# Contributing Factors to the Long Persistence of the Lightning Channel Plasma

C. L. da Silva[1], S. D. Salazar[1], R. G. Sonnenfeld[1], and H. E. Edens[1]

[1]*Department of Physics and Langmuir Laboratory, New Mexico Institute of Mining and Technology, Socorro, NM, 87801, USA, Email:* caitano.dasilva@nmt.edu

**Abstract:** The lightning channel can persist for 10s of milliseconds in the atmosphere in the absence of any significant (or detectable) current, maintaining a favorable pathway to the ground for subsequent ionization waves known as dart leaders. In this work, we introduce a physical model that can capture the evolution of the lightning channel's conductivity in long time scales, which indicates that the key factors contributing to their long persistence are: small residual currents and negative-ion chemistry.

**Keywords:** lightning, plasma, negative differential resistance, attachment

## 1. Introduction

The term recoil leader is used to describe an ionization wave that retraces a preexisting lightning channel [1]. After the first return stroke in a negative cloud-to-ground lightning flash, tens of recoil leaders may take place. Some of them make their way to ground, and in this case they are referred to as dart leaders. The terminology dart leader has been suggested for being descriptive of their fast and continuous propagation, with speeds of the order of $10^6$ m/s. This is in contrast to the lightning negative stepped leader, which propagates at a one-order-of-magnitude lower speed and in a stepwise manner. Dart leaders create subsequent returns strokes. Approximately 80% of flashes that lower negative charge contain more than one stroke, usually three to five. The typical interstroke interval is of the order of 50 ms. What makes few recoil leaders create dart leaders and subsequent return strokes? Why are they only observed travelling back through the remnants of positively-charged channels? It remains unknown [1].

To invoke a specific example, we refer to a rocket-triggered lightning flash recorded at the Langmuir Laboratory field facility in central New Mexico, U.S., during the Summer of 2010 [2,3]. This lightning flash produced 11 return strokes, as detected by the U.S. National Lightning Detection Network. The average interstroke interval was 30 ms. The flash started with positive lightning leaders departing from the tip of the rocket and moving upwards into the cloud base. A series of recoil leaders were observed to propagate through the developing channels in a retrograde manner towards the ground. Looking at the luminosity from a cross sectional area of the channel, as recorded with a 6,400-frames/second high-speed camera, these leaders were seen as a series of luminous pulses [2]. Roughly a total of 50 pulses were seen in the main channel connecting the discharge to the ground. The average time interval between two luminous pulses was 10 ms, but values ranged up to 60 ms.

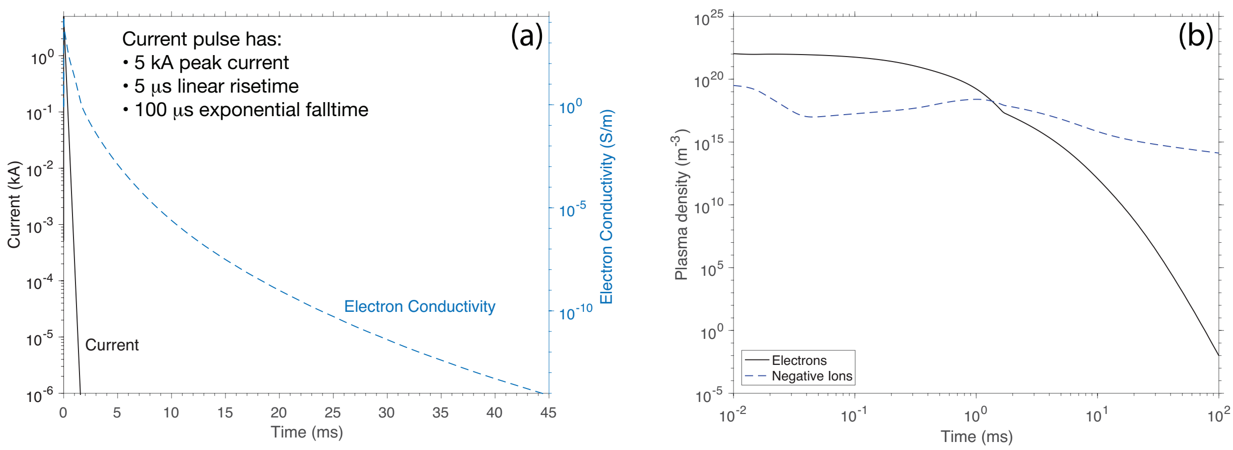


Fig. 1. Simulation of a return-stroke-like current pulse passing through a lightning channel. (a) Temporal variation of current and electronic conductivity. (c) Number density of electrons and negative ions. The temporal dependence of the current pulse is characterized by a linear rise and an exponential fall, with parameters listed in panel (a).

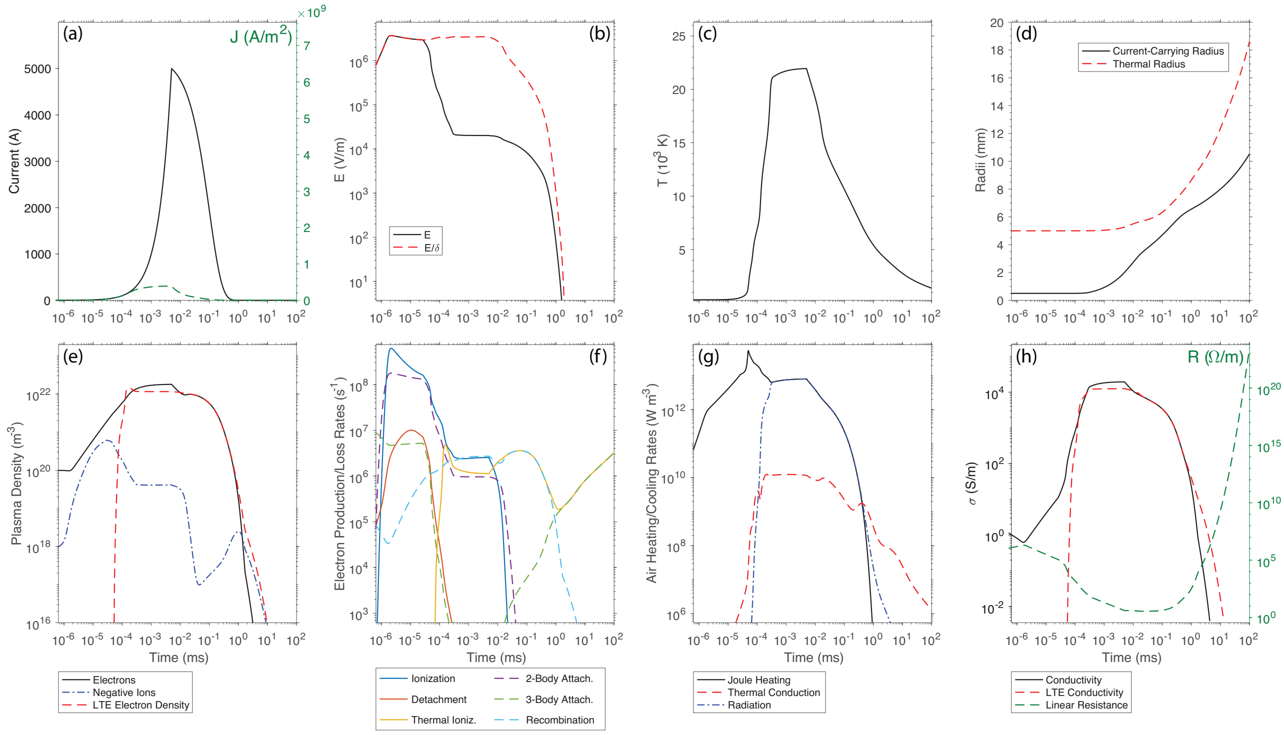


Fig. 2. Detailed simulation results corresponding to the same current pulse shown in Figure 1. The eight panels show: (a) current and current density, (b) electric field and reduced electric field, (c) temperature, (d) electrodynamic and thermal radii, (e) plasma density, (f) rates of electron production and loss, (g) air heating and cooling rates, and (h) conductivity and linear resistance.

This discussion and the aforementioned references illustrate that the lightning channel conductivity persists for a time scale of the order of 10s of ms. During this time maintaining a favorable pathway for current waves to be transferred to the ground. Spectroscopical measurements and computational simulations of the lightning plasma properties [4] indicate that the channel cools off in time scales shorter than 1 ms, and the electron conductivity dissipates even faster. In this paper, we use a computational model of the lightning channel's nonlinear plasma resistance to discuss which factors contribute to its long persistence.

## 2. Model Formulation

In this work we describe the minimal model to qualitatively capture the consequences of the plasma nature of lightning leader channels. The key simplification here is to solve a set of zero-dimensional equations that describe the temporal dynamics of the plasma in a given cross section of the channel. Starting from a general 3-D problem, we can progressively reduce the dimensionality of the system. It can be assumed that the lightning channel is a long cylinder. The axial symmetry indicates that the plasma conditions do not depend on the polar coordinate. Now the 2-D long cylinder geometry can be reduced to a 1-D radial one, by noting that the variation along the channel have significantly larger length scales than in the radial one. Thus, the change in plasma properties are driven by the conduction current created by the overall lightning tree dynamics and merely imposed in that channel section. Finally, the 1-D radial dynamics can be averaged over to produce self-similar solutions of average channel properties. The model consists of 6 equations: Ohm's law, energy balance of neutrals, two population balance equations (electrons and negative ions; positive ion density comes from charge neutrality), and two radial expansion equations (one for the electrodynamic, or current-carrying, radius, and another for the thermal radius). The energy balance equation accounts for input energy from Joule heating and output from thermal conduction and radiative cooling. The plasma population balance accounts for electron-impact ionization, two- and three-body attachment, detachment, thermal (associative) ionization, and recombination. The electrodynamic and thermal radii are assumed to expand according to ambipolar diffusion and thermal conduction, respectively. In the presentation, we will discuss in detail the model construction, emphasizing the key approximations, rate coefficients used, and methods of validation against previous simulation works and against well-established laboratory arc discharge results.

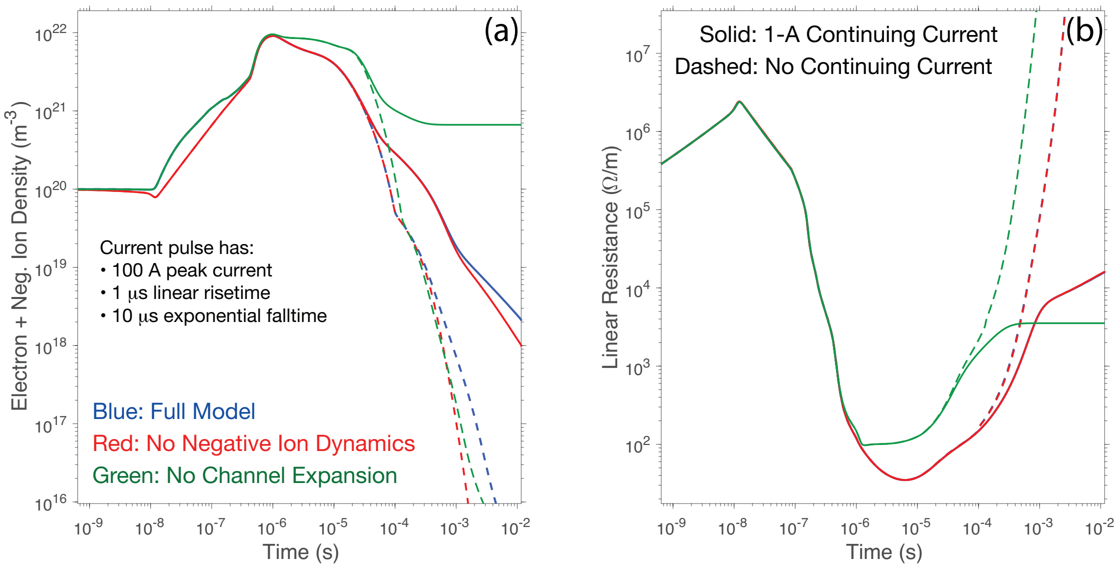


Fig. 3. Simulation results of a current pulse passing through a cross section of the lightning channel. (a) Electron plus negative-ion density, which is equal to the total positive-ion density by charge conservation. (b) Resistance per unit length. The blue curves show results from the complete model, the red-curve simulations have suppressed negative ion chemistry, and the green curves have suppressed channel expansion. Solid lines have a residual constant current of 1 A, while dashed lines have no continuing current at all. The current pulse waveform parameters are listed in panel (a).

## 3. Results

Figure 1 shows simulation results of a 5-kA current pulse passing through a cross section of the lightning channel. The plasma initial conditions are set to make the channel initially resemble a single streamer [5] (and are used throughout this manuscript). The current risetime and falltime are listed in Figure 1a. It can be seen that the electronic conductivity lasts for a time scale much longer than the 100 microseconds exponential fall time of the current pulse (Figure 1a). For reference the ambient conductivity of air at sea level is $10^{-14}$-$10^{-13}$ S/m. In the simulation it takes about 45 ms for the electron conductivity to reduce to this value range. Nonetheless, in comparison to the return stroke channel conductivity of $10^4$ S/m, the conductivity is very low in the 10-ms time scale (10 orders of magnitude lower). Figure 1b shows that although the electron density drops very quickly, a reservoir of negative ions is formed (read $O^-$ and $O_2^-$), which lasts much longer and is potentially the root cause of the long persistence of lightning channels.

The full story behind the simulation results shown in Figure 1 is given in Figure 2, where the temporal dynamics of all (important) quantities calculated by the model is presented. We would like to point out the three different regimes existing in Figure 2f. Initially, in the air heating stage (time <0.1 ms), the plasma density is dictated by a balance between ionization and two body attachment. Secondly, in the hot channel stage, it is determined by a balance between thermal ionization and recombination. Finally, in the cooling stage (>1 ms), recombination is surpassed by three-body attachment. To better understand Figure 2f, please refer to the temperature profile in Figure 2c.

Figure 3 shows sample simulation of a more moderate current pulse passing through the lightning channel (the peak current is 100 A). The figure shows 6 different simulation cases. Blue curves show the full-model calculations. Red curves demonstrate the effects of suppressing negative ion chemistry. While, green curves show the effects of suppressing channel expansion. Solid versus dashed lines show simulations with and without a small residual current, respectively. For all cases without continuing current (dashed lines), it can be seen that the plasma density decreases rapidly in the ms time scale (Figure 3a). However, the linear resistance is higher if channel expansion is suppressed (3b). It can also be seen form Figure 3a, that the negative ion dynamics has an important contribution towards the total plasma density. It can also be seen that the inclusion of a small residual current of 1 A can substantially change the simulation results (see the solid curves). The unrealistic case of suppressed radial dynamics provides appreciably different results with higher plasma density and lower linear resistance in the ms time range. In both cases, with and without continuing current, the negative ion density is comparable or larger than the electron density in the ms time range, similarly to the results shown in Figure 1b.

## 4. Conclusions

The simulation results shown in this paper indicate that the lightning channel conductivity can persist up to tens of milliseconds, in agreement with observations. Maintaining a favorable path for current to flow to the ground, in comparison to virgin air. However, the electronic conductivity in the millisecond time range is many orders of magnitude lower than peak values in the return stroke channel, and thus is likely not the sole reason for the long interstroke intervals observed in cloud-to-ground lightning flashes (which reuse the same channel). The simulations also show that negative-ion chemistry plays an important role in the plasma population balance at the millisecond time scale. The results reveal a substantial negative ion population that may serve as source of electrons for subsequent current pulses, since they would easily be freed by detachment.

## 5. Acknowledgments

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## 6. References

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