Mesospheric electric breakdown and delayed sprite ignition caused by associative electron detachment

A. Luque [1], F. J. Gordillo-Vázquez [1*]

[1] Instituto de Astrofísica de Andalucía (IAA – CSIC), Glorieta de la Astronomía s/n, 18008 Granada, Spain
(*) vazquez@iaa.es

The electric discharge of a thundercloud in the troposphere is often accompanied by upper-atmospheric electric discharges such as sprites or halos. Present models assume that the net change in the density of free electrons during these discharges is determined by the competition between electron impact ionization and electron dissociative attachment to oxygen molecules, and that balance is achieved in an electric field termed the conventional breakdown field. According to these models, free electrons are removed in an electric field whose strength is below the breakdown field, but multiply in a field that is stronger than the breakdown field. Here we use a simple model of the electric response of the mesosphere at timescales of tens of milliseconds to show that in the upper atmosphere, electrons multiply also under field strengths significantly below that of the conventional breakdown field because, at low pressure, electron associative detachment from atomic oxygen ions counteracts the effect of dissociative attachment [1].

Introduction

First predicted in 1924 by Wilson [2], electric discharges above thunderstorms were unambiguously observed in 1989. Although the mechanism of dielectric breakdown in these discharges was initially controversial, theoretical models based on conventional breakdown by Pasko and coauthors [3] and Raizer *et al.* [4] compared succesfully with the observations [5]. Conventional breakdown has been studied in laboratories since the 1920s and informs our understanding of ground-level electric discharges, including Lightning. Conventional breakdown assumes the existence of a critical or breakdown field E_k, proportional to the air density, with E_k/N = 120 Td, where N is the air number density and the Townsend (Td) is the conventional unit for reduced electric fields E/N (1 Td = 10^{-17} Vcm^2). In dry air at standard temperature and pressure (STP), $E_k \approx 3.2 \times 10^4$ Vcm^{-1}. Our purpose in this contribution is to show that at low pressures (high altitude in the atmosphere) one cannot define a fixed breakdown field and the conventional breakdown model has to be modified. We base this assertion on calculations from cross-sections and reaction rates accepted in the present literature and in recent observations of the inception times and altitudes of long-delayed sprites [6].

Conventional breakdown

In the conventional breakdown model [3] the dominant source of free electrons is electron impact ionization of N_2 and O_2:

$$e + N_2 \rightarrow 2e + N_2^+ \qquad (1a)$$
$$e + O_2 \rightarrow 2e + O_2^+ \qquad (1b)$$

whereas electron losses come from dissociative attachment to molecular oxygen:

$$e + O_2 \rightarrow O + O^- \qquad (2)$$

The reaction rates of ((1a), (1b)) and (2) depend strongly on the electron energy distribution and hence are usually written as functions of the local reduced electric field E/N. The threshold field E_k is the field that balances the weighted rates of ((1a), (1b)) and (2). Electrons attached to a heavy species (such as O^-) are unable to ionize further molecules; therefore conventional breakdown models usually ignore O^- ions created by the attachment reaction (2), which is considered merely as a loss process for the electrons. But in air O^- ions are short-lived. On one hand, they are transformed into much more stable ozone ions by a three-body clusterization reaction:

$$O^- + O_2 + M \rightarrow O_3^- + M \qquad (3)$$

with a kinetic reaction rate $k \approx 10^{-30}$ cm^{6}s^{-1} and where M represents any species (usually an abundant one such as N_2 or O_2). On the other hand, electrons can be released by associative detachment to N_2:

$$O^- + N_2 \rightarrow N_2O + e \qquad (4)$$

Note that the stabilizing reactions (3) are three-body reactions and therefore their importance relative to detachment (4) diminishes as the air density decreases. The conventional breakdown assumption that electrons are inert after they form O- is valid only at high pressures, close to 1 atm, where three-body stabilization of O- dominates. The relevance of associative detachment was known in the low-pressure plasma community already in the 1970s, when studies of low-pressure electric discharges [7], [8] showed that there is no apparent electron attachment in air below ~ 0.1 atm (corresponding to altitudes above ~15 km in the atmosphere), but it has apparently escaped the attention of researchers working on atmospheric electricity. Only very recently, we pointed out the relevance of associative detachment in sprites using a full chemical kinetic model [9], [10].

Breakdown initiated by associate detachment

We propose to extend the conventional breakdown model into a model that also includes the associative detachment reaction (4) [1]. We call this the CB + AD model. To analyse how associative detachment modifies the conventional breakdown model, we have assumed that the air density is low enough to neglect reaction (3); this is certainly the case in the upper atmosphere, where sprites and halos occur. We have modeled the local net growth rate of electrons by combining the reaction rates of (1), (2) and (4):

$$\frac{1}{n_e}\frac{dn_e}{dt} = \nu_{ion}(E/N) - \nu_{attach}(E/N) + \eta\nu_{detach}(E/N) \qquad (5)$$

where n_e is the electron density, $\eta = n_{O^-}/n_e$ is the ratio of O^- ions to electrons, $\nu_{ion} = [N_2]k$ (1a) + $[O_2]k$ (1b) is the ionization rate, $\nu_{attach} = [O_2]k$ (2) is the attachment rate and $\nu_{detach} = [N_2]k$ (4) is the detachment rate. Here k represents the kinetic rate of the indicated reaction. Note that, because we consider only two-body reactions, the left-hand side of (5) is proportional to the air density.

Figure 1 shows the areas in (η, *E/N*)-space where there is a net increase or decrease of free electrons according to (5). These areas do not depend on the air density. We also selected three values of η (indicated by a,b and c) to show, in the inset, the left-hand side of (5) at 75 km altitude as a function of *E/N*. As the O^- density is increased relative to the density of free electrons, the range of reduced electric fields where electron attachment dominates is reduced. When η is higher than about 2.6 the release of electrons dominates and electric breakdown occurs for any value of the reduced electric field [1]. We will see that this value is reached within tens of milliseconds in upper atmospheric discharges.

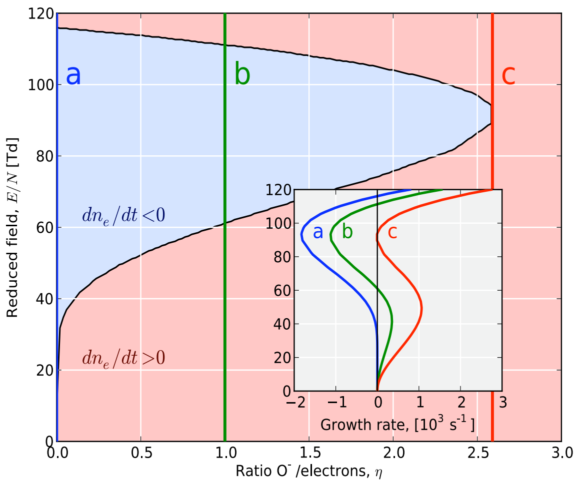

Figure 1 At low pressures the net growth rate of the electron density depends not only on the reduced electric field but also on the ratio of O^- ions to free electrons. Here we plot the regions where electrons multiply (red) or are depleted (blue). The inset shows the net growth rate of electrons at 75 km as function of the electric field for three different values of $\eta = n_{O^-}/n_e$. Note that, for η larger than about 2.6, the electron density increases for any value of the reduced field *E/N*.

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