Streamer-to-leader transition in gigantic jets

C. L. da Silva[1] and V. P. Pasko[1]

[1] *Communications and Space Sciences Laboratory, Department of Electrical Engineering, Pennsylvania State University, University Park, PA 16802, USA*
(Email: caitano.dasilva@psu.edu, vpasko@psu.edu)

Streamer-to-leader transition is the name given to a sequence of events occurring in a thin plasma channel through which a relatively strong current is forced through, culminating in heating of ambient gas and increase of the electrical conductivity of the channel. This process occurs during the inception of leaders (from sharp metallic structures, from hydrometeors inside the thundercloud, or in virgin air) and during their propagation (at the leader head or during the growth of a space leader). In this presentation, we describe the physics of streamer-to-leader transition at reduced air densities (upper altitudes in the Earth's atmosphere), and its role in the dynamics of gigantic jets.

1. Motivation

Gigantic jets (GJs) are large-scale electrical discharges between the thundercloud tops and the lower ionosphere [1,2]. It is estimated that an individual GJ can contribute as much as cloud-to-ground lightning in discharging a thunderstorm system, transferring hundreds of coulombs from thundercloud to the ionosphere [3]. Moreover, due to the lengthening of time scales at upper altitudes in the Earth's atmosphere (inversely proportional to the decreasing air density), GJs represent a unique opportunity to study the physics of lightning leaders. Recent observations by *Chou et al.* [4] report observation of positive- and negative-polarity GJ leaders, while *Lu et al.* [5] report VHF recordings of a negative GJ leader stepping up to 35 km altitude in the atmosphere above the thundercloud.

Since the discovery of GJs [1,2], several theoretical works were dedicated to the clarification of their physical mechanisms (e.g., [6-11]). The current understanding of the GJ process is that they are initiated deep inside the thundercloud as intracloud lightning discharges. Owing to a charge imbalance, meaning the upper charge center is depleted with respect to the midlevel charge center, the upward-directed lightning leaders manage to escape through the thundercloud top to form GJs [8,9]. As a GJ leader crosses the stratosphere its streamer zone becomes longer and longer, due to the dynamics of streamer growth in a medium with exponentially-decreasing air density, such as in the Earth's atmosphere [7]. The speed at which a leader propagates 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 [11]. Despite the expected deceleration of an upward-directed leader, GJs are observed to accelerate as they approach the ionosphere, as depicted in Figure 1.

2. Modeling of streamer-to-leader transition at gigantic jet altitudes

In order to investigate the mechanisms of GJ formation and propagation and to consistently estimate GJ speeds at stratospheric altitudes, we have developed a first-principles model do describe the interaction of the GJ currents with atmospheric air and formation of a hot and highly-conducting plasma channel, i.e., a leader. The physical model consists of four main blocks: (1) a set of nonlinear neutral gas dynamics equations; (2) a detailed kinetic scheme accounting for the most important processes in a gas discharge plasma; (3) energy exchange between charged and neutral particles accounting for the partitioning of the electronic power between elastic collisions, excitation of vibrations, and excitation of electronic states; and (4) delayed vibrational energy relaxation of nitrogen molecules [11]. We show that the interplay of the air heating rate and the rates of channel expansion and cooling set a limiting altitude in the Earth's atmosphere above which streamer-to-leader transition cannot occur.

We also introduce a simple time-dynamic model for GJ propagation that simulates the upward propagation of a leader discharge accounting for the effects of the expansion of its streamer zone. We propose that the GJ acceleration is a consequence of its vertical structuring, i.e., speeds of $<10^5$ m/s observed in the early stages of GJs are consistent with a leader escaping from the thundercloud and its

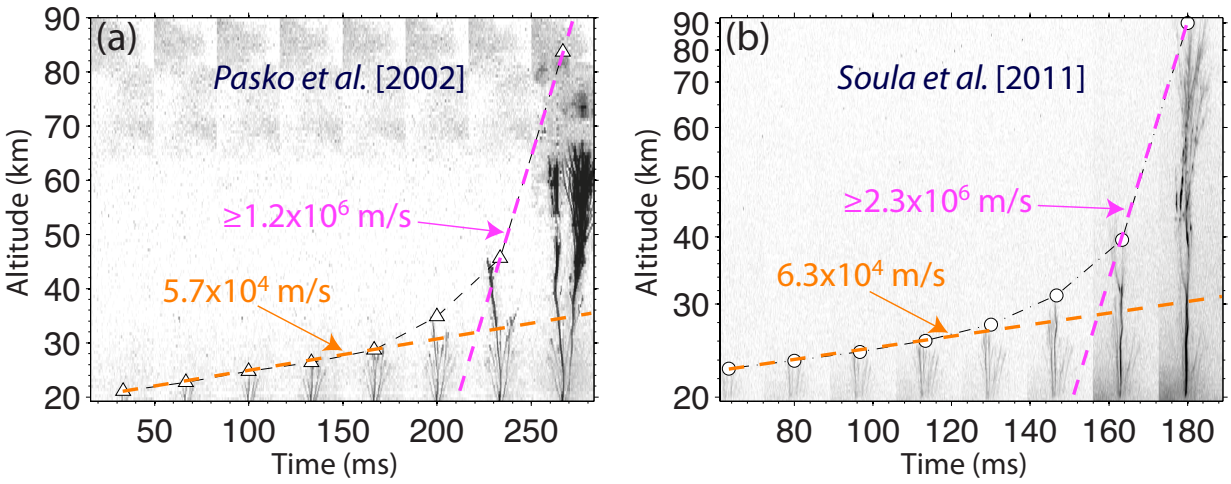

Figure 1. Experimentally registered acceleration in the upward propagation of two GJs, observed by (a) *Pasko et al.* [1] and (b) *Soula et al.* [12]. Reprinted from Figure 18 of [11] by permission from American Geophysical Union. Images in panel (b) are courtesy of Serge Soula.

acceleration is related to the growth of its streamer zone as the leader reaches higher altitudes in the Earth's atmosphere [13].

3. References

[1] Pasko, V. P., M. A. Stanley, J. D. Mathews, U. S. Inan, and T. G. Wood (2002), Electrical discharge from a thundercloud top to the lower ionosphere, *Nature*, 416(6877), 152–154, doi: 10.1038/416152a.

[2] Su, H. T., R. R. Hsu, A. B. Chen, Y. C. Wang, W. S. Hsiao, W. C. Lai, L. C. Lee, M. Sato, and H. Fukunishi (2003), Gigantic jets between a thundercloud and the ionosphere, *Nature*, *423*, 974–976, doi:10.1038/nature01759.

[3] Cummer, S. A., J. Li, F. Han, G. Lu, N. Jaugey, W. A. Lyons, and T. E. Nelson (2009), Quantification of the troposphere-to-ionosphere charge transfer in a gigantic jet, *Nat. Geosci.*, *2*(9), 617–620, doi:10.1038/ngeo607.

[4] Chou, J. K., et al. (2010), Gigantic jets with negative and positive polarity streamers, *J. Geophys. Res.*, *115*, A00E45, doi:10.1029/2009JA014831.

[5] Lu, G., et al. (2011), Lightning development associated with two negative gigantic jets, *Geophys. Res. Lett.*, *38*, L12801, doi:10.1029/2011GL047662.

[6] Pasko, V. P., and J. J. George (2002), Three-dimensional modeling of blue jets and blue starters, *J. Geophys. Res.*, 107(A12), 1458, doi:10.1029/2002JA009473.

[7] Raizer, Y. P., G. M. Milikh, and M. N. Shneider (2006), On the mechanism of blue jet formation and propagation, *Geophys. Res. Lett.*, *33*, L23801, doi:10.1029/2006GL027697.

[8] Krehbiel, P. R., J. A. Riousset, V. P. Pasko, R. J. Thomas, W. Rison, M. A. Stanley, and H. E. Edens (2008), Upward electrical discharges from thunderstorms, *Nat. Geosci.*, *1*, 233–237, doi: 10.1038/ngeo162.

[9] Riousset, J. A., V. P. Pasko, P. R. Krehbiel, W. Rison, and M. A. Stanley (2010), Modeling of thundercloud screening charges: Implications for blue and gigantic jets, *J. Geophys. Res.*, *115*, A00E10, doi:10.1029/2009JA014286.

[10] Neubert, T., O. Chanrion, E. Arnone, F. Zanotti, S. Cummer, J. Li, M. Füllekrug, S. Soula, and O. van der Velde (2011), The properties of a gigantic jet reflected in a simultaneous sprite: Observations interpreted by a model, *J. Geophys. Res.*, *116*, A12329, doi:10.1029/2011JA016928.

[11] da Silva, C. L., and V. P. Pasko (2013), Dynamics of streamer-to-leader transition at reduced air densities and its implications for propagation of lightning leaders and gigantic jets, *J. Geophys. Res.*, *118*, 13,561–13,590, doi:10.1002/2013JD020618.

[12] Soula, S., O. A. van der Velde, J. Montanya, P. Huet, C. Barthe, and J. Bór (2011), Gigantic jets produced by an isolated tropical thunderstorm near Réunion Island, *J. Geophys. Res.*, *116*, D19103, doi:10.1029/2010JD015581.

[13] da Silva, C. L., and V. P. Pasko (2013), Vertical structuring of gigantic jets, *Geophys. Res. Lett.*, *40*, 3315–3319, doi:10.1002/grl.50596.