Lightning inception from ice particles and extensive air showers

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The electric fields in thunderstorms can exceed the breakdown value locally near ice particles present in thunderclouds. But are fields high enough and the regions large enough to initiate a streamer discharge? And where would a sufficient density of free electrons come from to start the discharge in the humid air that rapidly binds electrons in water-clusters?

1. Introduction

We for the first time quantitatively demonstrated that a positive streamer discharge, as a precursor to lightning, can develop from an ice particle under thundercloud conditions at 5.5 km altitude which imply that the electric field is 0.1-0.6 of the breakdown value and almost all free electrons in humid air are bound in water clusters. We propose the first quantitative model in which the thundercloud electric field is locally enhanced due to the dielectric properties of ice. We have calculated that in the vicinity of an ice particle a density of at least 100 cm^{-3} of free electrons occurs every second due to extensive air showers created by high energy cosmic particles. We show that although the enhanced field can be larger than the classical breakdown field these two factors do not guarantee streamer formation from an ice particle with nonlinear dielectric permittivity. Based on the fluid description of positive streamer evolution in a cylindrical geometry we point out other important mechanisms that are essential for streamer formation, and in particular the importance of the nonlinear dielectric function of ice. With the full account of all the relevant mechanisms we quantitatively predict positive streamer inception.

2. Modeling

We study positive streamer inception in a cylindrical geometry from a ice particle under thundercloud conditions in artificial air at 0.5 bar and 243 K. Initially, the air is preionized with free electrons and negative ions with the ionization density of 100 cm^{-3}, homogeneously spread over the domain except for the interior of the ice particle. The net charge is initially zero. The length of the simulation domain is 8.5 cm and its diameter is 4 cm (see the scheme in FIg. 1). The system is exposed to a stationary electric field of E_{bg} = 2.7 kV/cm (for a scheme, see the upper left figure 2), which is 0.15E_k (E_k is the classical breakdown field) and is in accordance with balloon measurements [1].

An ice particle is modeled as a dielectric with frequency dependent dielectric function of ice $\varepsilon(\omega)$. The dielectric properties of ice particles play an important role in field enhancement. Remarkably, the dielectric permittivity of ice at constant electric fields is around 90, but when the field changes on the millisecond time scale or even faster, the dielectric permittivity of ice drops to around 3 [2]. Typically, a streamer discharge develops within tens of nanoseconds. On such a short time interval the polarization of ice changes very little. This results in a discharge feeling effectively lower field enhancement than it would if an ice particle had a dielectric function were constant and equal to 90.

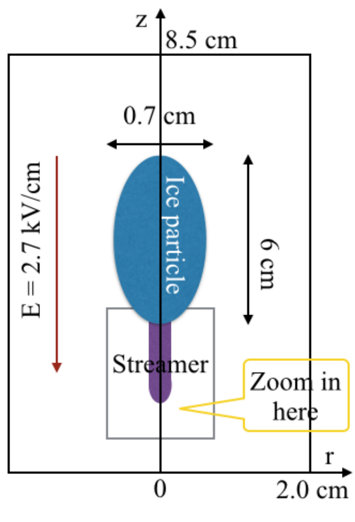

Fig. 1: Scheme of the simulated domain.

The ice particle is parameterized as a prolate ellipsoid of revolution. With cylindrical symmetry imposed, an ellipsoid can be characterized by its length and its radius of curvature at the tip. These two parameters play the most important role in electric field enhancement around the tip of the ice particle. The shape of a dielectric in direction perpendicular to the electric field does not contribute much to the field enhancement. The fact that ice particles in thunderclouds can enhance the electric field due to polarization effects is not new [3,4,6]. For the efficient field enhancement, not only the sharpness of the ice particles plays a role. The area of enhanced field should also be large enough to allow enough multiplications before an electron attaches to the ice particle. This is usually described by the Meek number. If $\alpha(E)$ is the effective Townsend coefficient calculated by BOLSIG+ [5], the Meek number is $M = \int \alpha \mathrm{d}z$, where the integration is performed along the z-axis to the point where the electric field falls below the classical breakdown value. It can be proven analytically that $M = \gamma l F(R/l, E_{bg}/E_k)$, where $M/\gamma l$ (at 0.5 bar and 243 K, $\gamma = N/N_0$) is plotted in Fig. 2. For a given E_{bg}, the function F reaches its maximum at a certain ratio R/l (sharpness of the ice particle). This is shown with a dashed curve. The parameters used in our simulations are indicated with a diamond sign, which correspond to the Meek number of 18. They are not far away from the optimal parameters. Getting closer to the optimal parameters would be computationally more demanding, because the model requires finer grids at the tip of sharper ice particles. The solid curve in Fig. 2 presents the curve from experiments in [6], whose authors measure the minimal electric field necessary to produce a positive streamer from an ice particle with

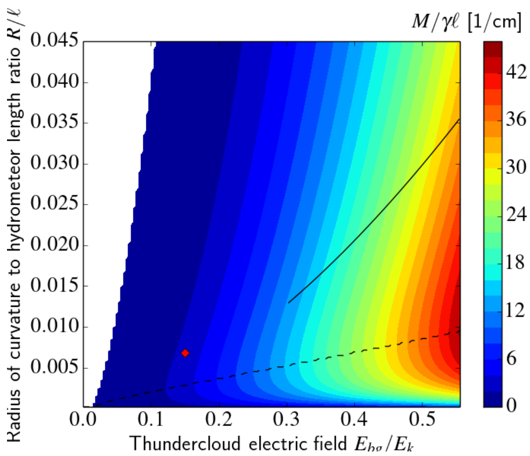

Fig. 2: The Meek number per ice particle length at 0.5 bar and 243 K. The curve indicates the optimal R/l ratio for a given thundercloud field. The diamond sign indicates the simulated parameters. The solid curve shows the measurements in [6].

given length and fixed radius of curvature at the tip. Even though, the shape of their ice particles are somewhat different from ours, they enhance the background field similarly to ellipsoidal ice particles with the same length and radius of curvature at the tip. The authors of [6] considered only small ice particles, therefore they measured only relatively high fields. From Fig. 2 it is clear that smaller ice particles with the same aspect ratio are less capable of initiating discharge. Therefore, at lower electric fields, larger ice particles with larger aspect ratio are better candidates to initiate a discharge.

2. Role of extensive air showers

We investigate the interaction of extensive air showers (created by high energy cosmic particles) with the ice particles in a thunderstorm. The extensive air showers are modeled in full detail with CORSIKA [7]. As extensive air showers occur with a frequency that strongly depends on their size, the proper stochastics are derived to cope with the large number of random variables in the system such as occurrence, primary energy, and altitude of first interaction and inclination. These variables are important factors that determine the extremes of the high energy particle flux passing through an ice particle at a given altitude.

3. References

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