



## RESEARCH LETTER

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## Spontaneous Emergence of Space Stems Ahead of Negative Leaders in Lightning and Long Sparks

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## Key Points:

- Space stems start as regions of locally lower conductivity in the streamer channels around the tip of negative leaders
- An attachment instability enhances the electric field at the space stem decreasing further the conductivity and leading to bright and locally warmer regions
- As the attachment instability is favoured by high electric fields inside negative streamer channels it explains why only negative leaders propagate in long steps

## Supporting Information:

- Supporting Information S1

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**Abstract** We investigate the emergence of space stems ahead of negative leaders. These are luminous spots that appear ahead of an advancing leader mediating the leader's stepped propagation. We show that space stems start as regions of locally depleted conductivity that form in the streamers of the corona around the leader. An attachment instability enhances the electric field leading to strongly inhomogeneous, bright, and locally warmer regions ahead of the leader that explain the existing observations. Since the attachment instability is only triggered by fields above 10 kV/cm and internal electric fields are lower in positive than in negative streamers, our results explain why, although common in negative leaders, space stems, and stepping are hardly observed if not absent in positive leaders. Further work is required to fully explain the streamer to leader transition, which requires an electric current persisting for timescales longer than the typical attachment time of electrons, around 100 ns.

**Plain Language Summary** Long electrical discharges of negative polarity, such as most cloud-to-ground lightning flashes, propagate in a stepped manner, that is, alternating between standing and jumping suddenly. The underlying mechanism explaining this behavior is not well understood, although we know that space stems are a key element. These are bright and locally warmer segments that appear ahead of a discharge channel and apparently isolated from it. For the first time, we show how these space stems emerge spontaneously in our simulations from regions of locally lower conductivity that later become bright and warm. Then on one hand, we propose a possible origin of the space stems and, on the other hand, we shed some light on possible mechanisms that grow these stems to longer times, beyond 100 ns.

## 1. Introduction

One of the outstanding mysteries in atmospheric electricity concerns the progression of negative lightning leaders. Being hot and ionized channels, leaders are initiated in a thundercloud and expand bipolarly, with their positive and negative extremes advancing in more or less opposite directions. For some elusive reason, negative leaders advance in a stepped fashion, with waiting times of tens of microseconds punctuated by sudden jumps of microsecond timescale (Dwyer & Uman, 2014). This behavior is observed not only in lightning leaders but also in negative laboratory discharges longer than about 2 m.

Besides being a fundamental but mysterious process in electrical discharges, leader steps are relevant because they produce the very high frequency radio pulses that reveal the development of lightning flashes in Lightning Mapping Arrays (Thomas et al., 2001). Leader steps are also correlated with X-ray emissions detected around a lightning discharge (Dwyer et al., 2005), and therefore, they are possibly linked to terrestrial gamma ray flashes detected by satellites orbiting hundreds of kilometers above ground (Briggs et al., 2013; Fishman et al., 1994; Marisaldi et al., 2010; Smith et al., 2005).

The first observation of leader stepping can be traced back to the pioneering work of Schonland et al. (1935) in the 1930s, who coined the term *stepped leader* for the intermittent advance of downward negative lightning channels recorded in their streak camera. In the decades after Schonland's work, advances in this topic arose mostly from laboratory experiments with meter-long spark discharges. The work of, among others, Gorin et al. (1976) and the Les Renardières group (1978) revealed the dynamics of a negative leader step: The leader tip is preceded by a filamentary corona containing a bright nucleus termed *space stem*. After some microseconds, the space stem evolves into a *space leader* that propagates in both directions and whose

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extremes are surrounded by additional coronas of both polarities. The leader completes one step when the space leader bridges the gap to the main leader channel.

Recordings with the high-framerate video cameras fielded in the last decade show that lightning leaders, although they involve slightly different space and time scales, follow the same pattern as long laboratory sparks. With integration times of a few microseconds, the observations of Hill et al. (2011) for natural stepped leaders and Biagi et al. (2014) and Gamerota et al. (2014) for leaders in triggered lightning captured images of the space stem ahead of the leader tip, embedded in a filamentary corona.

Despite these observational advances, our understanding about the physics of stepped leaders is still very incomplete. Measured optical spectra indicate that the leader temperature reaches around 5000 K (Cooray, 2003) for laboratory discharges and up to 30000 K in lightning leaders (Orville, 1968), which, in both cases and according to chemical models, suffices to sustain a high ionization (Gallimberti, 1979). On the other hand, the filaments in the corona, called *streamers*, are not much above ambient temperature; their ionization, lower than that of leaders, is created mostly at their tips, where they enhance the electric field strongly enough to accelerate electrons up to the threshold of impact ionization (Ebert et al., 2010). Models for the streamer-to-leader transition (da Silva & Pasko, 2013; Popov, 2003) successfully reproduce the transition timescale of around 1  $\mu$ s for atmospheric pressure but depend on manually imposing a total electric current that in reality is an outcome of the discharge physics. They also neglect the longitudinal inhomogeneity of the discharge and therefore they sideline leader stepping and the formation of space stems. The physical mechanism governing the latter remains a mystery (see, e.g., Biagi et al., 2010; Bazelyan & Raizer, 2010); a recent review (Dwyer & Uman, 2014) included this problem in the top 10 questions in lightning research.

In this letter, we show that space stems originate from an attachment instability inside streamer channels. Since space stems are the key to leader stepping, our results open the door to the full understanding of this mechanism as well as its associated radio and energetic particle emissions. Originally investigated in the 1970s (Douglas-Hamilton & Mani, 1974; Sigmond, 1984), the attachment instability is triggered by regions of lower conductance per unit length (i.e., conductivity integrated over a cross section) inside a corona, which we show arise spontaneously when a negative streamer emerges from a leader. One major and slightly counterintuitive aspect of our work is that bright regions inside a corona reveal regions of lower, not higher, electron density. Although this is in complete correspondence with a regular electrical circuit where energy is mostly dissipated in high-resistivity components, this insight has escaped previous interpretations of the space stem. At high-altitude, in leader-less discharges (sprites), the attachment instability forms standing patterns called *beads and glows* (Luque et al., 2016; Luque & Ebert, 2010; Liu, 2010).

## 2. Model

Since lightning leaders and long laboratory sparks share the same mechanism of propagation, to simplify our computations, we choose to focus here on the propagation of a leader under laboratory conditions. Typical laboratory leaders span from tens of centimeters to around one meter and are surrounded by streamer coronas with roughly the same extension (Kostinskiy et al., 2018). These dimensions are too computationally demanding so, as we detail below, our simulated system is somewhat smaller.

Even then and despite recent progress in three-dimensional streamer simulations (Luque & Ebert, 2014; Shi et al., 2017; Teunissen & Ebert, 2017), a full corona around a leader is presently out of reach for numerical models. We opt for simulating a single streamer that emerges from a leader tip; our assumption here is that the surrounding corona is not an essential component of the physics of space stems. We cannot rigorously justify this assumption, but it is beared out by the similarity between observations and our results.

We thus investigate the formation of space stems ahead of a negative leader channel with a 2-D cylindrically symmetric model ( $z, r$ ) for electric discharges that includes heating and expansion of the background gas fully self-consistently. The background gas follows the equation of state for an ideal gas and its dynamics is described by the compressible Euler equations (da Silva & Pasko, 2013; Landau & Lifshitz, 1987; Popov, 2003). These are conservation equations for mass, momentum, and energy:

$$\frac{\partial \rho}{\partial t} + \mathbf{u} \cdot \nabla \rho + \rho \nabla \cdot \mathbf{u} = 0, \quad (1a)$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} + \frac{\nabla p}{\rho} = 0, \quad (1b)$$

$$\frac{\partial \varepsilon}{\partial t} + \mathbf{u} \cdot \nabla \varepsilon + \frac{p}{\rho} \nabla \cdot \mathbf{u} = \frac{w}{\rho}. \quad (1c)$$

Here  $\rho$  is the mass density of air,  $\mathbf{u}$  is the local velocity at a given point and time,  $p$  is the pressure, and  $\varepsilon$  is the specific energy associated to the rotational and translational degrees of freedom, which we assume in thermal equilibrium. Finally,  $w$  is the local dissipated energy from the electric discharge. By using equations (1a)–(1c) and the equation of state for an ideal gas, we neglect thermal conduction and viscous dissipation, which have little effect on the timescale of around 100 ns on which space stems form.

All species are advected along with the fluid with a velocity  $\mathbf{u}$ . Furthermore, charged species drift on top of the background gas motion according to the local value of the electric field  $\mathbf{E}$ , so the resulting velocity is  $\mathbf{v}_s = \mathbf{u} + \mu_s \mathbf{E}$ , where  $s$  labels the species and  $\mu_s$  is the corresponding mobility. In our model, the dynamics of all charged species is described by diffusion-drift-reaction equations for electrons and ions,

$$\frac{\partial n_s}{\partial t} + \nabla \cdot (n_s \mathbf{v}_s) = C_s + \nabla \cdot (D_s \nabla n_s), \quad (1)$$

where  $n_s$  is the number density,  $D_s$  is the diffusion coefficient, and  $C_s$  is the net production of species  $s$ .

The kinetic scheme employed in our simulations includes impact ionization, attachment/detachment, and water cluster formation and breaking. A detailed description of the scheme can be found in the supporting information of Luque et al. (2017). The only difference is that for the three-body attachment reaction,



here we have used the rate from Kossyi et al. (1992).

We emphasize the presence of water in the chemical model of our simulations. The relevance of water vapor for the evolution of streamer channels was previously discussed by Gallimberti (1979) and Luque et al. (2017). By clustering around negative ions, even a small quantity of water molecules effectively suppresses electron detachment and thus strongly influences the evolution of the electron density on timescales of tens of nanoseconds.

The electric field  $\mathbf{E} = -\nabla \phi$  is determined by the balance of charged species and satisfies

$$-\nabla \cdot \mathbf{E} = \nabla^2 \phi = - \sum_s \frac{q_s n_s}{\epsilon_0}, \quad (3)$$

where  $q_s$  is the charge of species  $s$  and  $\epsilon_0$  is the vacuum permittivity, which we assume is also valid for air.

Streamer discharges develop as thin and elongated channels, which call for a narrow computational domain. To achieve this while suppressing the influence of the radial boundary conditions in the Poisson's equation, we use the domain decomposition method described by Malagón-Romero and Luque (2018). With this method, we first find the electrostatic potential created by the space charges with a homogeneous Dirichlet boundary at  $z = 0$  and free conditions in all other boundaries, meaning that the potential decays to 0 at large distances. To the potential obtained in this manner, we add a potential  $\phi_0 = -E_0 z$  that accounts for an external electric field  $E_0$ . The full domain size is 25 cm  $\times$  3 cm.

The term  $w$  couples the electrodynamics and bulk gas dynamics and accounts for dissipated power due to the electric current inside the corona. But note that this power is distributed unequally among the degrees of freedom of the underlying gas. Since the timescales involved in the streamer-to-leader transition are too short to reach thermodynamic equilibrium, the fraction of energy deposited into different degrees of freedom depends on the local conditions and, in particular, on the local electric field (da Silva & Pasko, 2013; Flitti & Pancheshnyi, 2009). A small fraction is directly converted into translational energy of gas molecules and quickly thermalized. A larger amount excites electronic and ionization states; this is responsible for the process of *fast heating* (Popov, 2001) and relaxes into thermal energy at timescales on the order of 100 ns. Another fraction of the energy is spent in dissociation of oxygen and nitrogen molecules, and, finally, the remaining energy excites vibrational states and its time to thermalization is on the order of 1 s at ambient temperature and only significant compared with our relevant timescales once the temperature reaches about

$10^4$  K: This relaxation is neglected in the present study. Since, as we describe later, most heating is due to energies dissipated at or around the conventional breakdown electric field, roughly 30 kV/cm, we take the energy branching ratios corresponding to this field, where about half of the energy is frozen into vibrational excitations (see, e.g., Figure 1 in Flitti & Pancheshnyi, 2009). Furthermore, since the characteristic time of gas temperature increase is much longer than 100 ns, for the sake of simplicity, we consider fast heating to be instantaneous. Then, we arrive at

$$w = \eta \mathbf{j} \cdot \mathbf{E}, \quad (4)$$

where  $\eta \approx 0.5$  and  $\mathbf{j} = \sum_s q_s n_s \mathbf{v}_s$ .

Our initial condition consists in a short portion of leader with an small ionization patch slightly ahead of the tip that mimicks an irregularity of the leader head. The initial electron density is thus the sum of a uniform background  $n_e^{\text{bg}}$  plus

$$n_e^{\text{leader}} = n_{e0} \exp\left(-\frac{\max(z - z_L, 0)^2}{2\sigma_L^2} - \frac{r^2}{2\sigma_L^2}\right), \quad (6a)$$

and

$$n_e^{\text{seed}} = n_{e0} \exp\left(-\frac{(z - z_S)^2}{2\sigma_S^2} - \frac{r^2}{2\sigma_S^2}\right), \quad (6b)$$

where the tip location is  $z_L = 5$  cm, the seed center is at  $z_S = 6.1$  cm, the  $e$ -folding lengths are  $\sigma_L = 3$  mm,  $\sigma_S = 1.5$  mm, and the electron density peaks at  $n_{e0} = 10^{21} \text{ m}^{-3}$ . The initial electron density is neutralized by an identical density of positive ions. Note that we selected these initial conditions after a few trials where we disregarded cases in which the streamer branches because these cannot be captured by our cylindrically symmetrical model. Besides, as mentioned above, to keep our computations feasible, the initial leader is somewhat shorter than experimental stepped leaders.

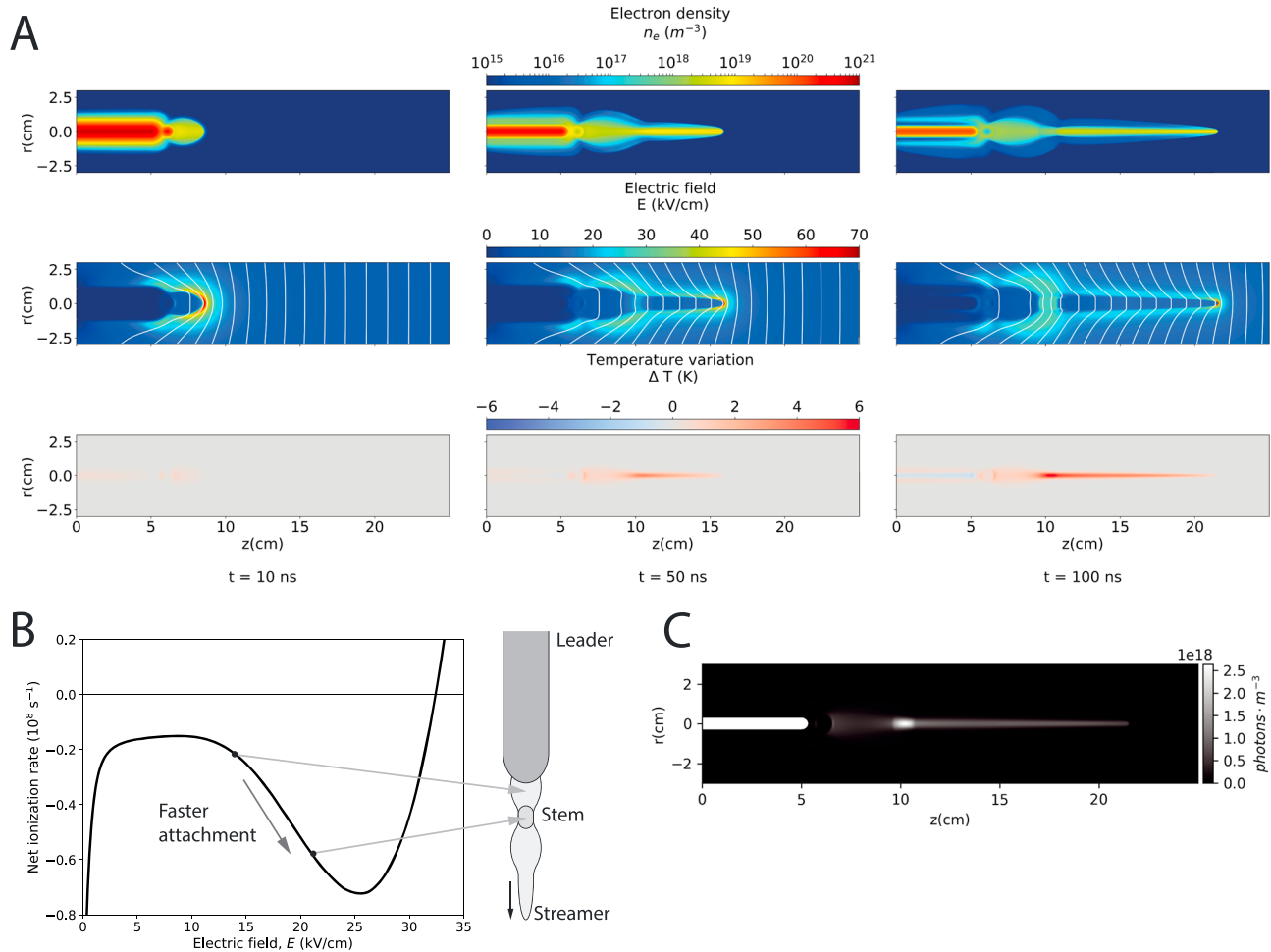
We have run two different simulations: one with photoionization ( $n_e^{\text{bg}} = 0$ ) following the method presented by Luque et al. (2007), and another with a preconditioning of the gas surrounding the leader due to preceding coronas by adding a constant background ionization level  $n_e^{\text{bg}} = 10^{15} \text{ m}^{-3}$ . In both cases, we observed similar formation of a space stem but the simulation with photoionization exhibited an oscillation of the electric field at the streamer head that we attribute to a numerical artifact due to insufficient resolution for the smallest length scales involved in photoionization (Wormeester et al., 2010; Zhelezniak et al., 1982). Henceforth, we limit ourselves to the simulation without photoionization. To check that this does not affect our key results we used another numerical code at our disposal (PESTO, described by Luque, 2017) that includes photoionization but does not account for gas heating or long-term chemistry. Using PESTO, we run simulations with a numerical resolution of 6  $\mu\text{m}$  that produced results similar to those described below.

The embedding gas is a mixture of 79%  $\text{N}_2$  and 21%  $\text{O}_2$ . Initially, the gas pressure is 1 atm and the mechanical energy is 0. The ambient temperature is 300 K, and the temperature of the leader follows the same distribution as  $n_e^{\text{leader}}$  with a peak value of 2700 K. Note that our model does not include high-temperature chemistry for the leader: In our simulation, the role of leader is merely to provide the electrostatic environment for the streamer propagation. Finally, the simulation is driven by an external electric field pointing toward the leader with magnitude  $|E_0| = 10 \text{ kV/cm} + (20 \text{ kV} \cdot \text{cm}^{-1} \cdot \mu\text{s}^{-1})t$ , where  $t$  is the simulation time.

With these conditions, we simulated the inception and propagation of a streamer emerging from the leader tip. Our total simulation time was limited to about 100 ns at which point the streamer leaves the simulation domain. As we see below, this time is enough to see the formation of the space stem but too short to observe the full streamer-to-leader transition.

### 3. Results

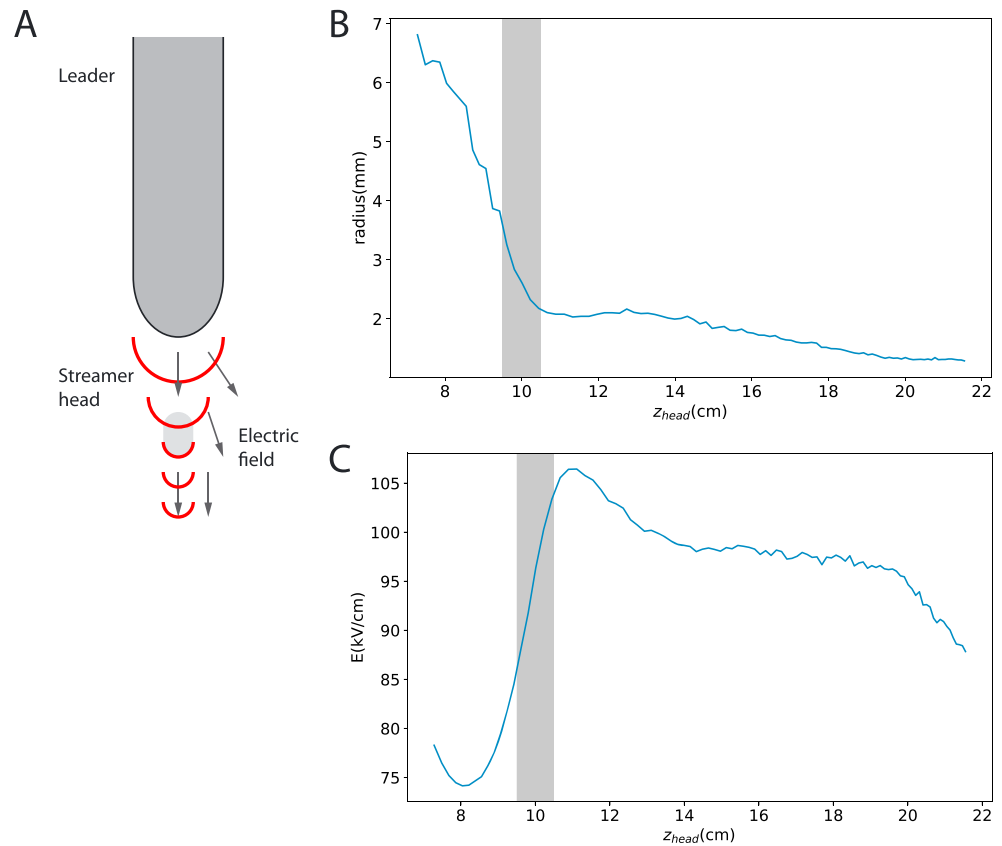
Figure 1A summarizes our simulation. As the streamer emerges from the leader, it goes through a narrowing phase where the conductance per unit length decreases. The charge transport through the streamer channel tends to homogenize the electric current flowing across the streamer channel, which implies a higher electric field in the narrow section. As sketched in Figure 1B, where we plot the effective ionization rate of air, this enhanced field triggers an attachment instability (Luque et al., 2016): The higher field increases the rate of associative electron attachment, decreasing further the conductance per unit length and increasing



**Figure 1.** As a streamer propagates out of a leader tip it creates a segment of reduced conductivity that evolves into a space stem. Panel A summarizes the evolution of the streamer in terms of the electron density (top), electric field (middle), and temperature (bottom). The electric field row includes equipotential lines with constant spacing 12.5, 13.5, and 14.5 kV (from left to right). The streamer leaves in its wake a segment of lower conductance per unit length that evolves into a space stem due to the attachment instability process sketched in panel B: a higher electric field accelerates the depletion of electrons, which in turns enhances the electric field. Finally, in panel C we show that our simulation reproduces the features of a space stem by plotting light emitted in the second positive system of the nitrogen molecule during the full simulation. We have masked (white region) leader emissions to focus on the space stem.

the field. This process enhances the electric field inside the narrow section of the channel until it saturates at an electric field where the net ionization curve slopes upward, between 25 and 30 kV/cm. A necessary condition for this process is that the electric field inside the streamer channel steps above the minimum of the effective attachment rate, around 10 kV/cm (see Figure 1B). The emergence of space stems is thus favored in streamers with high internal electric fields.

To check that the narrow segment with an enhanced electric field reproduces the observed features of a space stem, we computed the spatial distribution of light emissions. We included in our model the electron impact excitation of nitrogen molecules to the  $N_2(B^3\Pi_g)$  and  $N_2(C^3\Pi_u)$  electronic states, which are responsible respectively of the first and second positive systems of  $N_2$  (see the supporting information (Alghamdi et al., 2011; Balay et al., 2016b, 2016a; Capitelli et al., 2000; Clawpack Development Team, 2017; Hagelaar & Pitchford, 2005; LeVeque, 2002; Nijdam et al., 2014) for further details on the chemistry used to describe light emissions). We found that in our conditions the emissions of light are dominated by the second positive system and Figure 1C shows these emissions integrated over the 100 ns of simulation. There, we notice a bright spot embedded in a dim channel, clearly reminiscent of images in high-speed recordings of leader progression (Biagi et al., 2014; Gamerota et al., 2014; Hill et al., 2011). Based on this resemblance, we will henceforth use the name *stem* for this bright nucleus within the channel.



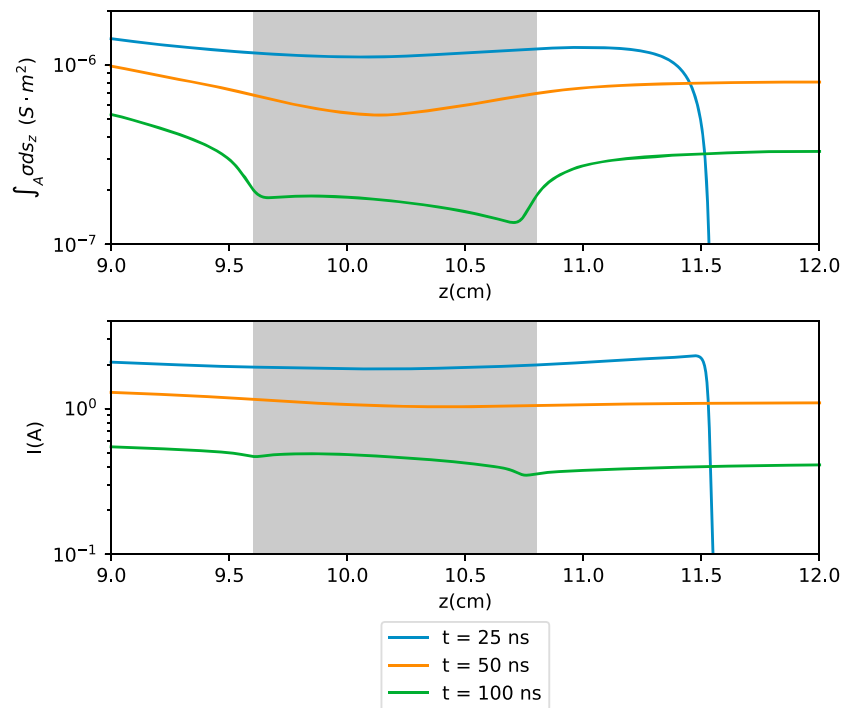
**Figure 2.** The space stem emerges due to the narrowing of the streamer channel. As sketched in panel A, when the streamer is still close to the leader tip, it is widened by the diverging electric field lines around the curved leader tip; as it distances itself from the leader, the streamer is driven by a more homogeneous electric field and becomes narrower. This is shown in panel B, where we plot the streamer radius as a function of time. The radius is defined here as the radius of curvature on the central axis of the surface defined by the maximum of the electric in the  $z$  direction around the head. The reduction of the radius leads to higher peak electric fields (panel C) and the resulting total channel conductance per unit length exhibits a minimum that afterward evolves into the space stem as described in Figure 1.

Let us now analyze the gas heating produced by the discharge. This is represented in the bottom row of Figure 1A, where we show the temperature variation relative to the initial conditions. The air in the stem heats up about 6 K in 100 ns. However, in our simulation, the electron density decreases both in the stem and in the surrounding channel with a timescale close to 100 ns. This is consistent with previous models and experiments that investigated the effect of the repetition rate in streamer discharges (Nijdam et al., 2014), and therefore, it is unlikely that this electron depletion is due to shortcomings of our model. In our context, it implies that the heating ratio diminishes: We do not expect a much higher temperature even if, by increasing our domain size, we extended our simulation time.

### 3.1. Formation of the Space Stem

Our key result is that the attachment instability is responsible for locally warmer regions ahead of a leader. A number of processes may reduce the channel conductance per unit length and trigger the instability, among them a jittering of the leader potential during the streamer propagation or preexisting conductivity or gas-density perturbations along the streamer path (Luque & Gordillo-Vázquez, 2011; Luque et al., 2016). Neither of these processes was included in our simulations and nevertheless the space stem formed spontaneously, which suggests that isolated stems are robust features of leader propagation.

In our simulation, the stem results from a narrowing of the channel. Note that the narrowing of negative streamers ahead of a leader or a pointed electrode has been observed by Kochkin et al. (2014) and by Kostinskiy et al. (2018). As we show in Figure 2, the streamer head is initially wide because it is affected by the divergence of electric field lines emerging from the leader's curved tip. As this divergence decreases away from the leader tip, the streamer head shrinks. The narrowing of the streamer channel enhances more



**Figure 3.** The upper panel shows the conductance per unit length around the space stem (gray area) at 25, 50, and 100 ns. As the streamer propagates away from the leader tip (25-ns curve), the channel undergoes a narrowing until the conductance per unit length reaches a minimum (space stem). Right after, the channel starts to be able to compensate this narrowing with an increase of the electron density produced by a higher electric field and then the conductance per unit length rises. The two remaining curves show latter states of the conductance at the space stem, where the electron depletion is clear after attachment instability effects. The lower panel supports the idea that the low conductance in the space stem is countered by a high electric field to achieve an homogeneous intensity along the channel.

strongly the electric field at the tip, increasing the degree of ionization left in the streamer head's wake. The total conductance per unit length of the channel scales approximately as  $R^2 n_e$ , where  $R$  is the channel radius and  $n_e$  the electron density: Initially, the significant decrease of the radius dominates and the conductance per unit length diminishes; afterward, the increase of  $n_e$  due to a higher field at the tip overcomes the narrowing and the conductance per unit length increases again. The resulting minimum is the origin of the space stem as we show in the upper panel of Figure 3. In the same figure (lower panel) and as we stated before, despite the noticeable variation of the conductance per unit length, the intensity is homogeneous across any section of the channel, including the space stem.

Let us now discuss the observed asymmetry between positive and negative leaders. Stepping is more prominent and readily observable in negative leaders but there are now clear observations (Kostinskiy et al., 2018) that under conditions of high relative humidity, positive leaders also experience stepped progression although space stems have never been observed in positive leaders. Our results provide a natural explanation for this asymmetry: The attachment instability is triggered by elevated electric fields inside a streamer channel and due to stronger ionization in positive streamers, these fields are higher in negative streamers (Luque et al., 2008) for the same external field. Besides, positive streamers are initiated more easily (Liu et al., 2012), so they are launched from the leader tip at a lower potential and thus a lower driving electric field than negative streamers. To check this explanation, we run simulations of positive streamers under driving electric fields of 10 and 7 kV/cm; there, the attachment instability was triggered only in regions of the channel very close to the leader tip, supporting the idea that steps in positive leaders exist, but they are so small that isolated space stems cannot be observed.

#### 4. Discussion and Conclusions

Our simulations show that the attachment instability explains the features of space stems ahead of propagating leaders. However, at around 100 ns, the overall conductivity of a streamer channel decays, stalling

the increase in temperature. Our results thus stress the role in maintaining the corona played by poorly understood processes such as the inception of counterpropagating streamers (Kochkin et al., 2016; Luque et al., 2016) or the propagation of successive ionization waves along preexisting channels (Babich et al., 2015; Nijdam et al., 2014; Phelps, 1974; Rison et al., 2016). Previous models (da Silva & Pasko, 2013; Popov, 2003) missed the relevance of these processes because they were not self-consistent and set a constant current intensity in the channel. In these models, a reduction of the electron density is immediately counteracted by an increase in the applied electric field so electrons are never significantly depleted. However, no physical mechanism with such an effect has been described in the literature.

As we have already shown, a single streamer discharge is unable to dissipate enough power to transit into a leader. Nonetheless, the relatively poor conductivity of a streamer corona together with a variable potential at the leader tip imply that there is often a significant electric field within the corona. This field triggers either new streamer bursts, as observed by Kochkin et al. (2014) or ionization waves retracing previous streamers, as proposed by Babich et al. (2015). It is also responsible for counterstreamers seeded by charges in existing stems. Remarkably, all of these mechanisms have been linked to X-ray emissions from long sparks (Babich et al., 2015; Babich & Bochkov, 2017; Ihaddadene & Celestin, 2015; Köhn et al., 2017; Kochkin et al., 2015; Luque, 2017; Østgaard et al., 2016), and these X-rays are in turn linked to leader stepping (Dwyer et al., 2005).

To check that these mechanisms may indeed explain the streamer-to-leader transition within the currently established observational constraints, we have developed a simplified model of a leader corona that we describe in the supporting information. The model shows that ionization waves increasing the electron density a factor of 10 and repeating every 100 ns would lead to a significant increase of the temperature of the channel. But the main outcome is that a small difference in initial electron density in the stem leads to large differences in the heating rate of this segment compared to the rest of the corona.

An important simplification of our model is the assumption that a space stem can form within a single streamer channel and that streamer branching, even if present, is not an essential ingredient in the process. We base this assumption in two key observations: (1) space stems are generally observed as bright segments within longer, dimmer channels (Biagi et al., 2010; Hill et al., 2011) and (2) in laboratory images negative streamer coronas contain thick, almost-straight channels with extensions of up to 1 m (Kochkin et al., 2014; Kostinskiy et al., 2018). Although these channels are surrounded by smaller streamers, there is no reason to believe that these short bifurcations play an essential role in the dynamics of the main channel. Interestingly, this is not the case for positive coronas (Kochkin et al., 2012; Kostinskiy et al., 2018), which may be yet another reason for the polarity asymmetry in leader propagation.

Our results explain the formation of brighter and warmer inhomogeneities ahead of a negative leader channel. This is the first stage in the streamer-to-leader transition in a stepped leader. The subsequent evolution of the space stem is still not understood: Namely, we do not know the mechanism that maintains the corona conductivity long enough to reach thousands of degrees. A full understanding of lightning progression and associated phenomena such as the emission of X-rays will only result from the successful investigation of this mechanism.

#### Acknowledgments

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