On the Upward Propagation of Gigantic Jet Leaders

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ABSTRACT: Gigantic Jets (GJs) are initiated deep inside the thundercloud as intracloud discharges whose upward-directed leaders manage to escape through the thundercloud top and propagate up to the ionosphere. The speed at which leaders propagate is limited by the air heating of every newly formed leader section, rate of which is slower at upper altitudes in the Earth's atmosphere. Despite the expected deceleration of an upward-directed leader, GJs are observed to accelerate as they approach the ionosphere. In this paper, we discuss the dependence of the leader speed on current density in the leader stem and we propose a simple time-dynamic model for GJ propagation that includes the effects of the expansion of the streamer zone adjacent to the leader head. We propose that the GJ acceleration is a consequence of its vertical structuring and, therefore, can be used to trace the transition altitude between the leader and streamer zone sections of GJs.

INTRODUCTION

Gigantic jets (GJs) are upward-directed large-scale electrical discharges that are observed to leave thundercloud tops and propagate up to $\sim$90 km altitude, connecting to the ionosphere [*Pasko et al.*, 2002; *Su et al.*, 2003]. In recent years, the number of ground-based [e.g., *Cummer et al.*, 2009; *van der Velde et al.*, 2010; *Soula et al.*, 2011; *Lu et al.*, 2011] and satellite-based [*Kuo et al.*, 2009, and references therein] observations of GJs has increased considerably. Remote-sensing of VLF emissions have revealed that most GJs are of negative polarity and transport hundreds of coulombs of negative charge to the ionosphere [e.g., *Cummer et al.*, 2009]. The current understanding of the GJ process, as derived from several theoretical works [e.g., *Pasko and George*, 2002; *Raizer et al.*, 2006; *Krehbiel et al.*, 2008; *Riousset et al.*, 2010; *Neubert et al.*, 2011; *da Silva and Pasko*, 2013a], describes it as an upward-directed discharge, analogous to cloud-to-ground lightning. In a normal-polarity thunderstorm (i.e., containing a midlevel negative and an upper positive charge centers), GJs are initiated between adjacent charge regions (similarly to intracloud lightning discharges), where the electric field is the strongest [*Krehbiel et al.*, 2008]. Lightning is initiated by a bi-directional discharge that propagates in the form of positive leaders in the negative charge region and in the form of negative leaders in the positive charge region [e.g., *Mazur*, 2002; *Riousset et al.*, 2007]. *Krehbiel et al.* [2008] demonstrated that when the two charges were not balanced (meaning the upper positive charge center contains less net charge than the midlevel negative charge center), the leader potential could be significantly shifted in the direction defined by the charge with dominant magnitude. In this situation the propagation of the leader becomes essentially independent from the weaker charge center, allowing it to penetrate through the weaker upper charge center and to escape from the thundercloud upward and serve as the initiation of a GJ [*Krehbiel et al.*, 2008; *Riousset et al.*, 2010].

Complementarily, *Raizer et al.* [2006] point out that as the leader propagates upward the streamer zone ahead of it becomes longer, because of the dynamics of streamer growth in a medium with exponentially-decreasing air density. Therefore, there is an altitude where the streamer corona in the leader head can "escape" to the ionosphere. In the present work, we present results of a streamer-to-leader transition model

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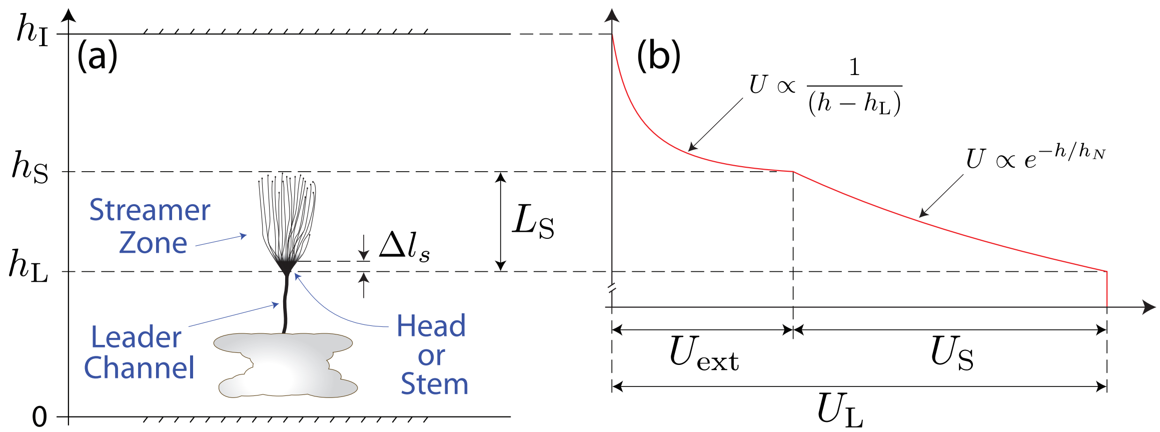

Figure 1: (a) Sketch of GJ upward propagation defining length scales discussed in text. (b) Sketch of electric potential drop from the leader head to the ionosphere [*da Silva and Pasko*, 2013b, Fig. 1]. Reprinted by permission from American Geophysical Union.

capable of describing the leader formation and propagation in a broad range of ambient air density encompassing the altitude range of GJs [*da Silva and Pasko*, 2013a]. We present a simple time dynamic model for the description of GJ propagation [*da Silva and Pasko*, 2013b] and, finally, we explain the vertical structuring of GJs by combining results of our time-dynamic model with the ideas introduced by *Raizer et al.* [2006] and *Krehbiel et al.* [2008].

MODELING OF LEADER SPEEDS

It is well accepted that the leader speed is dictated by the air heating in every newly formed portion of the elongating leader [e.g., *Bazelyan and Raizer*, 2000, pp. 66–67]. For this reason, both experimental [e.g., *Andreev et al.*, 2008] and theoretical [e.g., *Popov*, 2009] studies attempt to provide leader speed as a function of electrical current flowing through the leader head into the channel, i.e., $v_L = v_L(I)$. The theoretical approach for estimation of leader speed is to assume that a constant current I is flowing through the leader stem and to calculate the time τ_h to heat the stem up to $\sim$2000 K. When temperature reaches this threshold the formation of a highly-conducting new section of the leader is unavoidable [*Popov*, 2009]. The streamer-to-leader transition takes place on a time scale τ_h at which the leader extends a distance Δl_s in space. Therefore, leader speed can be estimated as $v_L = \Delta l_s/\tau_h$. The leader streamer zone is a conically shaped fan of thousands of streamers [e.g., *Bazelyan and Raizer*, 2000, Fig. 2.11]. Figure 1a illustrates this structuring in the context of GJs. The length of the conducting section behind the tips of individual streamers is $\Delta l_s = v_s\, \tau_{a3}$, where v_s is the streamer velocity and τ_{a3} is the three-body electron attachment time scale. For a streamer velocity $v_s \simeq 10^5$ m/s (typical of young weak streamers) and for $\tau_{a3} \simeq 10^{-7}\, N_0^2/N^2$ s it gives $\Delta l_s \simeq 1\, N_0^2/N^2$ cm [*da Silva and Pasko*, 2012, and references therein], where N_0 and N are air densities of ground level and altitude of interest, respectively. This size of Δl_s is comparable with the measured radius of the leader head in laboratory discharges at ground pressure [*Bazelyan et al.*, 2007]. Therefore, one can suppose that the leader head, which is clearly visible on laboratory photographs (and streak images), is a collection of initial, still conducting, closely located streamer segments [*Bazelyan et al.*, 2007]. In the present work, streamer properties at a given altitude h in the Earth's atmosphere are obtained by scaling the respective value at ground-level air density N_0 to the corresponding value at reduced air density $N(h)$,

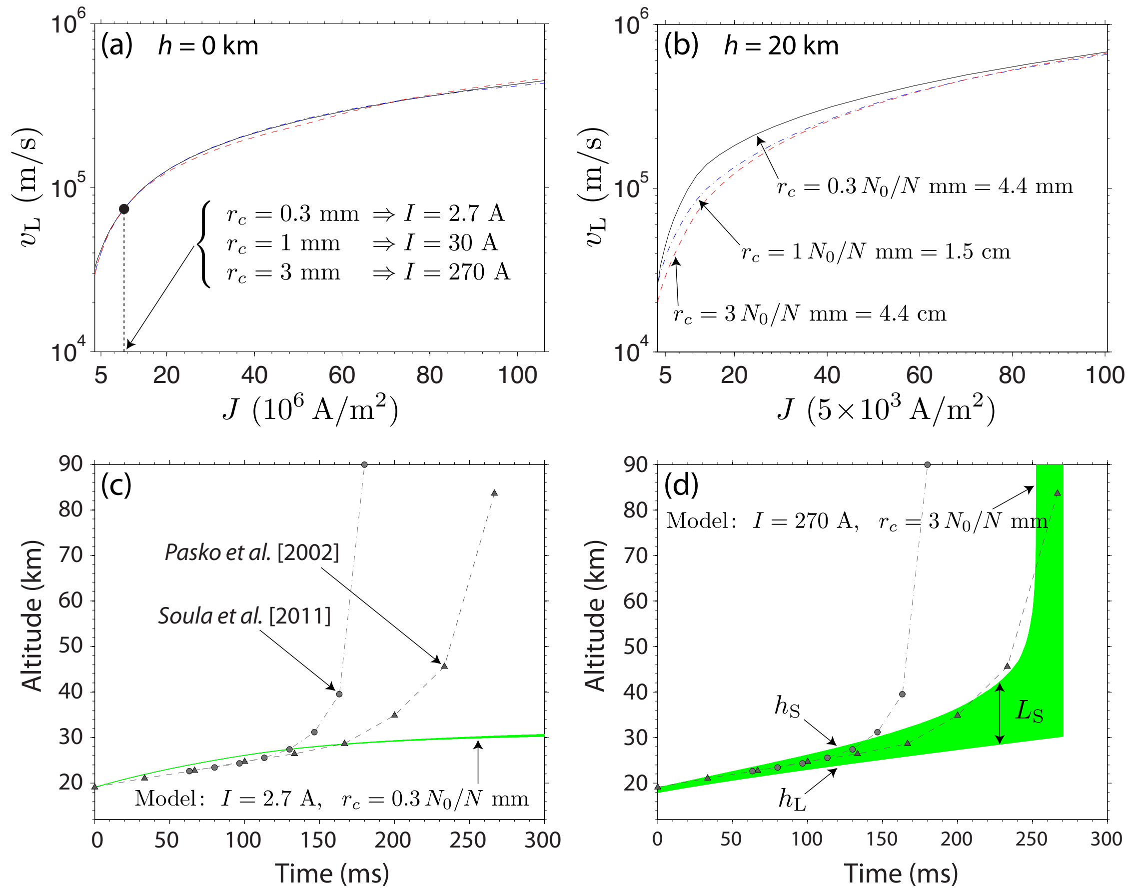

Figure 2: (a,b) Simulated leader speed as a function of initial current density in the leader stem at (a) ground and (b) 20 km altitude, for different values of stem radius. (c,d) Comparison of observed GJ propagation with modeled upward leader propagation for $J = 9.6\times10^6\,N^2/N_0^2$ A/m^2, including expansion of streamer zone, for two different values of stem radius (c) 0.3 mm and (d) 3 mm [*da Silva and Pasko*, 2013b, Fig. 2]. Reprinted by permission from American Geophysical Union.

following similarity laws for streamer physics [e.g., *Pasko*, 2006, pp. 265–267], where $N(h) = N_0\,e^{-h/h_N}$, with $h_N = 7.2$ km and $N_0 = 2.5\times10^{19}$ cm^{-3}. We note that three-body attachment is a very inefficient plasma decay process at mesospheric altitudes ($N \ll N_0$). Hence, the assumption that the streamer channel lifetime is dictated by τ_{a3} is not correct at sprite altitudes. However, the concept of $\Delta l_s \propto \tau_{a3}$ is only used here to estimate leader speeds below ∼30 km altitude, as shown in Figure 2.

In order to calculate the streamer-to-leader transition time scale, we have developed a model that simulates the air heating process in the leader stem. The model accounts for the Joule heating of air through the so-called fast heating mechanism, as well as vibrational excitation of nitrogen molecules and its delayed relaxation into translational energy [*da Silva and Pasko*, 2013a]. Figures 2a and 2b present simulated leader speed as a function of the initial current density in the leader stem, at ground ($\Delta l_s = 1$ cm) and 20 km altitude ($\Delta l_s = 2.1$ m), respectively. The initial radial distribution of electron density in the leader stem is $n_e = n_{e,a} e^{-r^2/r_c^2}$, with $n_{e,a} = 2\times10^{14}\,N^2/N_0^2$ cm^{-3} and $r_c = 0.3$–$3\,N_0/N$ mm. We note that current density scales with air density as $\propto N^2$ and the range of current values shown in Figure 2a and 2b is different by a factor of 200, approximately reflecting this scaling. We can see a similar dependence on $J = I/\pi r_c^2$ for both altitudes and for a one order of magnitude range of change in r_c. We can also see that the same leader speed can be obtained with two orders of magnitude difference in I. The value $r_c = 0.3$ mm has been proven to accurately reproduce the characteristics of laboratory leaders, which are generated in meter-long gaps, under potential differences of hundreds of kilovolts to a few megavolts [e.g., *Popov*, 2009]. Under these conditions the leader has $I \sim 1$ A and $v_{\rm L} \sim 10^4$ m/s [*Bazelyan and Raizer*, 2000, p. 67]. However, in the formation of a leader in open air with available thundercloud potential the initial radius for the stem might be significantly larger due to various reasons, as for example, streamer expansion and overlapping.

The two quantities that determine leader speed are $\tau_{\rm h}$ and Δl_s and they are dictated by air heating and three-body attachment, respectively. Time scale for both processes increases with reducing air density as $\propto 1/N^2$, therefore, leader speed presents weak dependence on ambient air density, as also shown in Figures 2a and 2b. Although we do not discuss details of the different dynamical features of positive and negative leaders, we assume that the streamer-to-leader transition is a fundamental process that defines leader propagation in both cases. In the case of a 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, and we assume that in time average sense it is the main process defining speed with which the negative leader advances in space [*da Silva and Pasko*, 2012, and references therein].

EXPANSION OF THE GIGANTIC JET STREAMER ZONE

Theory of leader discharges predicts the existence of an average constant electric field in the streamer zone equal to the critical electric field value for stable streamer propagation $E_{\rm cr}$ [*Bazelyan and Raizer*, 2000, pp. 67–69]. For positive leader, for example, at ambient ground pressure this value is $E_{\rm cr,0} \simeq 5$ kV/cm [*Bazelyan and Raizer*, 2000, p. 69]. The average electric field in a leader streamer zone is expected to reduce exponentially with altitude proportionally to air density, i.e., $E_{\rm cr} = E_{\rm cr,0}\, N/N_0$ [e.g., *Pasko*, 2006, p. 266]. As first noticed by *Raizer et al.* [2006], this fact has important consequences for an upward propagating leader, such as in the case of GJs escaping from thundercloud tops. A simple estimate for the streamer zone length $L_{\rm S}$ of an upward-propagating leader can be obtained analytically for a simple geometry (Figure 1). The length $L_{\rm S}$ is related to the potential drop in the streamer zone $U_{\rm S}$ and the altitude position of the leader head $h_{\rm L}$ as:

$$L_{\rm S} = h_N \ln\left[\left(1 - \frac{U_{\rm S}}{h_N E_{\rm cr,L}}\right)^{-1}\right], \qquad (1)$$

where $E_{\rm cr,L} = E_{\rm cr,0}\, \exp(-h_{\rm L}/h_N)$ [*da Silva and Pasko*, 2013b, Section 3]. Equation (1) is obtained by solving the equation for the potential drop across the streamer zone, $U_{\rm S} = \int_{h_{\rm L}}^{h_{\rm L}+L_{\rm S}} E_{\rm cr}(h)\, dh$, for $L_{\rm S}$. If the leader is close to ground ($h_{\rm L} \ll h_N$), such as in leaders initiated from tall buildings [e.g., *Lalande et al.*, 2002, Figs. 1–2], half of leader voltage drop $U_{\rm L}$ occurs in the streamer zone, i.e., $U_{\rm S} = U_{\rm L}/2$, and formula (1) reduces to $L_{\rm S} = U_{\rm L}/2E_{\rm cr,L}$ [*Bazelyan and Raizer*, 2000, p. 69]. The length of the streamer zone increases exponentially with altitude, i.e., $L_{\rm S} \propto \exp(h_{\rm L}/h_N)$ [*da Silva and Pasko*, 2013b, Fig. 3a]. For an upward-directed leader at mesospheric altitudes, such as in GJs, the potential drop in the streamer zone shifts from $U_{\rm L}/2$ to $U_{\rm L}$ [*da Silva and Pasko*, 2013b, Fig. 3c]. It can be seen from equation (1) that $L_{\rm S} \to \infty$ when $U_{\rm L} = h_N E_{\rm cr,L}$. Consequently, there is an altitude $h_{\rm jump} = h_N \ln(h_N E_{\rm cr,0}/U_{\rm L})$ at which the streamer zone "jumps" to the ionosphere [*da Silva and Pasko*, 2013b, Fig. 3d].

VERTICAL STRUCTURING OF GIGANTIC JETS

Figures 2c and 2d display the upward propagation as a function of time of two GJs observed by *Pasko et al.* [2002] and *Soula et al.* [2011] (see also *da Silva and Pasko* [2012, Fig. 1]). To model the GJ propagation we assume (for simplicity) that a constant current $I = 2.7$ A (Figure 2c) and 270 A (Figure 2d) flows through the leader stem. Initial current density $J = 9.6\times10^6\ N^2/N_0^2$ A/m^2 is the same in both cases. In view of the above discussion [see also *da Silva and Pasko*, 2013b, Section 2], the difference in current is due to different initial stem radius $r_c = 0.3\,N_0/N$ mm and $3\,N_0/N$ mm, respectively. For these two values of current the dependence $v_{\rm L}(I, h_{\rm L})$ is obtained and a leader upward propagation is simulated by solving the equation $dh_{\rm L}/dt = v_{\rm L}(I, h_{\rm L})$ [*da Silva and Pasko*, 2012]. For every position of the leader head $h_{\rm L}$ the size of the streamer zone is calculated from formula (1) assuming that $U_{\rm S} = U_{\rm L}/2$ and that the leader potential is defined for a cylindrically-shaped conductor elongating in an external uniform electric field, $U_{\rm L} = I/v_{\rm L}\mathcal{C}$, where the capacitance per unit length is $\mathcal{C} \approx 2\pi\varepsilon_0 = 5.56\times10^{-11}$ F/m [*Bazelyan and Raizer*, 2000, p. 62]. The shaded areas in Figures 2c and 2d show the length of the streamer zone $L_{\rm S}$ above the leader head, the lower boundaries of the shaded regions represent $h_{\rm L}$, while the upper boundaries $h_{\rm S}$ (compare to schematics in Figure 1). Leader potential varies within 0.8–30 MV and 84–121 MV in Figures 2c and 2d, respectively. Consequently the streamer zone is shorter in Figure 2c.

The conclusion to be drawn from Figures 2c and 2d is that the strong acceleration in GJs is a consequence of their vertical structure. GJs initiate inside the thundercloud as a conventional intracloud lightning discharge. As demonstrated by *Krehbiel et al.* [2008], owing to the charge imbalance in thunderclouds one or more lightning leaders can escape upward. The leader propagates upwards with a stable speed $\lesssim 10^5$ m/s, consistent to a current density of $\lesssim 10^7\ N^2/N_0^2$ A/m^2 in the leader stem (see Figures 2a and 2b). The leader is capable of bringing the high thundercloud potential $U_{\rm L}$ to upper altitudes [*Raizer et al.*, 2006]. When the leader approaches the jump altitude [*da Silva and Pasko*, 2013b, Fig. 3], the streamer zone expands causing the observed acceleration. During this stage the GJ speed is closer to that of fast streamers $\sim 10^6$–10^7 m/s [e.g., *Pasko*, 2006, p. 259]. Results presented in Figures 2c and 2d indicate that the initial leader stem radius (prior to channel contraction) should be larger than that of a single streamer, and more likely to be a few millimeters (scaled to ground pressure). Thus, the upward propagating GJ would carry a current of tens to hundreds of amperes, on the same order of magnitude as is reported in measurements [e.g., *Cummer et al.*, 2009].

SUMMARY

In this paper we have reported simulation results on leader speeds, pointing out their dependence on current density in the leader stem, instead of total current as typically assumed in existing literature. Our results demonstrate that the GJ acceleration can be understood as a consequence of the expansion of the leader streamer zone [*da Silva and Pasko*, 2013b]. Therefore, the jump altitude may serve as a first-order estimate for the transition region between leader and streamer portions of GJs.

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