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The chemistry of daytime sprite streamers – a model study

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Abstract

The chemical processes in daytime sprite streamers in the altitude range of 30–54 km are investigated by means of a detailed ion-neutral chemistry model (without consideration of transport). The model results indicate that ozone perturbations due to daytime sprites streamers differ considerably from the ones of nighttime events. Due to liberation of atomic oxygen there is an initial increase of ozone. In terms of relative ozone change, this effect decreases with altitude. While for nighttime conditions, reactive nitrogen produced during the electric breakdown is converted into less reactive NO₂, in the sunlit atmosphere NO_x causes catalytic ozone destruction. As a consequence, there is significant ozone loss in sprite streamers in the daytime atmosphere, in particular at higher altitudes. At an altitude of 54 km, ozone in the streamer column has decreased by about 15 % fifteen minutes after the breakdown event.

1 Introduction

Sprites are transient luminous discharges in the mesosphere occurring above active thunderstorms. Since Franz et al. (1990) reported on the detection of such an event, numerous sprite observations have been made from aircraft (Sentman et al., 1995), from space (e.g. Boeck et al., 1995; Chen et al., 2008), and by ground-based instruments, see Neubert et al. (2008), and references therein. Almost all sprites are associated with positive cloud-to-ground (+CG) lightning discharges (Boccippio et al., 1995), and it is well established that sprites are triggered by the underlying lightning. The initiation of sprites can be explained by conventional air breakdown at mesospheric altitudes caused by lightning-driven electric fields, e.g. Pasko et al. (1995); Cho and Rycroft (1998).

There are different types of sprites, and they can be classified based on shape, size, and structure, e.g. Bór (2013). Generally, sprites consist of three regions. There is a diffuse upper part (sprite halo), a bright transition region, and a lower streamer

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region, e.g. Pasko et al. (1998); Pasko and Stenbaek-Nielsen (2002). However, halo and streamers are not observed in all sprite events. Their development depends on the parameters of the parent lightning events, e.g. Adachi et al. (2008). Streamers are self-sustaining plasma filaments. Once formed, they can propagate through an under-voltage regime, i.e. regions where the ambient electric field is significantly smaller than the breakdown electric field. Typically, sprite streamers are initiated at altitudes ~ 70–85 km, and propagate downwards for several kilometers (Moudry et al., 2003; Cummer et al., 2006; McHarg et al., 2007).

During day, the conductivity of the middle atmosphere is higher than at night, and larger electric fields are required to cause air breakdown (Stanley et al., 2000). As a result, only exceptionally large lighting events can trigger daytime sprites. Additionally, sprites occurring in the sunlit atmosphere might be difficult to observe by optical devices. There are only a few reports on daytime sprites. All of them have been detected by non-optical methods: Stanley et al. (2000) have discovered three daytime sprites by their signatures in the electromagnetic extremely low frequency band. Farges et al. (2005) have detected infrasound signals of three daytime sprites. Kumar et al. (2008) measured electromagnetic perturbations in the very low frequency regime during day, and tentatively related them to sprite or elve events. All of these events occurred within a few hours after sunrise, or a few hours before sunset.

It is well established that atmospheric discharges have chemical effects. In particular there is a formation of reactive nitrogen, and a liberation of atomic oxygen. Both of which eventually affect the ozone chemistry, e.g. Borisov et al. (1993). Chemical impacts of sprites gained some interest in recent years. There have been attempts to find sprite induced enhancements of nitrogen species in the middle atmosphere by exploiting satellite data (Rodger et al., 2008; Arnone et al., 2009). On the other hand, a number of model studies on the chemical impacts of sprites have been presented, e.g. Sentman et al. (2008a); Gordillo-Vázquez (2008); Hiraki et al. (2008); Enell et al. (2008).

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To the authors' best knowledge, until now there are only two publications touching the chemistry of daytime sprites. Hiraki et al. (2004) have modelled the production of $O(^1D)$ in nighttime and daytime sprite halos, and Evtushenko and Mareev (2011) simulated sprite events for nighttime as well as daytime conditions. Both of these studies dealt with the diffuse region of sprites but not with streamers which are thought to significantly contribute to the chemical impact of sprites.

The present work is devoted to the investigation of chemical effects in the streamer zone of a daytime sprite. For this purpose, an ion/neutral chemistry model has been set up. In order to realistically simulate daytime conditions, the model includes photo-reactions of charged and neutral species. The model is applied to atmospheric conditions similar to the daytime sprites detected by Stanley et al. (2000).

2 Sprite chemistry

The electric fields in sprites drive electron impact ionisation, dissociation and excitation of air molecules and atoms. Due to the large abundance of N_2 and O_2 , the main ionisation processes are:



where the reaction products can be in their ground states or in excited states. Free atoms in ground state and excited states result also from dissociative electron impact:



Additionally, collisions of electrons with N_2 , and O_2 produce electronically/vibrationally excited molecules. Furthermore, electric fields facilitate electron attachment. Of partic-

ular importance is the reaction



The released reactive species initiate rapid ion/neutral reactions. Due to the complexity of air plasma reactions, detailed models are required to assess the subsequent chemical effects of discharges in air, e.g. Kossyi et al. (1992). The chemistry of sprites has been simulated in some detail. Sentman et al. (2008a) used an elaborate plasma chemistry model of more than 80 positive, negative and uncharged species to investigate the impact of a single sprite streamer at 70 km. Later, Sentman and Stenbaek-Nielsen (2009) expanded the model by considering the weak electric fields in the trailing column of the sprite streamer. Gordillo-Vázquez (2008) used a full time-dependent kinetic model of more than 75 ions and neutral species to simulate in detail the effect of a sprite streamer at three different altitudes in the upper mesosphere. Hiraki et al. (2008) modelled the impact of a sprite streamer on the positive ion chemistry in the mesosphere. Enell et al. (2008) have studied chemical effects of sprites on neutral compounds, considering both positive and negative ion reactions.

All of the model studies just mentioned were carried out for nighttime conditions. For the intended simulation of daytime sprite streamers, the photo-reactions of ions and neutral species have to be taken into account.

3 Model description

An atmospheric ion/neutral chemistry model has been set up to simulate a daytime sprite event similar to the ones reported on by Stanley et al. (2000). For nighttime sprites it is known that the onset altitudes of streamers are in agreement with the calculated altitudes of conventional breakdown, e.g. Fernsler and Rowland (1996); Hu et al. (2007); Gamerota et al. (2011). The working hypothesis here is that the same applies to the considered daytime sprite, i.e. that streamers are initiated at the estimated conventional breakdown altitude of 54 km (Stanley et al., 2000). This is motivated by

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the following consideration. For all three events detected by Stanley et al. (2000) there was a time lag between the triggering +CG stroke and the sprite onset of more than 10 ms. Therefore, the dielectric relaxation time constant at 54 km cannot have been much smaller than 10 ms. On the other hand, the characteristic time for the development of a streamer is of the order 1 ms at 54 km (Pasko et al., 1998). Consequently, streamer formation is expected to have taken place at that altitude. The lower terminal altitude of the daytime sprites was estimated to be about 30 km (Stanley, 2000). Accordingly, the model is applied to the streamer zone in the altitude range 30–54 km. The perhaps existing sprite halo is not considered.

3.1 Streamer parametrisation

In general, the electric field at the streamer head is significantly higher than the ambient field. As a result, the chemical perturbations in a sprite streamer zone are mainly driven by the fields at the streamer tips, e.g. Sentman et al. (2008a). The effect of the weaker electric fields in the streamer columns are modest compared to the impact at the streamer head (Sentman and Stenbaek-Nielsen, 2009). As streamer dynamics is outside the scope of this paper, the streamer parameters have to be prescribed. The electric field at a point passed by the streamer head is modelled as a boxcar field pulse of amplitude E . Its value is based on the scaling relation given by Raizer et al. (1998):

$$E = 1.5 \times 10^5 \text{ V cm}^{-1} (N/N_0), \quad (1)$$

where N is the air number density at the considered height, and N_0 the corresponding value at the Earth's surface. The number density of electrons n_e produced in the streamer tip is given by (Raizer et al., 1998):

$$n_e = 10^{14} \text{ cm}^{-3} (N/N_0)^2. \quad (2)$$

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3.2 Electron impact

The model accounts for the electron impact reactions with N_2 and O_2 given in Table 1. The rate coefficients for the electron impact reactions can be expressed as functions of the reduced electric field E/N with E being the electric field strength, and N the air density. The reaction coefficients have been calculated with the Boltzmann solver BOLSIG+ (Hagelaar and Pitchford, 2005). Additionally, the associative electron detachment process $O^- + N_2 \rightarrow N_2O + e$ is considered using the reaction rate coefficient as a function of E/N given by Luque and Gordillo-Vázquez (2012). This approach is justified if the electron energy distribution function (EDF) is close to the steady-state EDF. Gordillo-Vázquez (2008) has demonstrated that the EDF relaxation time is indeed small compared to the typical pulse duration of a streamer tip. Therefore, using the steady-state electron impact rate coefficients for a given E/N is a suitable approach to model the processes in streamers.

3.3 Chemistry

In order to simulate the chemical effects of sprite streamers, a model of the relevant chemical processes has been set up. The considered 91 species are given in Table 2. The change in the concentration of a species $n_i(\text{cm}^{-3})$ with time is modelled as

$$\frac{dn_i}{dt} = P_i - l_i n_i \quad (3)$$

where $P_i(\text{cm}^{-3}\text{s}^{-1})$ is the production rate, and $l_i(\text{s}^{-1})$ is the loss rate coefficient of the i th species, respectively. Concentration changes due to transport processes are not considered. This is a similar approach as taken by Sentman et al. (2008a) and Gordillo-Vázquez (2008). It is valid for the early phase after the passage of a streamer head. Sentman et al. (2008a) estimated the characteristic timescale for diffusion in sprite streamers, and defined an upper limit of ~ 1000 s for sprite streamer simulations neglecting diffusion processes. Therefore, the model results presented in this paper

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are limited to 15 min after the passage of the streamer tip. Loss and production terms have been added to the model so that a chemical steady state is achieved if no electric breakdown takes place (in order to avoid a drift of the model due to the missing atmospheric transport processes).

The Eq. (3) constitutes a system of coupled ordinary differential equations. It is solved by means of the semi-implicit symmetric method (Ramaroson, 1989; Ramaroson et al., 1992). Electrons are known to rapidly thermalize in the streamer trailing columns (Sentman et al., 2008a). Accordingly, the ambient atmospheric temperature is used as the kinetic temperature of electrons and all other species behind the streamer tip. Thermodynamic effects such as collisional, chemical or radiative heating are not considered. This is the same approach as the one of Gordillo-Vázquez (2008); Sentman et al. (2008a).

The model accounts for electron impact processes (Table 1), photo-reactions discussed below, and ion/neutral reactions listed in the Supplement to this paper. Most of the reactions, and rate coefficients are taken from Kossyi et al. (1992); Kazil (2002); Gordillo-Vázquez (2008) and Sentman et al. (2008b).

The model is initialised with profiles of pressure, temperature, and trace-gas concentrations originating from a two-dimensional atmospheric chemistry and transport model (Winkler et al., 2009). The atmospheric background ionisation due to galactic cosmic rays is parametrized as in Lehtinen and Inan (2007).

A few remarks are in order concerning some of the modelled species. Following Kossyi et al. (1992) it is assumed that the species N_2O_2^+ formed in collisions of O_2^+ or O_4^+ with N_2 is the cluster ion $\text{O}_2^+(\text{N}_2)$. The isomerization barrier between $\text{O}_2^+(\text{N}_2)$ and $\text{NO}^+(\text{NO})$ is higher than the dissociation energies (Bowers et al., 1983). Therefore, it is assumed that collisional dissociation, and recombination of N_2O_2^+ leads to O_2 and N_2 . The species H_2O_2^- is assumed to be the ion-dipole complex $\text{O}^-(\text{H}_2\text{O})$ and not the slightly less stable $\text{OH}^-(\text{OH})$, see e.g. Deyerl et al. (2001). Similarly, H_2O_3^- and H_2O_4^- are treated as $\text{O}_2^-(\text{H}_2\text{O})$ and $\text{O}_3^-(\text{H}_2\text{O})$, respectively.

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For the calculation of photo-dissociation and photoelectron detachment rates, the radiative transfer module of an atmospheric chemistry model (Winkler et al., 2009) is used. It originates from the model of Chipperfield (1999), and is based on the scheme of Lary and Pyle (1991). The calculation of photolysis rates of neutral compounds was already part of the model (C-177 to C-190 in the reaction scheme in the Supplement to this paper). Photo-destruction and photoelectron detachment of ions were added to the model. The rates for these processes are calculated using the actinic flux provided by the radiative transfer module, and cross section data from the literature. The considered ion-photo reactions are listed in Table 3. For the negative chlorine clusters $\text{Cl}^-(\text{H}_2\text{O})$, $\text{Cl}^-(\text{CO}_2)$, and $\text{Cl}^-(\text{HCl})$ no photo-dissociation cross section could be found in the literature. The same applies to $\text{O}^-(\text{H}_2\text{O})$. Motivated by Ho et al. (1990), the photo-dissociation rates of these species are set equal to the rate of $\text{NO}_3^-(\text{H}_2\text{O})$ calculated with the cross section data of Smith et al. (1979a); Hodges et al. (1980). Symmetric cations and O_2^+ -clusters are known to have large photo-dissociation cross sections, but NO^+ -clusters and H_3O^+ -clusters have small cross sections (Smith et al., 1977; Smith and Lee, 1978). Therefore, only photo-destruction of N_4^+ , O_4^+ , and $\text{O}_2^+(\text{H}_2\text{O})$ is considered in the model.

4 Results

Corresponding to the first daytime sprite event detected by Stanley et al. (2000), the model simulations were performed for latitude 27.5°N , 14 August, 4.41 p.m. local time, almost two hours before sunset (solar zenith angle $\sim 65^\circ$). Figure 1 shows the modelled evolution of the electron density under the influence of the electric field pulse at the tip of a streamer at 31 km, 42 km, and 54 km. At all altitudes there is a rapid increase of the electron density by orders of magnitude during the pulse. The peak electron density is largest at 31 km, and smallest at 54 km. This is because the number of electrons produced in the streamer tip scales with the square of the air density (Eq. (2) in Sect. 3.1). The relaxation to background values is faster at lower altitudes due to

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pressure dependent electron loss reactions such as attachment to O_2 and three-body recombination with positive ions. If not stated otherwise, the results presented in the following are for an altitude of 42 km. Figure 2 depicts the concentrations of electrons and the most abundant negative ions as a function of time. The electrons liberated during the electric field pulse undergo attachment to O_2 , and after ~ 1 ms, O_2^- has become the principal anion. Eventually CO_3^- and CO_4^- are formed. A few seconds after the electric field pulse, the total charge density is back to pre-breakdown values. In comparison to higher altitudes (Gordillo-Vázquez, 2008) the peak ion concentration is higher but the “ionic phase” is shorter. The main positive ions are shown in Fig. 3. Just after the electric field pulse, N_2^+ is the most abundant cation. Rapid charge exchange with O_2 leads to a production of O_2^+ from which heavier cluster ions are formed. The abundance of $N_2O_2^+$ (not shown) is always small. This is in contrast to the sprite model predictions of Sentman et al. (2008a) and Gordillo-Vázquez (2008). The reason for this are the additionally included loss reactions with N_2 and O_2 (Kossyi et al., 1992), as well as with H_2O (Howard et al., 1972) (P-53 to P-55 in the reaction scheme in the Supplement to this paper). On the short time scale of the “ionic phase”, photo-processes turn out to be negligible. The results (not shown) of a test simulation with deactivated photoelectron detachment and photo-dissociations do basically not differ from the results just presented.

In the remaining section, the impact of the sprite streamer on neutral species will be discussed. The focus lies on nitrogen, hydrogen and oxygen, and in particular on ozone perturbations. In order to compare the chemical effects in a daytime sprite streamer with those in a nighttime sprite streamer, an additional simulation was carried out for midnight (same location, same day). In Fig. 4 the response of oxygen species to the electric field pulse is shown for daytime and for nighttime conditions. The concentration of atomic oxygen increases due to electron impact dissociation of O_2 , but it is always significantly smaller than the concentration of O_3 . The lifetime of the ground state atomic oxygen produced during the electric breakdown is of the order of a few seconds. For daytime conditions, there is a small concentration of atomic oxygen be-

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fore and after the sprite event, mainly due to photolysis of O_2 and O_3 . This is important for the interaction of oxygen and nitrogen species as discussed below. The evolution of the most important hydrogen species is shown in Fig. 5. As a result of the electric breakdown, there is significant production of hydroxyl molecules, followed by an increase of HO_2 . After a few minutes, the concentration of OH is basically back to pre-breakdown values, HO_2 has started to decrease again, and H_2O_2 has increased. All this is similar for both daytime and nighttime events. On the contrary, concerning nitrogen species, there are considerable differences between daytime and nighttime as shown in Fig. 6. Electron impact dissociation of N_2 leads to a significant increase of nitrogen atoms followed by a rapid production of nitric oxide. An important subsequent reaction of nitric oxide is the destruction of ozone molecules:



In the nighttime atmosphere, NO_2 is rather stable. It becomes the principal NO_x species a few seconds after the electric breakdown. The concentration of NO decreases continuously (Fig. 6). In contrast to that, in the daytime atmosphere there are reactions converting NO_2 back into nitric oxide, in particular:



and



As a result, NO is recycled back from NO_2 , and the Reactions (R6), and (R7)/(R8) constitute a catalytic ozone destruction cycle. Figure 7 shows the most important loss reactions of ozone for the daytime sprite streamer. It can be seen that, after a few seconds $OH + O_3$ is the main ozone sink, and after some minutes it is Reaction (R6). While the former also takes place in the nighttime case, the latter is basically missing in the nighttime atmosphere as almost all NO_x is in form of NO_2 after some minutes

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(Fig. 6). Therefore, the impact of a daytime sprite streamer on ozone differs from the effect of a nighttime sprite streamer. This is clearly demonstrated in Fig. 8 where the relative change of ozone in the sprite streamer at three selected altitudes is shown. While there is basically no effect on O_3 at 54 km for the nighttime event, the catalytic ozone destruction during daytime causes a continuous decrease of ozone exceeding 15% after 15 min of model time. At lower altitudes, there is initially an increase of ozone resulting from the liberation of oxygen atoms during the electric pulse. In terms of relative change, this effect increases with air number density N because the amount of oxygen atoms produced scales with the number of electrons behind the streamer tip ($\sim N^2$), whereas the atmospheric O_3 roughly scales with N . During night, the enhanced ozone values are basically stable, but in the sunlit atmosphere, ozone eventually decreases (Fig. 8). The fact that the NO_x catalyzed ozone decrease is less pronounced at lower altitudes can be understood by the following considerations: At lower altitudes, the three body reaction $O + O_2 + M \rightarrow O_3 + M$ is faster than at higher altitudes. This reaction produces ozone and competes with Reaction (R7). Furthermore, the NO_2 photolysis frequency of Reaction (R8) is smaller than at higher altitudes. Therefore, the rate at which NO is recycled from NO_2 is smaller at lower altitudes.

5 Summary and conclusions

The chemical processes in daytime sprite streamers in the upper stratosphere have been investigated by means of a detailed ion-neutral chemistry model. As transport processes such as diffusive mixing with ambient air are neglected, the simulations are limited to 15 min after the passage of the streamer tip. For comparison, additional model simulations for nighttime conditions have been carried out. The model results indicate that the ozone perturbations due to daytime sprites streamers differ considerably from the ones of nighttime events.

An initial effect of the breakdown electric fields at the tip of sprite streamers is the production of atomic oxygen, and the subsequent formation of ozone. In terms of rel-

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ative ozone change, this effect decreases with altitude. Additionally, reactive nitrogen is produced at the streamer heads. For nighttime conditions, this reactive nitrogen is rapidly converted into significantly less reactive NO_2 , and there is basically no ozone depletion. The situation is different for daytime conditions where NO_x causes catalytic ozone destruction. As a consequence, there is significant ozone loss in sprite streamers in the daytime atmosphere, in particular at higher altitudes. At an altitude of 54 km, ozone has decreased by about 15 % fifteen minutes after the sprite event.

Note that the presented model results give only a first indication of the chemical effects of daytime sprite streamers in comparison with their nighttime counterparts. For the assessment of chemical effects on longer time scales, mixing of the streamer gas with the ambient air will have to be taken into account.

Supplementary material related to this article is available online at
[http://www.atmos-chem-phys-discuss.net/13/29521/2013/
acpd-13-29521-2013-supplement.pdf](http://www.atmos-chem-phys-discuss.net/13/29521/2013/acpd-13-29521-2013-supplement.pdf).

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Table 1. Electric field driven processes in the model. The reaction rate coefficients as functions of the reduced electric field are calculated with the Boltzmann solver BOLSIG+ (Hagelaar and Pitchford, 2005), and cross section data from the literature. Only for the last reaction, the reaction rate coefficient as a function of the reduced electric field is directly taken from the reference.

Reaction	Reference(s)*
Ionisation	
$e + N_2 \rightarrow N_2^+ + 2 e$	1, 2
$e + N_2 \rightarrow N_2^+ + N + 2 e$	2, 3
$e + N_2 \rightarrow N^+ + N(^2D) + 2 e$	3
$e + O_2 \rightarrow O_2^+ + 2 e$	5
$e + O_2 \rightarrow O_2^+ + O + 2 e$	5
Attachment	
$e + O_2 \rightarrow O^- + O$	1
Dissociation	
$e + N_2 \rightarrow N + N + e$	3, 4
$e + N_2 \rightarrow N + N(^2D) + e$	3
$e + N_2 \rightarrow N + N(^2P) + e$	3
$e + O_2 \rightarrow O + O + e$	6
$e + O_2 \rightarrow O + O(^1D) + e$	5
$e + O_2 \rightarrow O + O(^1S) + e$	7
Excitation	
$e + N_2 \rightarrow N_2(A) + e$	1
$e + N_2 \rightarrow N_2(B) + e$	1
$e + N_2 \rightarrow N_2(a^1) + e$	1
$e + N_2 \rightarrow N_2(a^1) + e$	1
$e + N_2 \rightarrow N_2(C) + e$	1
$e + O_2 \rightarrow O_2(a) + e$	1
$e + O_2 \rightarrow O_2(b) + e$	1
Detachment	
$O^- + N_2 \rightarrow N_2O + e$	8

* [1] http://jila.colorado.edu/~avp/collision_data/ (download 3 January 2012); [2] Itikawa (2006); [3] Zipf et al. (1980); [4] Cosby (1993a); [5] Itikawa (2009); [6] Cosby (1993b); [7] LeClair and McConkey (1993); [8] Luque and Gordillo-Vázquez (2012).

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Table 2. Modelled species.

Anions

e , O^- , O_2^- , O_3^- , O_4^- , NO^- , NO_2^- , NO_3^- , CO_3^- , CO_4^- ,
 $O^-(H_2O)$, $O_2^-(H_2O)$, $O_3^-(H_2O)$, OH^- , HCO_3^- ,
 Cl^- , ClO^- , $Cl^-(H_2O)$, $Cl^-(CO_2)$, $Cl^-(HCl)$

Cations

N^+ , N_2^+ , N_3^+ , N_4^+ , O^+ , O_2^+ , O_4^+ , NO^+ , NO_2^+ , N_2O^+ , $N_2O_2^+$, $NO^+(N_2)$, $NO^+(O_2)$,
 H_2O^+ , OH^+ , $H^+(H_2O)_{n=1-7}$, $H^+(H_2O)(OH)$, $H^+(H_2O)(CO_2)$, $H^+(H_2O)_2(CO_2)$,
 $H^+(H_2O)(N_2)$, $H^+(H_2O)_2(N_2)$, $O_2^+(H_2O)$, $NO^+(H_2O)_{n=1-3}$,
 $NO^+(CO_2)$, $NO^+(H_2O)(CO_2)$, $NO^+(H_2O)_2(CO_2)$,
 $NO^+(H_2O)(N_2)$, $NO^+(H_2O)_2(N_2)$

Neutrals

N , $N(^2D)$, $N(^2P)$, O , $O(^1D)$, $O(^1S)$, O_3 , NO , NO_2 , NO_3 ,
 N_2O , N_2O_5 , HNO_3 , HNO_2 , HNO , H_2O_2 ,
 $N_2(A)$, $N_2(B)$, $N_2(C)$, $N_2(a^1)$, $N_2(a^1)$, $O_2(a)$, $O_2(b)$,
 H_2O , HO_2 , OH , $OH(v)$, H ,
 HCl , Cl , ClO ,
 N_2 , O_2 , H_2 , CO_2

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Table 3. Photoelectron detachment, photo-dissociation of ions, and photo-ionisation in the model. The rate coefficients are calculated using cross section data from the references.

Reaction	Reference(s)*
Electron detachment	
$O^- + hv \rightarrow e + O$	1,2
$O_2^- + hv \rightarrow e + O_2$	1,2
$O_3^- + hv \rightarrow e + O_3$	3
$O_4^- + hv \rightarrow e + O_2 + O_2$	1
$CO_4^- + hv \rightarrow e + CO_2 + O_2$	2,3
$OH^- + hv \rightarrow e + OH$	1
$NO^- + hv \rightarrow e + NO$	4
$NO_2^- + hv \rightarrow e + NO_2$	2,5
$NO_3^- + hv \rightarrow e + NO_3$	2,5,6
$O_2^-(H_2O) + hv \rightarrow e + H_2O + O_2$	1
$Cl^- + hv \rightarrow e + Cl$	7,8
$ClO^- + hv \rightarrow e + ClO$	9
Decomposition	
$O_3^- + hv \rightarrow O^- + O_2$	1,2,3
$CO_3^- + hv \rightarrow O^- + CO_2$	1,3,10
$O^-(H_2O) + hv \rightarrow O^- + H_2O$	see text
$O_3^-(H_2O) + hv \rightarrow O_3^- + H_2O$	11
$ClO^- + hv \rightarrow Cl^- + O$	9
$Cl^-(H_2O) + hv \rightarrow Cl^- + H_2O$	see text
$Cl^-(CO_2) + hv \rightarrow Cl^- + CO_2$	see text
$Cl^-(HCl) + hv \rightarrow Cl^- + HCl$	see text
$N_4^+ + hv \rightarrow N_2^+ + N_2$	12,13
$O_4^+ + hv \rightarrow O_2^+ + O_2$	12,13
$O_2^+(H_2O) + hv \rightarrow H_2O^+ + O_2$	12,13
Ionisation	
$NO + hv \rightarrow e + NO^+$	14

* [1] Lee and Smith (1979); [2] Hodges et al. (1980); [3] Cosby et al. (1976); [4] Al-Za'al et al. (1986); [5] Smith et al. (1979a); [6] Smith et al. (1978); [7] Mandl (1976); [8] Radojević et al. (1987); [9] Lee et al. (1979); [10] Smith et al. (1979b); [11] Cosby et al. (1978); [12] Smith et al. (1977); [13] Smith and Lee (1978); [14] Kull et al. (1997).

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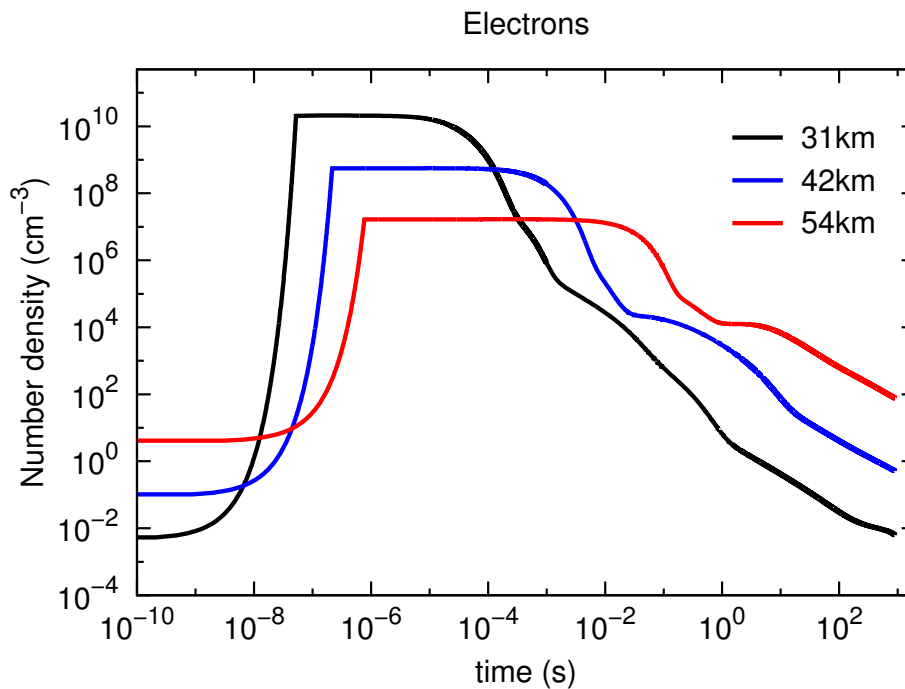


Fig. 1. Modelled evolution of the electron number density in a daytime sprite streamer at three selected altitudes.

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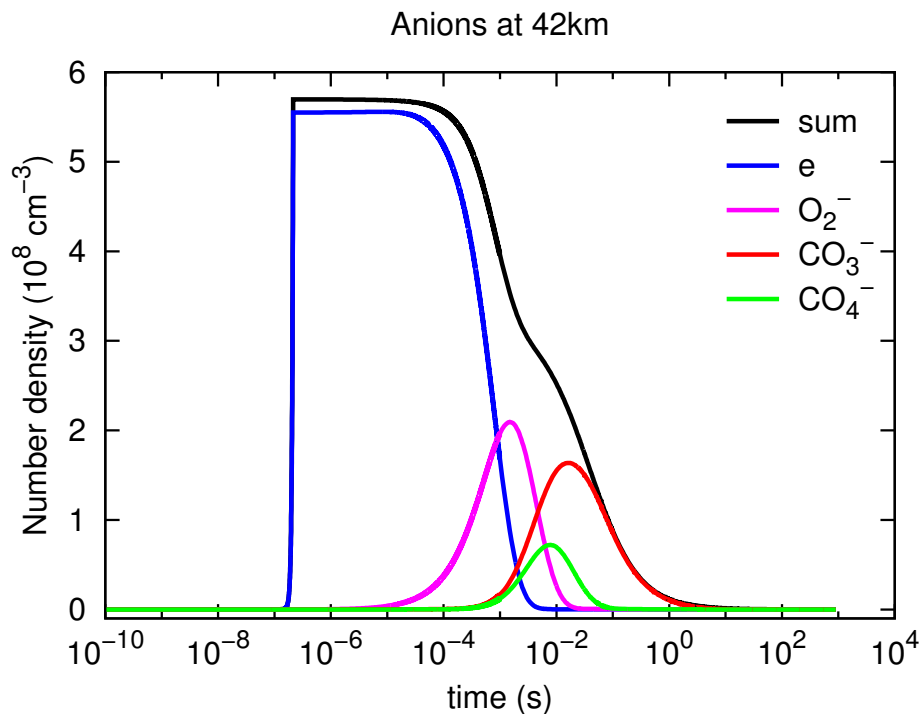


Fig. 2. Modelled evolution of the most abundant negative ions in a daytime sprite streamer at 42 km altitude.

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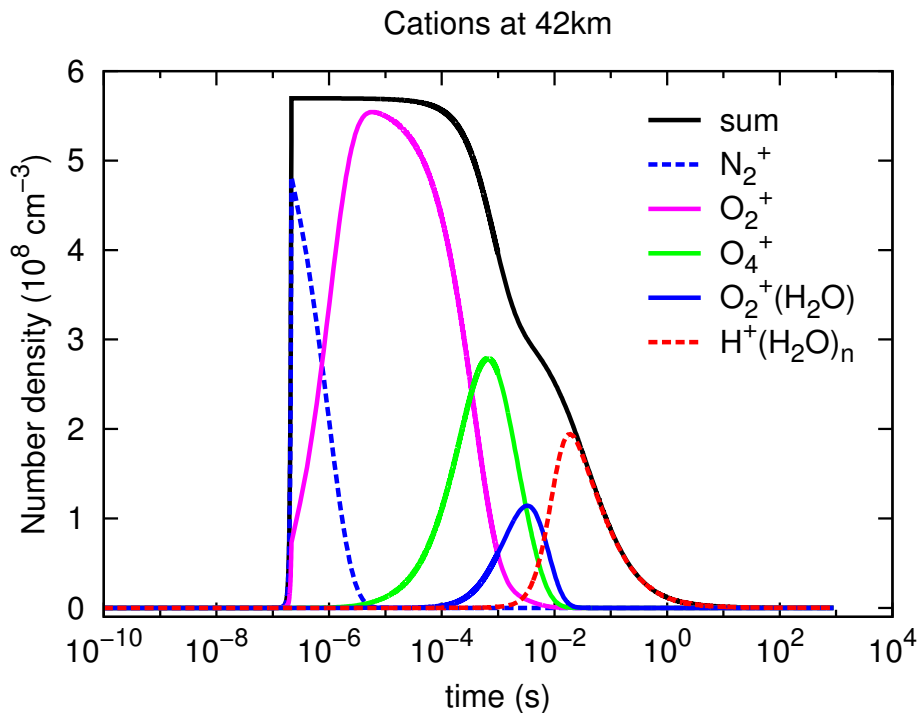


Fig. 3. Modelled evolution of the most abundant positive ions in a daytime sprite streamer at 42 km altitude.

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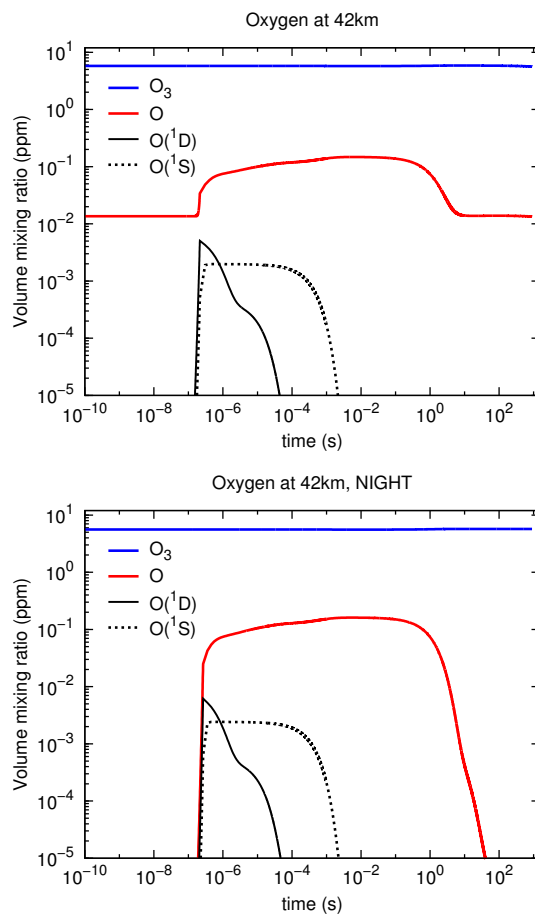


Fig. 4. Modelled evolution of the volume mixing ratios of oxygen species in a sprite streamer at 42 km altitude. Upper plot: daytime; lower plot: nighttime.

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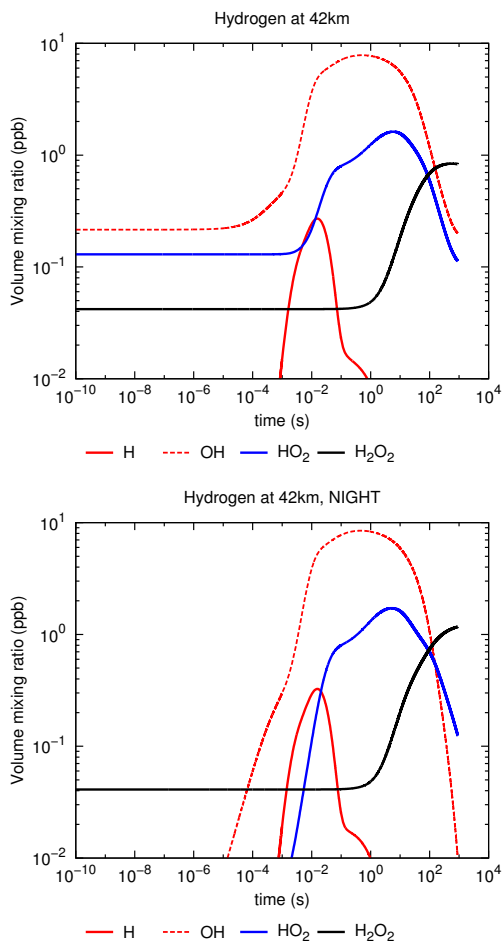


Fig. 5. Modelled evolution of the volume mixing ratios of hydrogen species in a sprite streamer at 42 km altitude. Upper plot: daytime; lower plot: nighttime.

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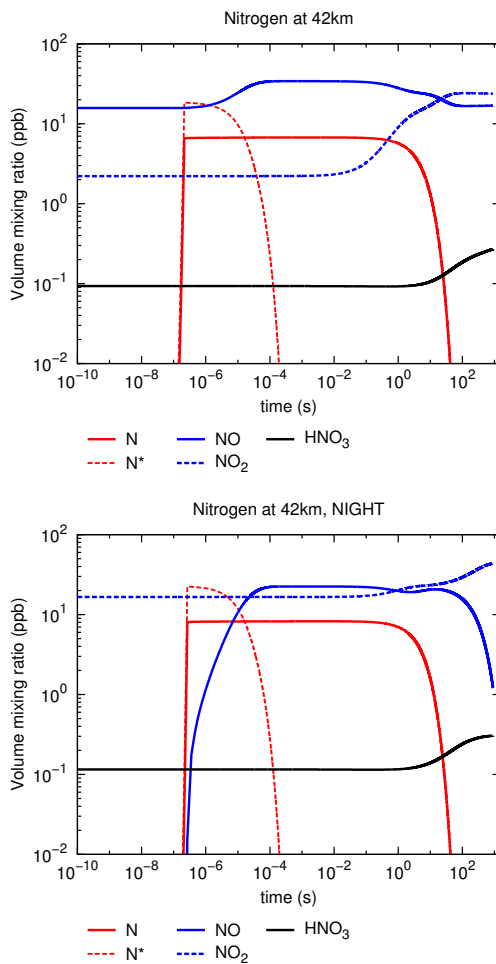


Fig. 6. Modelled evolution of the volume mixing ratios of nitrogen species in a sprite streamer at 42 km altitude. Upper plot: daytime; lower plot: nighttime.

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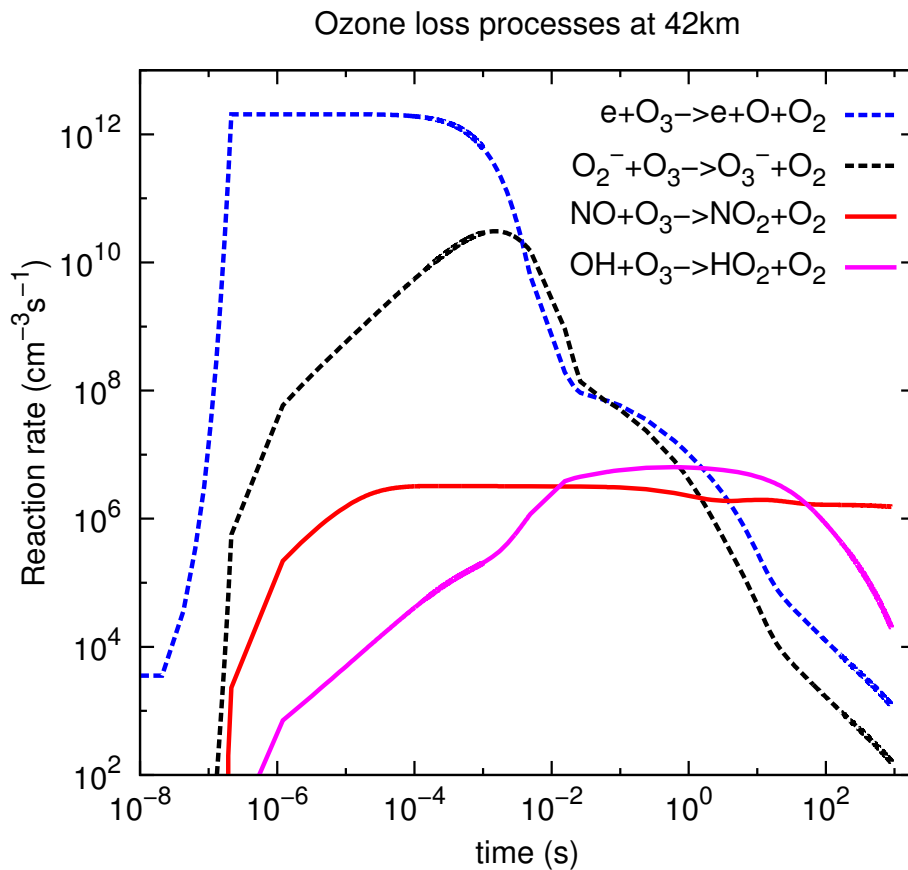


Fig. 7. The four most important ozone loss reactions in a daytime sprite streamer at 42 km. Shown are the two main (dotted) ionic and (solid) neutral processes, respectively.

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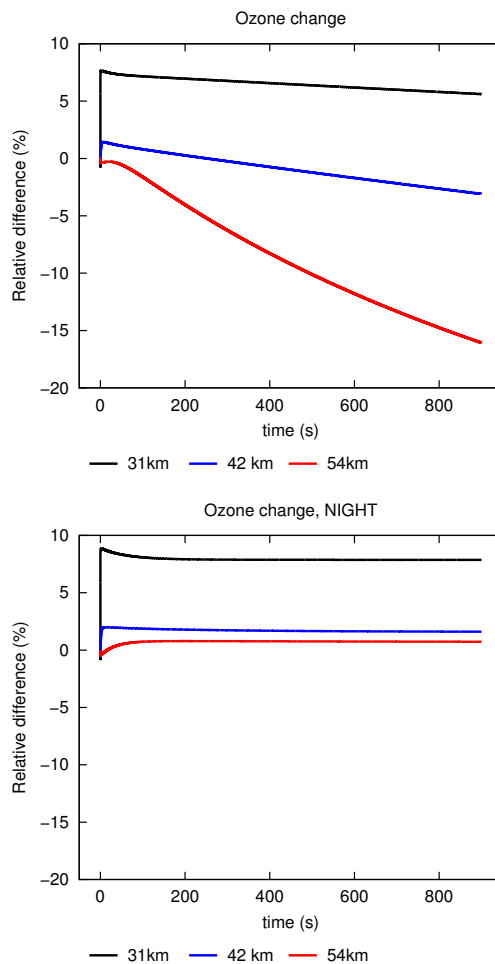


Fig. 8. Modelled change of ozone in sprite streamers at three selected altitudes. Upper plot: daytime; lower plot: nighttime.