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Escape of Hot O and C from the Atmosphere of Mars

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Abstract

The escape of hot O and C atoms from the present martian atmosphere during low and high solar activity conditions has been studied with a Monte-Carlo model. The model includes the initial energy distribution of hot atoms, elastic, inelastic, and quenching collisions between the suprathermal atoms and the ambient cooler neutral atmosphere, and applies energy dependent total and differential cross sections for the determination of the collision probability and the scattering angles. The results indicate that dissociative recombination of O_2^+ and CO_2^+ are the major sources for the loss of hot oxygen giving loss rates of about $3 \times 10^{25}\,\mathrm{s}^{-1}$ during low and high solar activity conditions, whereas the loss of atomic carbon is mainly due to photodissociation of CO with escape rates of about $1 \times 10^{24}\,\mathrm{s}^{-1}$ and $3 \times 10^{24}\,\mathrm{s}^{-1}$ for low and high solar activity, respectively. Depending on solar activity, the obtained carbon loss rates are up to ~ 35 times higher than the CO_2^+ ion loss rate inferred from Mars Express ASPERA-3 observations.

1. Introduction

The simulations are based – if available – on the most recent data for both the atmospheric input and the collision cross sections. The model is limited by various circumstances: (a) the background atmosphere is represented by 1D ion and neutral density profiles, valid for 60° solar zenith angle, taken from [3], (b) the hot particles are treated as test particles, i.e. their influence on the background gas is neglected, (c) due to the lack of data, some types of collisions are simulated by using approximate values of the parameters.

Possible sources of hot O and C atoms due to dissociative and radiative recombination, photodissociation as well as charge exchange and chemical reactions are included. The simulation of the hot particle corona is initiated by calculating for a specific reaction the corresponding velocity distribution of the products at discrete altitudes. These products are represented by a number of particles and their motion is followed through the thermosphere up to the exobase. On their way the hot particles can interact with the background neutral atmosphere via elastic, inelastic and quenching collisions and will loose on average part of their initial energy. For those particles which cross the exobase, the energy distribution function is determined which in turn serves as input for the exosphere density calculations. A more detailed description of the Monte-Carlo model can be found in [5] and [4].

2. Results

According to the input parameters used in our simulations, the calculated exobase altitude for low and high solar activity at Mars is located at about 220 and $260\,\mathrm{km}$, respectively, above the surface.

2.1 Oxygen

The escape fluxes together with the escape rates for various sources of hot oxygen are listed in Table 1 for LSA and HSA. Although the production rates are generally larger during HSA, there is little difference in the escape of hot O between HSA and LSA. This is mainly due to the fact that at HSA also the neutral background density is higher, leading to an increase

Table 1: Escape fluxes and loss rates of hot O atoms.

Source	Escape flux $[\mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$	Escape rate $[\mathrm{s}^{-1}]$
Low solar activity (220 km)		
$O_2^+ + e \rightarrow O + O$	1.7×10^7	1.4×10^{25}
$CO_2^+ + e \rightarrow CO + O$	1.5×10^7	1.3×10^{25}
$O_2 + C \rightarrow CO + O(^1D)$	8.3×10^5	6.8×10^{23}
$O_2^+ + N \rightarrow NO + O$	9.8×10^4	8.0×10^{22}
total	$\mathbf{3.3 \times 10^7}$	$\mathbf{2.8 \times 10^{25}}$
High solar activity (260 km)		
$O_2^+ + e \rightarrow O + O$	1.9×10^7	1.6×10^{25}
$CO_2^+ + e \rightarrow CO + O$	1.2×10^7	1.0×10^{25}
$O_2 + C \rightarrow CO + O(^1D)$	7.2×10^5	6.0×10^{23}
$O_2^+ + N \rightarrow NO + O$	9.3×10^5	7.8×10^{23}
total	$\mathbf{3.2 \times 10^7}$	$\mathbf{2.7 \times 10^{25}}$

in the number of collisions between the suprathermal particles and the cold atmosphere and thus to a more efficient thermalization of the hot particles compared to LSA conditions.

2.2 Carbon

Our results suggest – in agreement with previous studies – that the main loss of atomic carbon at present Mars is due to photodissociation of CO. According to the present simulations, the total carbon loss is about 1 and $3 \times 10^{24}\,\mathrm{s}^{-1}$ for low and high solar activity (Table 2) , respectively, which is $\sim 5 - 15$ times higher compared to the estimated average atmospheric sputtering of C atoms [2] and up to ~ 35 times higher compared to the estimated CO_2^+ molecular ion escape from ASPERA-3 [1]. The present results are in accord with the suggestion of [6] that the escape of photochemically produced suprathermal C atoms, which originate from the dissociation of CO_2^+, CO^+ and CO are the most efficient processes for the loss of the martian CO_2 atmosphere at present. Therefore, these exothermic reactions may play a major role for the escape of the martian atmosphere since the end of the Noachian. It is important to note that the modeled hot C and O and the related CO_2 losses depend on a complex interplay of many physical and chemical processes – e.g. the change of the solar XUV flux and the corresponding response of the upper neutral and ionized atmosphere – and that the present escape rates can not be easily extrapolated backwards during the planet's history.

Table 2: Escape fluxes and loss rates of hot C atoms.

Source	Escape flux $[\mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$	Escape rate $[\mathrm{s}^{-1}]$
Low solar activity (220 km)		
$CO + h\nu \longrightarrow C + O$	10.3×10^5	0.8×10^{24}
$CO_2^+ + e \longrightarrow O_2 + C^a$	1.4×10^5	0.1×10^{24}
$CO^+ + e \longrightarrow C + O$	0.8×10^5	0.1×10^{24}
total - without $CO_2^+ + e$	$\mathbf{11.1 \times 10^5}$	$\mathbf{0.9 \times 10^{24}}$
total - including $CO_2^+ + e$	$\mathbf{12.5 \times 10^5}$	$\mathbf{1.0 \times 10^{24}}$
High solar activity (260 km)		
$CO + h\nu \longrightarrow C + O$	30.8×10^5	2.6×10^{24}
$CO^+ + e \longrightarrow C + O$	2.3×10^5	0.2×10^{24}
$CO_2^+ + e \longrightarrow O_2 + C^a$	1.0×10^5	0.1×10^{24}
total - without $CO_2^+ + e$	$\mathbf{33.2 \times 10^5}$	$\mathbf{2.8 \times 10^{24}}$
total - including $CO_2^+ + e$	$\mathbf{34.2 \times 10^5}$	$\mathbf{2.9 \times 10^{24}}$

[a] the branching ratio of this process is assumed to be 4%

3. Summary and Conclusions

A number of possible sources for hot C and O atoms and the resulting escape rates during low and high solar activity conditions from present Mars have been studied by applying a Monte-Carlo model to simulate the stochastic motion of these particles through the upper atmosphere. The main sources of escaping oxygen are dissociative recombination of O_2^+ and CO_2^+ leading to a total loss of $\sim 3 \times 10^{25}\,\mathrm{s}^{-1}$. This loss appears to be almost independent over the solar cycle. The vast majority of escaping carbon is delivered through photodissociation of CO with a total loss of 1 to $3 \times 10^{24}\,\mathrm{s}^{-1}$. This value is distinctly higher than the estimated present loss due to atmospheric sputtering and the observed CO_2^+ escape at Mars.

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