most excitations occur at the streamer tip and use the electric field at the tip as the input to our Boltzmann code to compute the excitation rates of the N_2(1P) emission band. These results are revealed by Figure 6c, which shows that regardless of the initiation height the optical emissions from sprites experience a broad maximum at 57–67 km which reflects the existing sprites observations (see Figure 6d).

[18] Therefore, the presented numerical model provides a good qualitative description of long descending streamers of sprites.

4. Leader-like Structure of Blue Jets

[19] Beams of light propagating upward from the top of thunderstorms were discovered during the Sprites 94 aircraft campaign [*Wescott et al.*, 1995] and were termed blue jets (BJs) due to their primary blue color. Blue jets were narrowly collimated with an apparent fan out near the terminal altitude at about 40–50 km. They were slowly moving with a velocity of 80–115 km/s. A number of BJs have subsequently been captured during ground and aircraft observations [*Wescott et al.*, 1998; *Lyons et al.*, 2003]. Figure 7 (top) shows a BJ with a well pronounced streamer structure [*Wescott et al.*, 2001]. *Pasko et al.* [2002] and *Su et al.* [2003] discovered the so-called gigantic jets (GJs) propagating into the lower ionosphere (Figure 7, bottom). Recently, a number of GJ events have been identified from

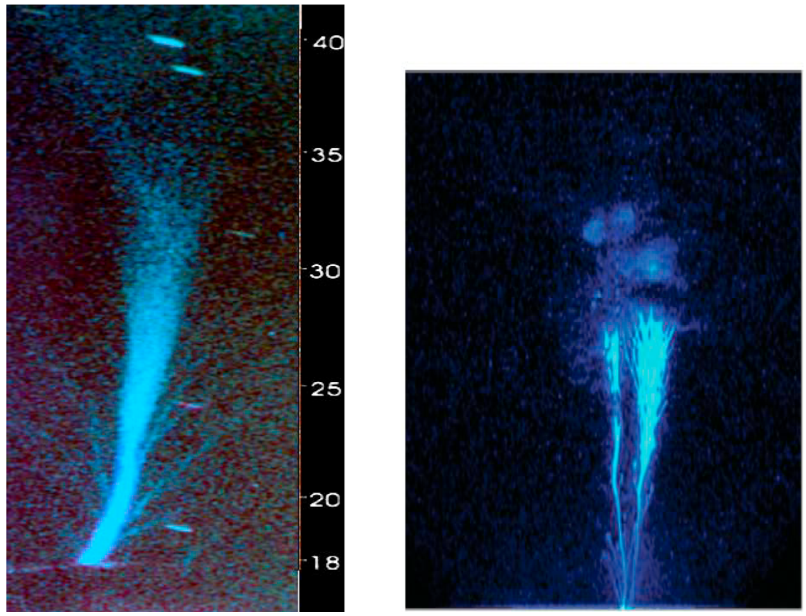

Figure 7. (left) Image of a blue jet (adapted from *Wescott et al.* [2001]) and (right) image of a gigantic blue jet (adapted from *Pasko et al.* [2002] with permission from Macmillan Publishers Ltd).

the imager named ISUAL aboard the FORMOSAT-2 satellite [*Kuo et al.*, 2008] and from the ground [*van der Velde et al.*, 2007]. BJs and GJs resemble a tall tree with a thin trunk and branches on the top. We note that there is another type of blue jet which propagates only a few kilometers above the top of the thundercloud and terminates below 26 km. They were dubbed blue starters [*Wescott et al.*, 1996].

[20] Earlier BJ theories included the runaway breakdown [*Roussel-Dupré and Gurevich*, 1996] and gigantic streamers of positive [*Pasko et al.*, 1996] and negative [*Sukhorukov et al.*, 1996] polarity. More rigorous analysis made by *Petrov and Petrova* [1999] came to the conclusion that BJs are formed by the streamer zone of a leader (streamer corona). This idea was further explored by *Pasko and George* [2002], who numerically simulated a BJ as a stochastic (fractal) process. However, in those models, unrealistically high thundercloud charges are required to sustain the streamers [see *Marshall et al.*, 2001; *Mishin and Milikh*, 2008]. In addition, at the BJ altitude of about 18 km, cold plasma decays in 10 μs; thus, the jet streamers cannot be supplied with current during their lifetime, which is approximately 1 s. To clear those hurdles, *Raizer et al.* [2006, 2007] proposed a new model which will be briefly reviewed below.

[21] The model is based on the formation of a bidirectional uncharged leader [*Kasemir*, 1960] inside the thun-

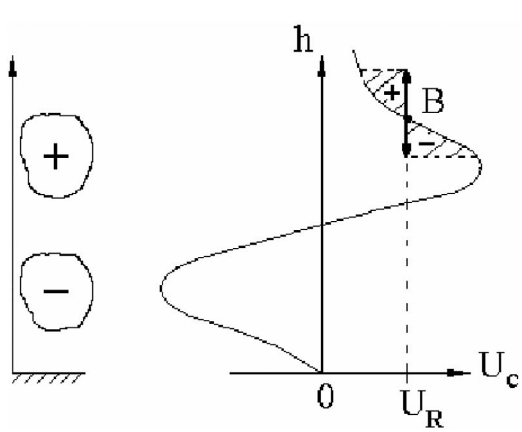

Figure 8. A schematic of the bileader initiation in a thundercloud.

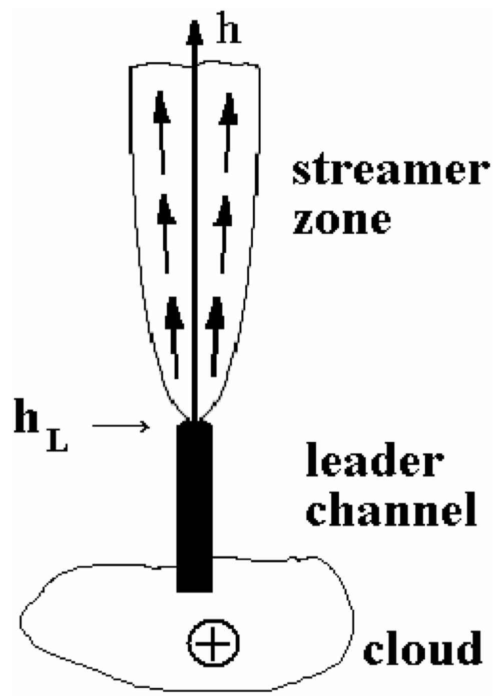

Figure 9. A schematic jet model.

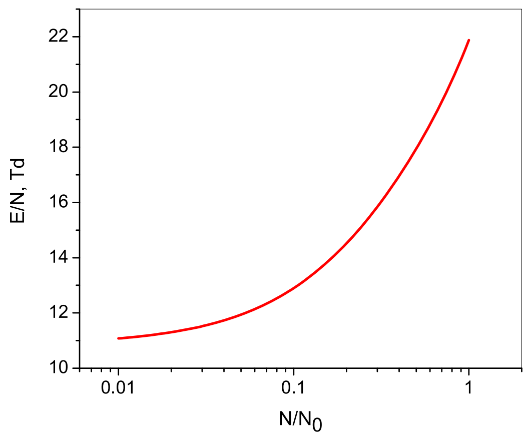

Figure 10. Values E_S/N required for the streamer growth versus the air density.

dercloud. In fact, the leader could be initiated in the bending point of the cloud charge potential curve where the electric field peaks (see Figure 8). The leader then moves upward and transfers the high potential U~30–50 MV outside the cloud top up to h~30 km, as illustrated by Figure 9. At such a height the electron attachment time scale rises to 10^{-2} s, and thus, the conductivity in the streamers channels is kept much longer than at the cloud top. In addition, at these heights the streamer governing field ($E_s \propto N$) is much smaller than at the leader origination point.

[22] Like a laboratory leader, a BJ emits a fan of streamers; however, in the exponential atmosphere those long streamers grow preferentially upward, producing a narrow cone.

[23] Since the streamer governing field $E_S = E_{S0}\, e^{-h/H}$ due to similarity relation, a streamer born at the altitude h_L can grow up to "infinity" as soon as its source, which role is played by the leader tip, has the potential

$$U = \int_{h_L}^{\infty} E_S dh \;=\; E_{SL} H \;=\; E_{S0} H\, e^{-h_L/H}$$

Such a streamer can escape to the ionosphere if it starts from the altitude

$$h_L \;=\; H\, \ell n(E_{S0}\, H/U)$$

The escape altitude could be as low as 25–30 km under a moderate leader potential U ~ 30–50 MV, while if the escape occurs from the lower height h_L = 18 km, it requires unrealistically high potential U = 350 MV.

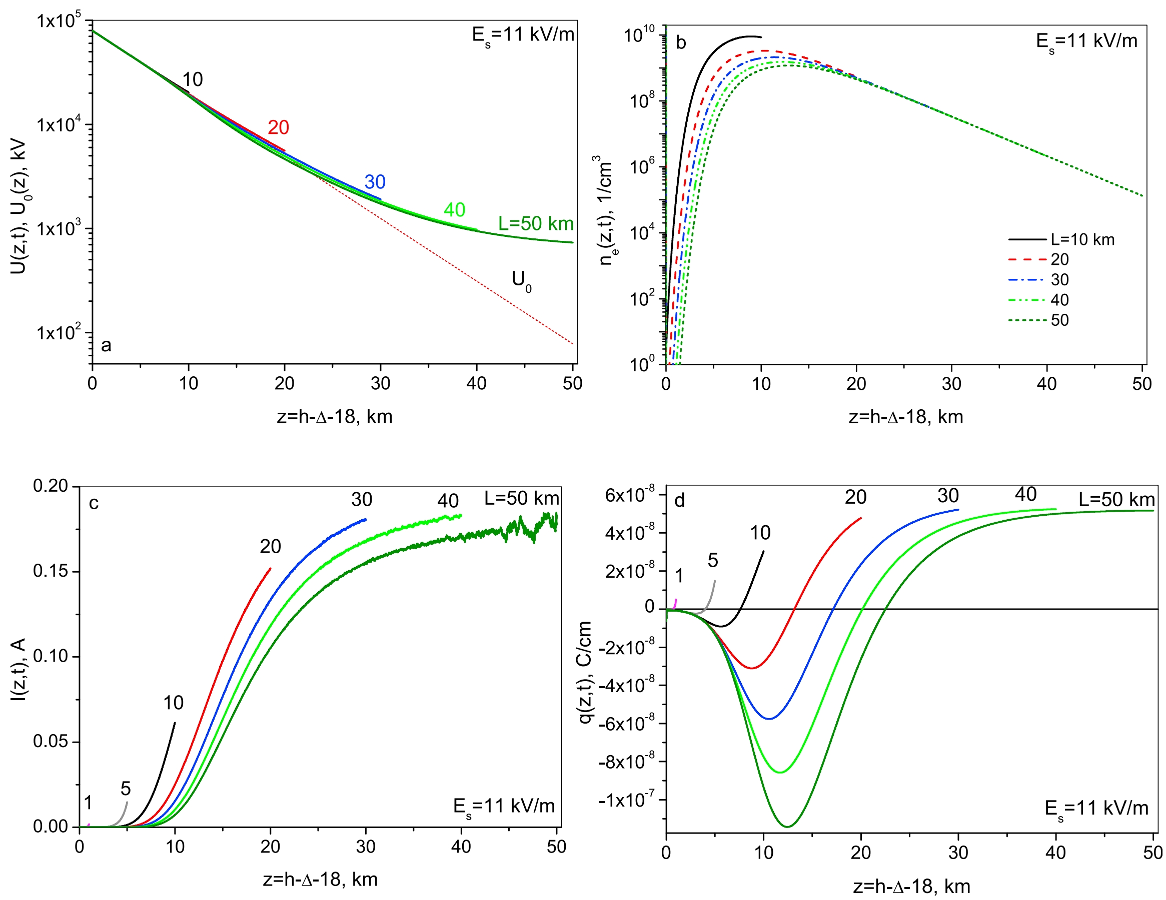

Figure 11. Results of numerical computations of a long streamer growing in the exponential atmosphere and in the exponentially changing external field. Thus, the similarity law holds. (a) The potential distribution along the streamer channel computed at different times when the streamer's length is 5, 10, 20, 30, 40 or 50 km. (b) Respective distribution of the electron density. (c) Current distribution. (d) Charge per unit channel.

[24] Such a numerical model of a long positive streamer growing upward in the exponential atmosphere was previously described in the studies of upward streamers in BJ [*Raizer et al.*, 2006, 2007]. It is similar to the earlier model used to describe downward streamers in sprites [*Raizer et al.*, 1998]. The model by *Raizer et al.* [2006, 2007], first, allowed a verification of the similarity law. In order to do it the value E_S/N required for a stable streamer growth in uniform atmosphere was found. This value is shown in Figure 10 as a function of the air density. Here the value of E_S/N is given in Townsend (1 Td = 10^{-21} V m^2). Figure 10 reveals that the similarity law E_S/N = constant holds with a good accuracy in the atmosphere above 15 km, where $N/N_0 <$ 0.1. It is due to the fact that a violation of the similarity law is caused by electron losses in the streamer channel, which happens at low altitude, where the electron attachment due to triple collisions with oxygen is dominant.

[25] The model by *Raizer et al.* [2006, 2007] computes the growth of a long positive streamer in the near-exponential atmosphere, such that the similarity law holds. This is illustrated by Figure 11. The streamer is initiated at the leader tip (x = 0) and runs upward. Here is shown the electron density distribution along with the charge distribution given per unit length of the channel length.

[26] The computations are made at different instants when the streamer length is 10, 20, 30, 40, and 50 km. It is noticeable that the electron density peaks at 10 km from the initiation height (see Figure 11a). In addition, although the whole charge of the long streamer is positive, its bottom part is negative (see Figure 11b).

[27] In summary, leaders are indispensable parts of blue jets and transfer the upward high potential of the thundercloud. Leaders also emit streamers, which form the corona, and thus produce a self-consistent governing field. Finally, due to the presence of a number of streamers of different "age" positive segments of younger streamers neutralize negative segments of old ones.

[28] There are some outstanding issues that still exist: (1) a comprehensive description of the formation of the self-consistent field in the streamer zone of a laboratory leader, as well as in blue jet, and (2) the process which determines the low velocity of blue jets.

[29] One can assume that the observed velocity of about 100 km/s is the minimum propagation velocity of the streamer, which should be independent of the neutral density. It mimics what happened in the streamer zone of a laboratory leader, where streamers have low velocity which only weakly depends upon the gas density.

[30] The two above outstanding problems are coupled.

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