The relevance of electron associative detachment in upper-atmospheric electricity

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In models of upper-atmospheric electrical phenomena it is often assumed that the most relevant reactions are electron-impact ionization and electron associative attachment to oxygen. Many models are limited to these two reactions and assume that the electron density grows if the electric field is above a breakdown threshold, where ionization dominates, and decays otherwise. Here we show that for time-scales above the tens of milliseconds at mesospheric altitudes, the above assumptions break down and one must also take account of electron associative detachment from oxygen negative ions, which drastically changes the electric response of the upper mesosphere and lower ionosphere. We illustrate the relevance of associative detachment with a simple model for delayed sprite inception. This model shows a significant increase of the electron density (i.e. electric breakdown) at the observed time of delayed-sprite inception.

1. Electric breakdown from associative dettachment

Electric breakdown is defined by an exponential multiplication of free electrons under the action of an electric field. Researchers in upper-atmospheric electricity have traditionally used *conventional breakdown* (CB) models [1–3] where the dominant source of free electrons is impact ionization:

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

whereas electron losses come from dissociative attachment to oxygen:

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

The reaction rates of (1) 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 breakdown field E_k is the field that balances the weighted rates of (1) and (2).

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 [1]

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

with a kinetic reaction rate $k \approx 10^{-30}\,\mathrm{cm^6/s}$ 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 (AD) to N_2:

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

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 CB 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 AD was known in the low pressure plasma community already in the 1970s, when studies of low pressure electric discharges [4, 5] showed that there is no apparent electron attachment in air below $\sim$ 0.1 atm (corresponding to about $\sim$ 15 km altitude in the atmosphere) but it has apparently escaped the attention of atmospheric electricity researchers. Only very recently, we pointed out the relevance of AD in sprites [6–8].

2. Delayed sprite inception

The relevance of associative detachment is exemplified in the inception of "delayed sprites." In most cases the delay between a cloud-to-ground return stroke and its associated sprite is shorter than 10 ms, with 2-3 ms being typical. However, there are consistent observations of sprites emerging with significantly longer delays, up to about 150 ms [9–11]. Remote magnetic field measurements by Cummer and his group [10–12] have linked the inception of delayed sprites to a long-lasting cloud-to-ground, positive continuing current with an intensity of a few kiloamperes (assuming a $\sim$ 10 km altitude of the discharging cloud).

Recently, Gamerota *et al.* [13] used triangulation and high-speed video imaging to determine inception times and altitudes for delayed sprites. They also estimated the lightning source current moment waveform from broadband magnetic field measurements [14]. In order to investigate the inception of

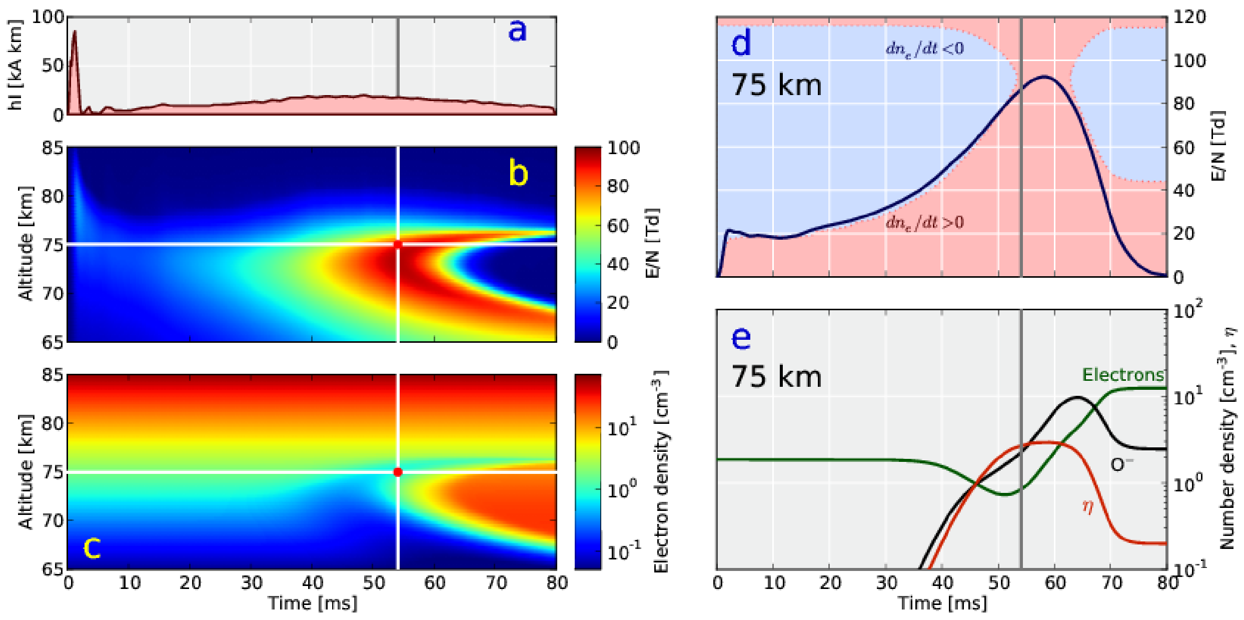

Fig. 1: **Associative detachment from O^- ions explains the delayed inception of a sprite**. Current moment waveform **(a)** of a thunderstroke on 3 July 2008, 08:55:11 UT obtained by Gamerota *et al.* [13] and simulated E/N **(b)** and electron density **(c)**. The red spot and the straight lines mark the observed inception time and altitude. At the inception altitude (75 km) we show E/N **(d)** and the densities of electrons and O^- with their ratio η **(e)**.

delayed sprites, we implemented a simplified, zero-dimensional model that couples chemical kinetics to dielectric relaxation; its results suggest that associative detachment can explain the observations by Gamerota *et al.* of the time and altitude of inception of delayed sprites [8].

Figure 1 shows the results of a simulation with a current moment obtained by Gamerota and coauthors [13]. The resulting reduced electric field is at all times and everywhere below the classical breakdown field $E_k/N \approx 120\,\mathrm{Td}$ but there is a large multiplication of electrons visible from about $t \approx 50\,\mathrm{ms}$ at about 75 km altitude. The reason is the increase in the density of O^- ions due to electron dissociative attachment (2); once this density is high enough, electrons are released through AD and breakdown occurs. This process takes some tens of milliseconds.

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