Towards a fluid model for the streamer-to-leader transition in lightning channels

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One of the still unknown phenomena involved in electric discharges is the streamer-to-leader transition. Here, as a first approach to investigate this transition, we present our recent steps modelling heating and gas expansion produced in streamer discharges, coupled to electromagnetic and air plasma chemistry. So far, we have applied this model to the mechanism of air heating and pressure perturbations present in sprite discharges, without losing sight of our final aim, i.e., to disentangle the streamer-to-leader transition in lightning channels by testing whether attachment instability leads to heating of air to a temperature high enough develop space stems.

Electric discharges are a very common phenomenon on Earth's atmosphere. However some of their features are still poorly understood. A sufficiently long electric discharge, such as a lightning channel, propagates along two phases. The first phase is known as "streamer phase" and consists in thin filaments of ionised air that advance due to a high electric field at their tip. The dominant process of ionisation is impact ionisation, involving electrons and the two major components in the air mass, which are nitrogen and oxygen. In the second phase called "leader phase", the electric current of the streamers has increased the air temperature highly enough so the thermal energy of the molecules present in the air is comparable to the ionisation potential of nitrogen and oxygen. The underlying mechanism whereby the streamer-to-leader transition occurs is not precisely known. High-speed observations show that in negative discharges, comprising 90% of cloud-to-ground lightning, this transition is not smooth but rather mediated by the formation of a "space leader", that is, an isolated hot segment within the streamer region. This space leader is connected to the main leader in a sudden jump and therefore one speaks of a "stepped leader". However, the origin of the space leader is so far unknown.

Here we present recent steps in the modelling of the streamer-to-leader transition, which requires coupling fluid mechanics, electromagnetism and air plasma chemistry. We discuss our work towards a model that solves Euler's equations (3 dimensions reduced to 2 by virtue of symmetry) coupled to electron drift using high-resolution finite volume methods for hyperbolic systems [1] implemented in the software package CLAWPACK. The drift of electrons is determined by a self-consistent electric field, which we obtain by solving Poisson's equation by means of off-the-shelf solvers. Our model also includes a selection of chemical reactions that have a relevant effect on the electron density in air, such as impact ionisation, attachment and detachment.

Besides the streamer-to-leader transition, our model can also be applied to the mechanism of air heating and pressure perturbations caused by sprite discharges in the upper atmosphere. We present here preliminary simulation results on this topic.

Our final aim is however to test the hypothesis that leader stepping results from an attachment instability that creates low-conductivity, high-field regions in a streamer corona, as recently discussed for sprites in [2]. With our detailed model for gas heating and expansion we will investigate whether the attachment instability leads to heating of air to a temperature high enough to develop space stems. A positive answer to this question would elucidate the physical mechanism of leader stepping.

[1] R.J. LeVeque. Finite Volume Methods for Hyperbolic Problems. Cambridge Texts in Applied Mathematics. Cambridge University Press, 2002.

[2] A. Luque, H. C. Stenbaek-Nielsen, M. G. McHarg, and R.K. Haaland. Srpite beads and glows arising from the attachment instability in streamer channels. J. Geophys. Res. (Space Phys), 121, 2016.