Simulation of leader speeds at gigantic jet altitudes

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[1] Lightning leaders advance in space by creating a heating conversion zone in their tips (i.e., streamer-to-leader transition) in which Joule heating produced by currents of many non-thermal corona streamers transforms into a hot and conducting leader channel. It is believed that the initial stages of transient luminous events termed gigantic jets (GJs) propagating toward the lower ionosphere are directly related to leaders initiated by conventional intra-cloud lightning discharges and escaping upward from thundercloud tops. In the present work we provide quantitative description of speeds of these leaders as a function of leader current and ambient air density (altitude). The direct comparisons with available experimental data indicate that the initial speeds of GJs of ∼50 km/s are consistent with leaders possessing currents 2–8 A. The observed acceleration of GJs can be explained by growth of the leader current, and at high altitudes (low air densities) may be significantly affected by predominance of non-thermal (i.e., streamer) discharge forms. **Citation:** da Silva, C. L., and V. P. Pasko (2012), Simulation of leader speeds at gigantic jet altitudes, *Geophys. Res. Lett.*, *39*, L13805, doi:10.1029/2012GL052251.

1. Introduction

[2] Gigantic jets (GJs, illustrated in Figure 1) are upward discharges that leave the thundercloud top and propagate up to ∼90 km altitude. Similarly to cloud-to-ground lightning, these events neutralize thundercloud charge, however, in the case of GJs the charge is transferred to the ionosphere [*Krehbiel et al.*, 2008]. Modeling efforts to describe features of GJs and their shorter siblings, the blue jets [e.g., *Wescott et al.*, 2001], are based on the assumption that these jets are extension of the streamer zones of conventional lightning leaders [*Pasko and George*, 2002, and references therein]. However, as stated by *Raizer et al.* [2006], due to strong electron losses it is unlikely that cold streamers would leave the thundercloud top and make their way to the ionosphere. At thundercloud top altitudes, electron losses through attachment to O_2 molecules occur on a time scale of tens of microseconds, while the GJ propagation occurs on time scales of hundreds of milliseconds (see Figure 1). Thus, the most probable scenario is that a leader-like discharge, in which the electron losses are compensated by electron production in strongly heated air, emerges from the thundercloud and propagates up to altitudes of ∼40 km. This leader acts like an electrode, bringing the cloud potential to higher altitudes, and facilitating the streamer corona in its head in connecting to the ionosphere.

[3] Another fundamental feature of jets that supports this argument is that they emerge from thundercloud tops with speeds on the order of or less than the lower limit of streamer speeds, which is $\sim 10^5$ m/s [*Bazelyan and Raizer*, 2000, p. 39], but consistent with speeds of laboratory leaders [*Bazelyan and Raizer*, 1998, section 6.2]. Propagating streamers normally present speeds around 10^6–10^7 m/s [e.g., *Liu and Pasko*, 2004]. In the present paper we perform streamer-to-leader transition simulations in order to calculate leader speeds in the altitude range 20–45 km corresponding to lower extremities of GJs. We also perform direct comparisons of calculated speeds with available experimental data.

2. Model

[4] The formation and propagation of a leader is only made possible by the action of the streamer corona in its head. The currents of many streamers are added together in a region called stem. Air is heated up to thousands of kelvins and a new section of the leader is formed. This streamer-to-leader transition occurs on the time scale τ_h, defined here as the time needed to increase the ambient gas temperature up to 2000 K [*Popov*, 2009]. The only way of preventing plasma decay in near-ground pressure air is by air heating, because in hot air electron losses through attachment are compensated by accelerated detachment, stepwise and associative ionization reactions [*Bazelyan and Raizer*, 2000, p. 59]. Although positive and negative leaders exhibit different dynamical features [e.g., *Pasko*, 2008, section 2] we assume that the streamer-to-leader transition is a fundamental process that defines leader propagation in both cases. In case of negative leader this process occurs during the growth of a space leader ahead of the main leader channel. The growth of the space leader is the slowest process in the sequence of relatively fast events accompanying development of a stepped leader [e.g., *Bazelyan and Raizer*, 2000, p. 199], and we assume that in time average sense it is the main process defining speed with which the negative leader advances in space.

[5] Electron losses in the streamer corona are dictated by three-body attachment and, therefore, the length of a young streamer in this zone can be estimated as $\Delta l_s = v_s \tau_{a3}$, where v_s is the streamer velocity and τ_{a3} is the three-body attachment time scale. At ground pressure $\tau_{a3} \simeq 10^{-7}$ s and for streamer speed $v_s \simeq 10^5$ m/s this gives $\Delta l_s \simeq 1$ cm, which is comparable to the leader tip radius [*Bazelyan and Raizer*, 2000, section 2.3.4]. Thus, the leader propagation speed can be estimated as [*Bazelyan et al.*, 2007]:

$$v_L = \frac{\Delta l_s}{\tau_h}. \quad (1)$$

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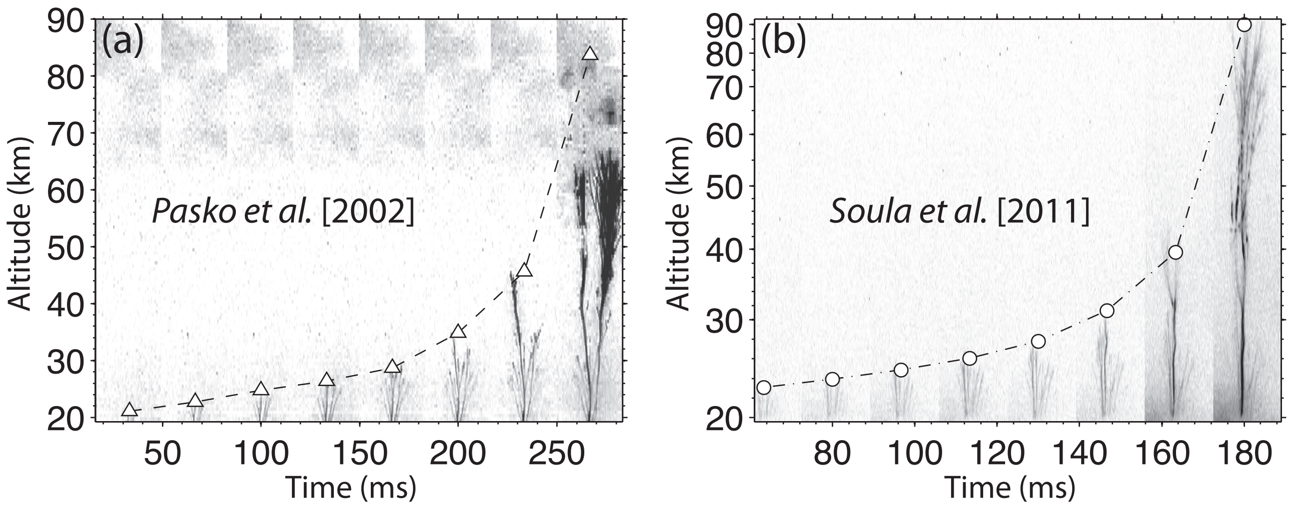

Figure 1. Gigantic jets observed by (a) *Pasko et al.* [2002] and (b) *Soula et al.* [2011]. Symbols show estimated top altitudes. Time reference is arbitrary and it is the same as used in subsequent figures. The sequence of images for *Pasko et al.*'s [2002] jet is spaced in time by 33 ms, while for *Soula et al.*'s [2011] jet by 16.7 ms. Reprinted by permission from Nature Publishing Group and American Geophysical Union, respectively.

[6] In order to calculate τ_h, we have developed a one-dimensional axisymmetric model representing an extension of the work done by *Riousset et al.* [2010]. The model describes the evolution of density, velocity and energy of neutral gas, and vibrational energy of N_2 molecules. Energy is transferred from the discharge to air through collisions of electrons and ions with neutrals, leading to Joule energy deposition and vibrational excitation of N_2 molecules. A total of 17 species are considered that participate in 67 reactions presented in *Riousset et al.* [2010, Table 2]. We note that there is a misprint in Table 2 of *Riousset et al.* [2010] and the correction factor *F*, that takes into account the effect of non-zero vibrational temperature on electron-impact processes, should be included in all such processes (as done by *Benilov and Naidis* [2003]).

[7] *Riousset et al.*'s [2010] model is dedicated to the description of streamer-to-spark transition in short gaps, where the controlled laboratory conditions allow one to keep the externally applied voltage and the electric field in the gap approximately constant [*Naidis*, 2005]. However, in the simulation of streamer-to-leader transition, the assumption of constant field is no longer valid. In this case, electrical current is produced in the streamer zone in the leader head and its continuity along the length of the streamer-to-leader transition region and the leader channel becomes the primary condition defining electrodynamics of the leader. Therefore, the current is considered as an external, independent parameter, for the streamer-to-leader transition region [*Aleksandrov et al.*, 2001]. Thus, the electric field (E) can be determined from current (I) through Ohm's law:

$$E = \frac{I}{\int_0^\infty \sigma(r) 2\pi r dr}, \tag{2}$$

where $\sigma(r)$ is the radially dependent electrical conductivity, which is integrated along the channel's cross section [*Popov*, 2003].

[8] We describe the evolution of the plasma species by continuity equations that allow the radial motion of particles through diffusion [*Popov*, 2003, 2009]. We note that *Riousset et al.* [2010] assume Gaussian radial distribution of plasma species with fixed spatial scale, $n_e(r) \propto \exp(-r^2/r_c^2)$, where n_e is the electron density and r_c is the channel radius. This technique, introduced by *Naidis* [2005], is suitable for description of streamer-to-spark transition, but not for leader inception, where channel contraction triggers the thermal-ionizational instability that culminates with streamer-to-leader transition [*Bazelyan et al.*, 2007]. We assume that the Gaussian profiles (with *e*-fold scale of 0.3 mm) define the initial conditions for the concentrations of electrons and O_2^+ ions (both initial values are 2×10^{14} cm^{-3}), and that concentrations of all other plasma species are negligible. Ambipolar diffusion of plasma is followed using description provided by *Raizer* [1991, p. 29]. The initial air parameters are assumed to correspond to a homogeneous background with temperature of 300 K at ground pressure. Initial conditions for simulations at reduced air density are calculated by application of similarity laws [*Pasko*, 2006, p. 267]. Spatial dynamics are solved with second-order accuracy in time and space using Lax-Wendroff scheme, and chemical time dynamics is described with fourth-order Runge-Kutta method.

3. Results

[9] The model was first validated by calculations for the constant electric field regimes identical to those studied by *Naidis* [2005] and *Riousset et al.* [2010]. The results of comparisons with experimental data reported by *Černák et al.* [1995] and *Larsson* [1998] appeared to be very similar (maximum deviations not exceeding 18% at 1 atm and 5% at 0.75 atm) to those reported in *Riousset et al.* [2010, Figure 4] (not shown here for the sake of brevity).

[10] The model used in the present work represents an extension of the model developed by *Naidis* [2005] by including equation (2) and introducing other modifications outlined in section 2. When supplied with standard initial conditions for the leader stem [*Popov*, 2003], the model allows one to calculate the heating time τ_h as a function of only two input parameters: electrical current and ambient air density (or altitude in atmosphere). Figure 2a shows the calculated values of τ_h for four different currents: 2, 10, 40, and

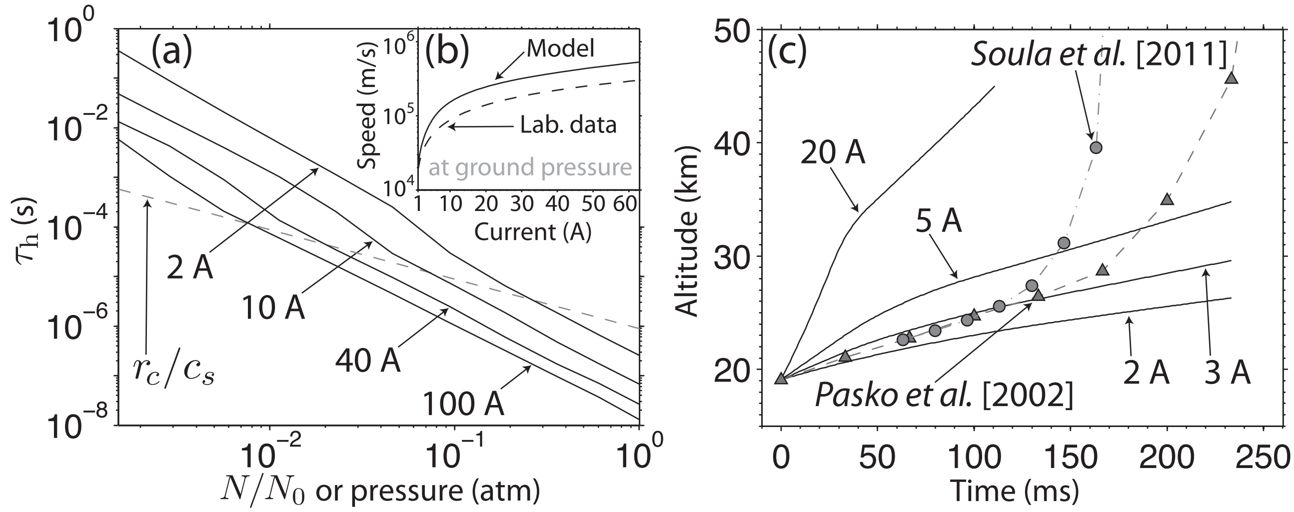

Figure 2. (a) Calculated streamer-leader transition time scales for different leader currents as a function of reduced air density N/N_0, where N_0 corresponds to a reference value at ground level. (b) Dependence of the leader speed on the current at ground pressure. (c) The vertical height of the two GJs shown in Figure 1 as a function of time. Solid lines depict modeled jet propagation for several different constant currents.

100 A, in the pressure range of 0.0015–1 atm, corresponding to the decreasing pressure between ground and 45 km altitude in the Earth's atmosphere. Our results indicate that τ_h scales with ambient air density N (or pressure) close to the Joule heating time scaling $\sim N^{-2}$ [*Pasko,* 2006, p.267]. More precisely, ranging between $\sim N^{-2.2}$ to $\sim N^{-1.9}$ as the current increases from 2 A to 100 A. Figure 2a is plotted in a format similar to that used in *Popov* [2009, Figure 10], although we note that *Popov* [2009] finds a scaling $\sim N^{-1.5}$ for a 100A current. In the same figure, we also present the ratio r_c/c_s, where r_c is the initial stem radius and c_s is the speed of sound, which is an estimate for the time scale of gas dynamics channel expansion [e.g., *Naidis*, 2005]. We can see a slight change in slope when τ_h exceeds r_c/c_s. The related increase in the heating time occurs because deposited energy spreads radially in the channel on this time scale, effectively requiring longer time to reach the same gas temperature.

[11] We use equation (1) to estimate the speed of a leader, provided Δl_s = 1 cm at ground pressure [*Bazelyan et al.*, 2007]. Figure 2b presents the calculated dependence of the leader speed on the electrical current at ground pressure. For reference, the figure also presents the dependence $v_L \sim I^{0.67}$, experimentally obtained for laboratory leaders [*Andreev et al.*, 2008] (further discussion is provided by *Popov* [2009]). We assume that Δl_s scales with air density in the same way as the three-body attachment process, $\sim N^{-2}$. Therefore, Δl_s has the value of 2.1 m and 1 km at 20 km and 40 km altitude, respectively. The quantity Δl_s should not be confused with the length of the leader streamer zone, which can be much longer [*Bazelyan and Raizer*, 2000, section 2.3.4]. We do not perform simulations above 45 km altitude, because at 45 km Δl_s reaches the value of 4.3 km (around half of atmospheric scale height) and estimated speeds are expected to be inaccurate. We note that a 50 A streamer corona would have to persist 11 ms to support streamer-to-leader transition at this altitude. We also note that both blue and gigantic jets exhibit blue color at altitudes well below 45 km (see discussion by *Riousset et al.* [2010] and *Soula et al.* [2011]) indicating predominance of cold streamer coronas above these altitudes.

[12] Figure 2c presents experimental data and model calculations for the propagation of the two GJs shown in Figure 1. As suggested by *van der Velde et al.* [2010], we have reestimated the distance between the observation site and the most probable location of *Pasko et al.*'s [2002] jet to be 235 ± 20 km, which implies a correction of ~18 % in the estimated altitudes, positioning the jet's top at 83.7 ± 7 km altitude. The corrected altitudes are shown in Figures 1a and 2c. The altitude range of *Soula et al.* [2011] jet was estimated from their Figure 7a. *Soula et al.*'s [2011] jet was observed at 53 km range. The fact that the jet's top is seen at larger distances than the bottom introduces the non-uniform altitude scale seen in Figure 1b. This correction is not necessary for *Pasko et al.*'s [2002] jet because it was observed at a much greater distance. Figure 3a shows the GJ speeds. Both GJs initiate with speeds of ~5–10 × 10^4 m/s, compatible to the speed of laboratory leaders with currents of a few amperes [e.g., *Popov*, 2009, Figure 6, and references therein]. It is also noticeable that both GJs accelerate to speeds greater than 10^6 m/s, compatible to streamer speeds [e.g., *Liu and Pasko*, 2004, Table 2]. The last point of each data set in Figure 3a represents a lower estimate of the jet speed.

[13] The model jet propagation is calculated by solving the differential equation $dh/dt = v_L(h, I)$ between 19–45 km altitude. Solid lines in Figures 2c and 3a present modeled height (h) and speed (dh/dt), respectively, for several constant currents. It is evident from the figures that a constant current leader does not match a GJ propagation. The current behavior that best mimics the propagation of the two GJ is shown in Figure 3b. We can see that initially, in the range of altitudes of 19–29 km, *Pasko et al.*'s [2002] GJ speeds are consistent with currents of 2–8 A, while at the altitude range of 35–46 km the speeds are consistent with 28–60 A currents. Similarly, *Soula et al.*'s [2011] GJ has speeds consistent with currents of 2.5–8.5 A in the altitude range of 22–27 km, and 18–64 A in the altitude range of 31–40 km. It is

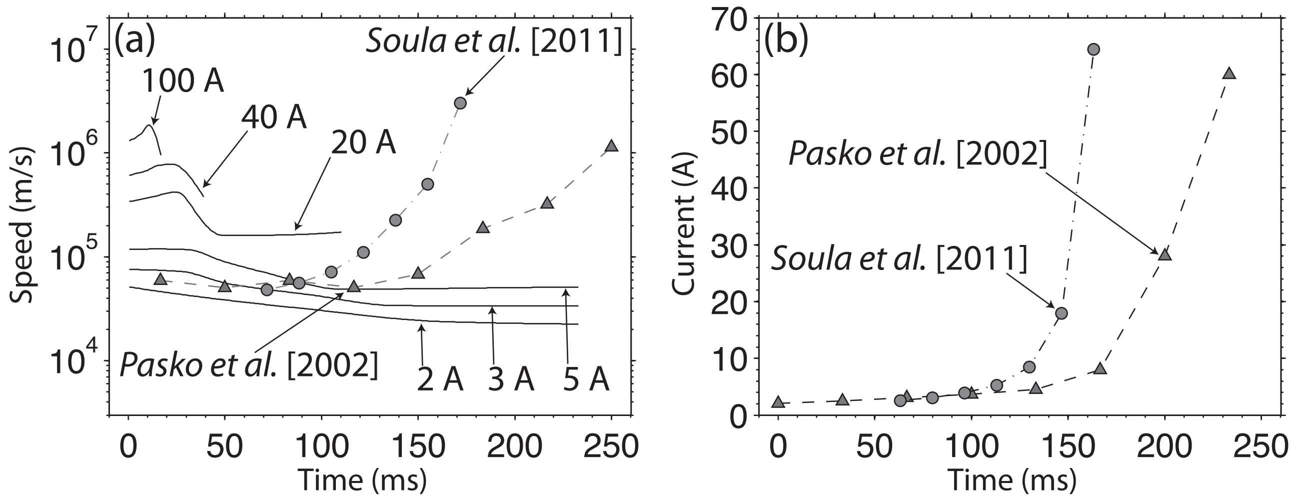

Figure 3. (a) Velocity of the two GJs as a function of time. Solid lines depict model results for several different constant currents. We note that for >40 A currents it takes <50 ms for modeled jet to reach altitudes >45 km. (b) Electric current time behavior required to match observed propagation characteristics of GJs.

evident from Figure 3a that for the same current the leader speed presents a complex, but weak, dependence on the ambient air density, because Δl_s and τ_h scale approximately in the same way, $\sim N^{-2}$. Speeds appear to slightly decrease at low pressures, due to the effects of gas dynamic expansion discussed above.

4. Discussion

[14] Our simulation results show that leader speeds do not have significant dependence on pressure, in agreement with experimental results of *Bazelyan et al.* [2007] in the pressure range of 0.3–1 atm. The similarity laws $\tau_h \sim N^{-2}$, $\Delta l_s \sim N^{-2}$, and, consequently, $v_L \sim N^0$, for a given constant current, lead to a good first-order estimate for the leader speed at pressures $\gtrsim 10^{-3}$ atm. Therefore, to mimic the experimentally observed GJ acceleration, a strong increase in the leader current (Figure 3b) is required to obtain speeds of $\gtrsim 5 \times 10^5$ m/s. Nevertheless, the scaling used here for Δl_s is a very rough estimate and may introduce a considerable error at low pressures. For instance, *Bazelyan et al.* [2007] measured Δl_s as 1 cm and 7 cm at the pressures 1 atm and 0.3 atm, respectively, which gives the dependence $\Delta l_s \sim N^{-1.6}$. On the other hand, the heating time scaling calculated in the present work differs from that obtained by *Popov* [2009]. This discrepancy is probably associated with the differences in the kinetic models. Consequently, these two aspects are the main sources of uncertainty in the evaluation of leader speeds at reduced air pressures.

[15] It is known that leader current and speed increase as the leader propagates through the gap in laboratory experiments [e.g., *Bazelyan et al.*, 2007]. For instance, experimental results at ground pressure of *Andreev et al.* [2008] point out that it is possible to write the relationship $v_L = v_L(I)$, independently of the leader phase. *Andreev et al.* [2008] found that initially the leader propagates through the gap at approximately constant speed and current. They also observed that when the leader enters the final jump phase, both speed and current increase. They also show that speed and current are related by the same relation $v_L \sim I^{0.67}$ (Figure 2b) during both initial and final jump phases. Therefore, the observed GJ acceleration is not due to the decrease in air density with altitude, but is more likely to be an evidence of a final-jump-like process. The leaders initiating cloud-to-ground lightning discharges are seen to accelerate as they approach the ground, in spite of the fact that they are propagating in the direction of increase in air density [*Saba et al.*, 2008, Figure 3], providing further support for the above discussed idea.

[16] However, we emphasize that it is unlikely that the whole GJ is converted to a thermalized channel. In fact, a 1 kA current would have to persist for 350 ms at 70 km altitude to allow streamer-to-leader transition. This time scale is comparable to the duration of the whole jet, which is 333–850 ms [*Soula et al.*, 2011], while current is higher than the estimated peak current of 750 A, by *Cummer et al.* [2009]. Thus, it is likely that the strong acceleration of the upper parts of GJs marks a transition region between leader and streamer propagation mechanisms. As a leader propagates upwards, the streamer zone around its head increases in length due to the reduction in air density. A rough estimate gives 700 m at 20 km altitude and 16 km at 40 km altitude, for a 50 MV leader [*Bazelyan and Raizer*, 2000, p. 69]. These numbers indicate that the estimated GJ speed, in its upper part, may actually be the speed of the streamer corona moving away of the leader head. The streamer nature of the upper part of GJs is evidenced by the blue color seen in color pictures [*Soula et al.*, 2011, Figure 11], by the observed electron energy spectrum with energies in the range of 8.5–12.3 eV, characteristic of streamer coronas [*Kuo et al.*, 2009], and by experimentally measured ratio of blue and red emission intensities in jet discharges [*Wescott et al.*, 2001; *Pasko and George*, 2002]. Our results quantitatively demonstrate that the initial stages of GJs have speeds compatible to the speed of leaders and that on time scales of GJs currents as low as 2 A can produce leaders at $\sim$20–30 km altitude.

5. Summary

[17] We have developed a model to calculate the streamer-to-leader transition time scale and leader speeds in the

pressure range between 0.0015 atm and ground pressure. We have shown that the streamer-to-leader time scales very close to $\sim N^{-2}$,in agreement with simple similarity laws for Joule heating. Our calculations demonstrate that constant-current leaders do not exhibit significant acceleration as they propagate in the direction of reduced air density. It is shown that the initial speeds of gigantic jets are consistent with the speeds of leaders with currents in the range of few amperes. Our results point out that the acceleration observed in gigantic jets may be evidence of the vertical structure of the phenomenon, indicative of a transition between leader and streamer mechanisms.

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