Negative streamers branch like coral reefs

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We present the study of the onset of branching in the fully 3-D case, analytically and numerically, based on an interface dynamics streamer model and show that growth and splitting of streamers takes place as the result of stabilizing forces due to diffusion which tend to dampen out any disturbances, combined with destabilizing forces due to electrostatic repulsion of the net charge that concentrates at the boundary of the ionized gas region.

1. Introduction

Although a electric discharge is a very complex phenomena, with radiation and chemistry processes involved, the description of its initial stage is simpler. A single free electron travelling in a strong, uniform electric field ionizes the gaseous molecules around it, generating more electrons and starting a chain reaction of ionization. The ionized gas creates its own electric field, which speeds up the reaction, and a streamer is born. The streamers of ionized gas have an inevitable tendency to break up at their tips, creating the familiar tree-like pattern.

2. Branching in 3D

The work we present during the talk represents the culmination of long standing efforts to understand the formation of patterns in electric discharges. These patterns result from multiple bifurcations leading to the characteristic tree-like shape that can be observed in lightning or sparks. Therefore, connecting the basic mechanisms for the production of weakly ionized plasmas (the ionization produced by free electrons accelerated by an electric field and electron diffusion) with the macroscopic observation of a tree-like pattern is a fundamental physical problem not only in the area of plasma physics but also from a general scientific viewpoint. Early efforts [1] were able to identify a minimal streamer model with which, after numerical simulations under the hypothesis of cylindrical symmetry, an instability was observed. Later on [2], the dispersion relation for planar fronts was computed and the existence of an instability leading to the development of fingers was found. Due to the enormous difficulty for performing full numerical simulations of the minimal streamer model, simplified descriptions have been developed in the last years (see [3] for a recent review) but, in our opinion, they fail to provide a fully coherent connection with the original model by introducing various ad hoc assumptions and are restricted to 2D. A fully consistent description, deduced in the asymptotic limit of small electron diffusion (or large electric field) from the minimal model, was introduced by us in [4] (see also the extended version in [5]) but still lacked the 3D ingredient and we could not produce examples of multiple branching. This has been achieved in the present work, therefore closing positively the original problem: The fundamental effects at molecular level, impact ionization and electron diffusion, are sufficient to explain the formation of tree-like patterns in electric discharges.

3. References

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