ELECTRON TRANSPORT AND PROPAGATION OF STREAMERS IN THE ATMOSPHERE OF TITAN

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Abstract. Electron transport coefficients in the atmosphere of Titan are calculated from the solution of the non-conservative Boltzmann equation. Calculations are performed in various N_2-CH_4 mixtures and values of the mean energy, drift velocity, diffusion tensor and rate coefficients are reported here. These transport coefficients are then used as an input in fluid equation based models to investigate the propagation of streamers with the aim of investigating the possibility for the occurrence of lightning in Titan's atmosphere.

1. INTRODUCTION

There are numerous evidences of lightning activity in the atmospheres of the planets of our solar system. In particular, since the era of the Voyager missions in 1980s the possibility of lightning on Titan has been investigated by theoretical and experimental studies of its complex atmospheric chemistry. Titan is the largest satellite of Saturn and its atmosphere is mostly composed of N_2 and CH_4 and trace amounts of H_2 and HCN. The presence of C_2H_2, C_2H_4 and C_2H_6 and other hydrocarbons and nitriles has also been detected. The modeling studies of Titan's atmospheric chemistry suggested the existence of lightning since the amount of HCN and C_2H_2 in the atmosphere cannot be explained as the results of photo-chemistry or charged-particle chemistry [1]. Additionally, another promising factor for the development of lightning is the presence of convective CH_4 clouds over the South pole of Titan as observed by the Cassini spacecraft [2]. However, no electromagnetic signatures of lightning were detected with either Voyager or Cassini flybys of Titan. This suggests that lightning is most probably a rare event with a very low rate of occurrence. On the other hand, it is well known that Titan's upper atmosphere and ionosphere have a rather high conductivity due to very efficient ionization by galactic cosmic rays. As a consequence, the electromagnetic waves produced by lightning cannot penetrate Titan's upper atmosphere and ionosphere and hence their signatures were not detected by Voyager and Cassini. So, the question arises: does the lightning on Titan exist or not?

2. METHODS OF CALCULATION

In order to resolve the issue surrounding the existence of lightning on Titan, we have recently undertaken a program to understand the possible occurrence of lightning in the atmosphere of Titan. In the present work we approach this by investigating electron transport in various N_2-CH_4 mixtures in the presence of electric fields by solving the non-conservative Boltzmann equation and by applying Monte Carlo simulations [3]. We are focused how the transport coefficients are influenced by the amount of CH_4 in the mixture and by the temperature of the background gas. Calculations have also been performed in time-dependent electric and magnetic fields aiming to understand the response of electrons towards the electromagnetic pulses generated by lightning discharges.

As a second step of our analysis, we apply the calculated transport coefficients as input for fluid equation based models with the aim of investigating the transition from an electron avalanche into a streamer. Streamers are thin channels of low-temperature plasma whose dynamics is entirely controlled by the highly-localized non-linear regions of space charge and steep gradients of the electron number density. They occur in the initial stages of lightning and in sprite discharges above thunderclouds. We employ the classical fluid model which combines the equation of continuity for electrons and ions as well as the drift-diffusion approximation for electrons, and Poisson's equation for the calculation of the space charge electric field [4]. These fluid equations are closed by the local-field approximation in which all transport properties are assumed to be functions of the local electric field. In addition, we use our recently developed fluid model in which the electron collisional term in the continuity equation is expanded in terms of gradients of the electron number density. The expansion coefficients are calculated in Monte Carlo simulations. Both fluid models are numerically implemented in a 1.5-dimensional setup.

Finally, in addition to fluid models, we also use a 2.5D PIC/MC (Particle in cell/Monte Carlo) model with a cylindrical symmetry to simulate the development of both positive and negative streamers in the ambient electric field [5]. In order to simulate positive streamers, the photoionization model initially developed by Zheleznyak and co-workers [6] is implemented into the code.

3. RESULTS AND DISCUSSION

On Titan clouds form between 20 and 35 km altitude with the pressure varying between approximately 0.1 bar and 0.6 bar, the ambient temperature varying between 70 and 75 K and the level of CH_4 varying between 1.6% and 2.0%. In our calculations we choose 1.6% of CH_4 while the pressure and temperature are set to 0.3 bar and 75 K, respectively. We cover a range of the reduced electric field E/N between 10^{-3} and 10^3 Td where 1 $\text{Td} = 1 \times 10^{-21}$ Vm^2.

In figure 1 we show the variation of the mean energy (a), drift velocity (b) and rate coefficients for ionization and attachment (c) for a mixture with 1.6% CH_4 as a function of E/N. We observe that the mean energy is a monotonically increasing function of E/N. The properties of the cross sections are reflected in the E/N-profile of the mean energy. From the profile of the drift velocity, we see that there are no signs of a negative differential conductivity effect (NDC), i.e., the drift velocity is a monotonically increasing function of E/N. In pure CH_4, however, the drift velocity exhibits a very strong NDC.

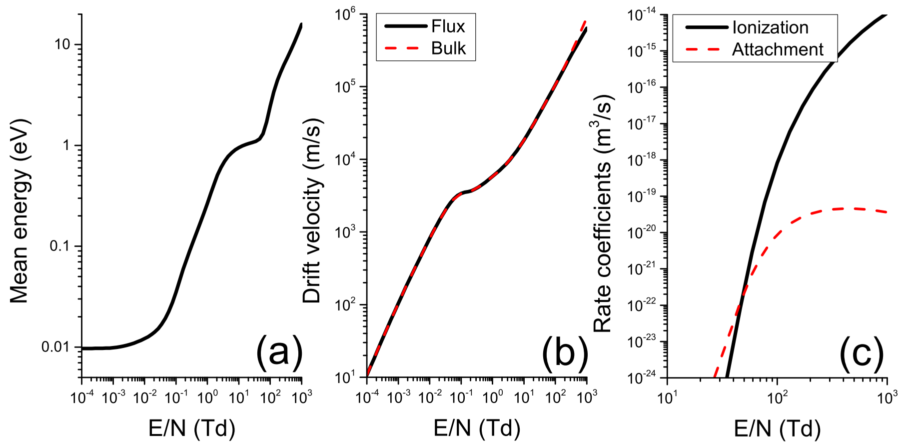

Figure 1. Variation of the mean energy (a), drift velocity (b) and rate coefficients for ionization and attachment with E/N.

Figure 2 displays the spatio-temporal evolution of the electron density and the electric field for different percentages of CH_4 when the reduced electric field E/N ahead of the front is fixed to 480 Td. The simulation is started with the same initial Gaussian-type distribution of electrons and positive ions reflecting the macroscopic plasma neutrality (panel a). In the early stage of evolution we see that the electron density grows due to electron impact ionization (panel b). The electrons drift in the direction opposite to the electric field while positive ions slowly drift in the opposite direction. The mobility of positive ions is much lower and as a consequence, the charge separation starts to distort the initial homogeneous electric field (panel c).

As the evolution continues, for mixtures with the higher concentrations of CH_4, the electric field in the ionized region gets almost completely screened, and further ionization processes cannot occur in this region (panel d). We observe that by adding CH_4 to N_2 the electron density and streamer velocity are increased. This can be expected, since the addition of CH_4 to N_2 increases the electron drift velocity and ionization rate.

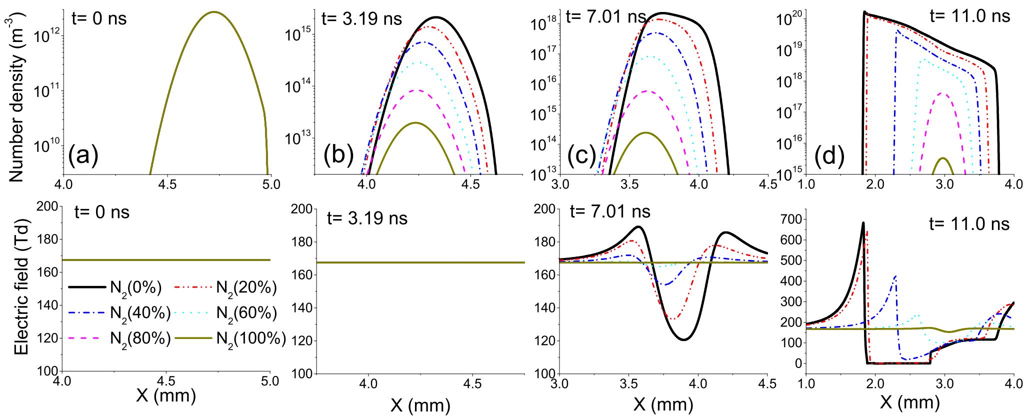

Figure 2. Evolution of the electron density (upper row) and the electric field (bottom row) in a negative planar ionization front for various N_2-CH_4 mixtures.

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