On the Breakdown Electric Field of the Mesosphere

A. Schou Jacobsen, T. Neubert, O. Chanrion

National Space Institute, Technical University of Denmark, 2100 Copenhagen Ø, Denmark

We discuss the concept of a breakdown electric field, E_k, in the mesosphere. It is often assumed that E_k has a fixed value in the atmosphere, given by the condition that the ionization rate equals the attachment rate of electrons to neutral atoms and molecules. Here we consider the effect of ion chemistry by including the dominant detachment process of the mesosphere. When exposed to a constant electric field, the electron and negative ion densities continue to grow exponentially in time for all field magnitudes. A necessary (but not sufficient) condition for an electron avalanche to grow into a discharge is that the electron density growth rate exceeds the electric field relaxation time of the partially ionized mesosphere. This condition is satisfied below 80 km for $E/E_k=1$, falling to below 65 km for $E/E_k=0.5$. The decrease of the threshold electric field at lower altitudes relaxes the requirements on the electric field magnitude needed for sprites to develop.

1. Introduction

Sprites are electric discharges in the mesosphere normally powered by the quasi-electrostatic field following a positive cloud-to-ground lightning discharge in a cloud below. The threshold electric field for gas breakdown is traditionally thought of as the field value where the loss of free electrons by attachment to neutral species balances the creation of new electrons due to ionization. In a recent paper [1] it was shown that in the mesosphere, the detachment process of electrons from negative ions is also important and can explain the observations of delayed sprites, triggered at fields below the classical threshold field.

In this paper we derive the analytical expressions of the temporal evolution of the electron and ion number densities under some simplifying assumptions and determine their growth rate and asymptotic behavior as functions of electric field magnitude and altitude. We finally discuss the consequences of detachment for discharges of the mesosphere and the atmosphere in general.

2. Theory

Following [1,2] we assume that the dominant reactions of the mesosphere are attachment of free electrons to atomic oxygen through $O_2 + e^- + 3.7\text{eV} \rightarrow O + O^-$ and detachment through $O^- + N_2 \rightarrow N_2O + e^-$. The effect of these reactions is that a reservoir of electrons is built up as negative ions.

The equations for the negative ions, n_i, and electrons, n_e, of the mesosphere, exposed to an electric field, E, are:

$$\partial n_e/\partial t = (\gamma_i(E) - \gamma_a(E))n_e + \gamma_d(E)n_i \qquad (1)$$

$$\partial n_i/\partial t = \gamma_a(E)n_e - \gamma_d(E)n_i \qquad (2)$$

where E drives attachment, detachment, and ionization with the rates γ_a, γ_d, and γ_i according to [2]. In the equations we have ignored the gradients in the currents that would be established in a real mesosphere. This allows an analytical parameter study of the influence of electric fields and densities corresponding to an environment with no spatial gradients.

We use the initial conditions $n_i(t=0) = 0$, $n_e(t=0) = n_e^o\exp(z/z^o)$, where, z is the altitude, z^o = 4.3 km and n_e^o = 0.08 m^{-3}. The neutral number density of molecular nitrogen is found from the MSISE-90 model. We further assume that the atmosphere initially consists of 80% N_2 and 20% O_2.

3. Results

If exposed to a constant electric field, the ratio $\eta=n_i/n_e$ approaches an asymptotic value where both densities increase exponentially with time, even for fields below the classical threshold electric field, E_k ~120 Td. Figure 1 shows the time constant, τ_g, of the electron density growth rate as a function of altitude and normalized electric field, E/E_k. The time constant decreases with increasing electric field and with decreasing altitude.

The significance of the growth can be evaluated by considering the plasma electric field relaxation time, τ_σ, which is the characteristic time it takes for the free charges in the atmosphere to screen out an imposed electric field. The time constant is:

$$\tau_\sigma = \varepsilon_o/\sigma \quad (3)$$

where σ is the electric conductivity and ε_o the permittivity of free space.

Figure 1 shows for comparison τ_σ corresponding to the initial electron density n_e^o. The green region is where $\tau_g < \tau_\sigma$, which is a necessary (but not sufficient) condition for a discharge to be generated. The condition is satisfied for altitudes below 80 km for E/E_k=1, consistent with past work, decreasing to altitudes below 65 km for E/E_k=0.5. This decrease of the threshold electric field relaxes the requirements on the electric field magnitude needed for sprites to develop. Below ~50 km, other ion chemical reactions take over than those considered here.

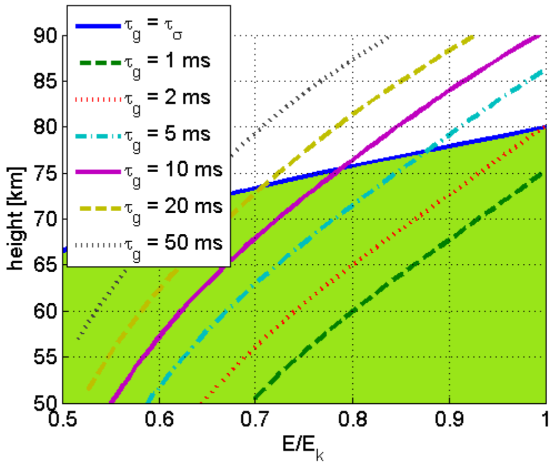

Figure 1. The time constant of the electron density growth rate as a function of electric field and altitude. The colored region is where $\tau_g < \tau_\sigma$.

4. Discussion

The results can be generalized to other atmospheric systems that can be described by one effective attachment rate, detachment rate and ionization rate.

5. References

[1] A. Luque, and F. J. Gordillo-Vázquez (2012), Mesospheric electric breakdown and delayed sprite ignition caused by electron detachment. *Nature Geoscience*, *5*, doi:10.1038/NGEO1314.

[2] Neubert, T., O. Chanrion, E. Arnone, F. Zanotti, S. Cummer, J. Li, M. Füllekrug, S. Soula, and O. Van der Velde, The Properties of a Giant Jet Reflected in a Simultaneous Sprite, *J. Geophys. Res.*, *116*, A12329, doi:10.1029/2011JA016928, 2011.