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# Modeling the Evolution of Halos and Sprites

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**ABSTRACT:** We present simulations of halos and sprites, resolving the many length scales of the underlying problem. We account for air density changing with altitude, and model the parent lightning stroke in electrostatic approximation. We discuss how the emergence properties of sprite streamers depend on the temporal evolution of the lightning current and on the initial electron density distribution. We present electrodynamic mechanisms for the formation of glowing trails and beads in sprite streamers, and we provide an argument why the breakdown electric field is frequently observed in current carrying discharges like halos and sprites. We also present new results on noise triggered streamer branching in full three dimensions.

## 1. INTRODUCTION

Sprite discharges bear many similarities with streamer discharges at standard temperature and pressure. This similarity can be quantified; and it can be explored for laboratory experiments on sprites, as discussed by Dubrovin, Nijdam and others at this conference. On the other hand, sprite emergence is determined by the specific conditions of lower ionosphere and mesosphere. We here focus on simulation results of Alejandro Luque on formation and evolution of halo’s and sprites.

## 2. HOW SPRITE FORMATION DEPENDS ON LIGHTNING PULSE SHAPE

Sprite streamers initially propagate downwards from the ionosphere, sometimes out of a visible halo. The large spatial extension of the ionosphere together with the fine inner structure of the sprite discharge pose a challenge to simulations, but they can be treated with adaptive mesh refinement. For a recent review of the numerical techniques, we refer to Luque and Ebert [2011a]. We take into account that air density changes with altitude, and model the parent lightning stroke in electrostatic approximation. In [Luque, Ebert, 2009], we succeeded in simulating a halo with subsequent formation of a sprite channel. We discussed 1. the evolution of the screening-ionization wave in the ionosphere, that sometimes is seen as a halo, 2. its sharpening and destabilization into a sprite streamer, and 3. velocity and diameter of the sprite streamer.

In the supplementary material of that paper, we already discussed that the sprite formation sensitively depends on the initial electron density. In that particular example, a local change of the electron density by only 20% shifts the sprite formation altitude by 4 km. This observation documents that sprite formation actually can be used as a measure for the local electron density, if supported by good modeling and good measurements of the electrodynamics.

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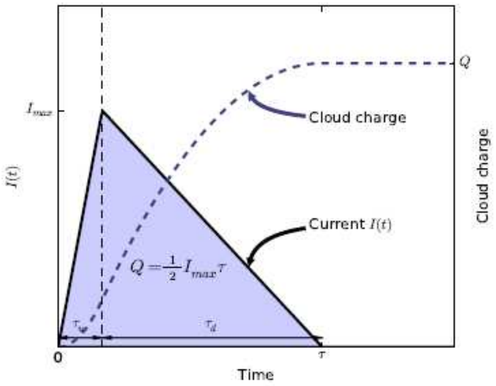
Here we present new results on how sprite formation depends on the charge moment change and on the temporal evolution of the parent lightning stroke. All other model parameters are the same as in [Luque and Ebert, 2009]. The lightning stroke is characterized by its current evolution I(t) as plotted in Fig. 1. First, the lightning current increases linearly during a time $\tau_u$ up to the value $I_{max}$, then it decreases linearly during a time $\tau_d$; the total duration of the lightning stroke is $\tau = \tau_u + \tau_d$, the transferred charge during the stroke is $Q = I_{max}\,\tau/2$. The electric field high above a lightning stroke is well approximated by a dipole field created by cloud charge and conducting ground; it is characterized by the charge moment change, LQ, where L is the altitude of the cloud charge. The charge moment change together with the times $\tau_u$ and $\tau_d$ characterize the stroke. E.g., the current waveform measured by Hu et al. [2007] in their Fig. 4, after removing the sprite current, is reasonably approximated by LQ = 750 C km, $\tau$ = 3 ms and $\tau_u$ =0.5 ms.



$\tau$

Fig. 1: Parametrization of sprite producing lightning discharges.

Our simulations show that for LQ = 750 C km and $\tau$ = 3 ms, the distribution into rise and fall time $\tau_u$ and $\tau_d$ has little influence on the results. Therefore we take $\tau_u = \tau_d = \tau/2$ in the sequel.

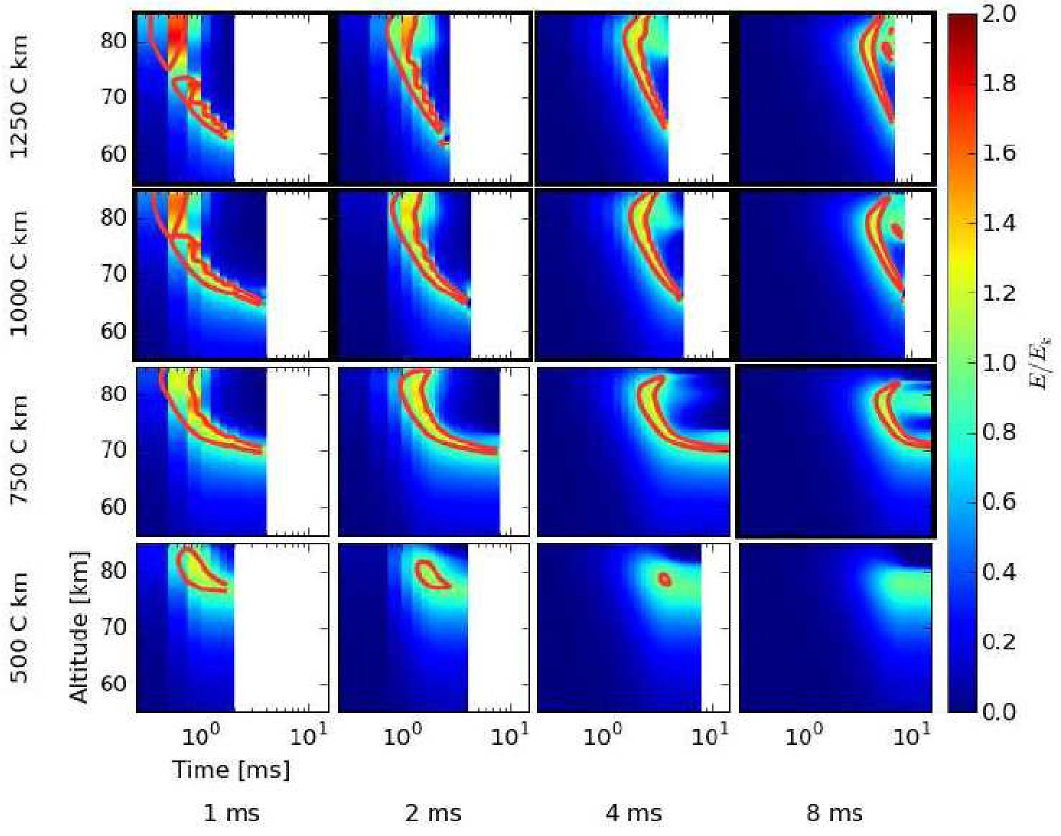


Fig. 2: Evolution of the reduced field $E/E_k$ along the vertical axis through the cloud charge for various values of the stroke duration $\tau$ (horizontal axis) and charge moment change LQ (vertical axis). The red line corresponds to $E=E_k$. The black frames indicate that a sprite streamer emerges in this simulation.

Fig. 2 shows panels with the evolution of the reduced electric field on the symmetry axis of the simulation; the panels are ordered in a matrix form where each row has the same charge moment change LQ and each column the same duration of the lightning stroke. The black frames indicate cases where a sprite emerged. This is the case for all lightning durations, for LQ = 1000 and 1250 C km, and for none for 500 C km. However, for 750 C km, a sprite emerges only if the lightning stroke takes as long as 8 ms to transfer this charge, but not for the shorter strokes of 4 ms or shorter. Inspecting the simulation results, the reason is probably, that electron attachment has not yet sufficiently proceeded below the halo. Therefore the local electron density is still too high for a sprite streamer to propagate.

However, there is a caveat: Including the associative detachment of electrons from $O^-$ changes significantly the picture for long time intervals so the ionization/attachment model used here is valid only for times shorter than about 10 ms, which is just about the range of Fig. 2.

## 3. GLOWING TRAILS AND BEADS IN THE SPRITE STREAMER

After the glowing streamer head has created a conducting channel, luminous structures can be seen like a glowing trail or a persistent bead structure. For both, there is an electrodynamic explanation.

A luminous trail of a sprite streamer can be caused by a secondary ionization wave in the streamer channel. This phenomenon is due to the rising charge content of the streamer head, either when the streamer is propagating downwards into regions with higher air density [Luque and Ebert, 2010], or when the streamer is expanding and accelerating in a sufficiently high background field at constant air density [Liu, 2010]. The increasing charge content requires electric current to flow into the streamer head. A continuous current in a medium with a locally varying conductivity requires a locally varying electric field. But furthermore, the conductivity can also increase or decrease due to ionization or attachment reactions in the local field. The same mechanism probably underlies the so-called secondary streamers in laboratory and technical discharges.

According to Luque and Gordillo-Vazquez [2011], sprite beads can be the remainders of spots of initially enhanced electron density. When a streamer runs into a region of enhanced electron density, the ionization front gets smeared out, the local field is less enhanced, and the ionization rate is lower. Therefore after the passage of the ionization front, the electron density is lower than in the rest of the channel. Current continuity requires a higher local field in this region of lower conductivity, and space charge effects; and a local ionization reaction with light emission sets in that can explain glowing beads.

## 4. WHY THE BREAK-DOWN FIELD IS OBSERVED IN HALOS AND SPRITES

There are a number of indications in simulations as well as in measurements that the electric field inside a halo [Luque and Ebert, 2009] or in the glowing trail of a sprite is close to the breakdown value [Liu 2010; Luque and Ebert, 2010]. We will argue that the break-down field is a dynamic attractor of a current-carrying discharge, i.e., many discharges will approach that state after a sufficiently long time.

## 5. STREAMER BRANCHING IS ACCELERATED BY PARTICLE DENSITY FLUCTUATIONS

We recently presented three dimensional simulations of the onset of branching of positive streamers in air at standard temperature and pressure. In [Luque and Ebert, 2011a] results of the standard fluid approximation were given, while in [Luque and Ebert, 2011b] the effect of electron density fluctuations due to their discrete particle nature is included. We find that these fluctuations somewhat accelerate the branching process, and our simulation results roughly agree with experimental measurements. When air density is lower (as in sprites), the fluctuations decrease.

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