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Simulation of deuterium and hydrogen loss on Mars by thermal, photochemical and solar wind processes

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Introduction

D/H measured on Mars suggest an important loss of water vapor
 Evolution of $[D]/[H](t)$ is given by

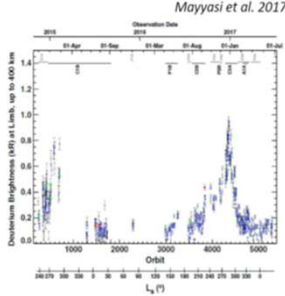
$$\frac{d(D/H)}{dt} = (D/H) \frac{1-f(t)}{\tau_H(t)} \quad f(t) = \frac{\Phi(D)/\Phi(H)}{D/H}$$

2 important parameters:

- $\tau_H(t)$: time scale of escape = hydrogen abundance/escape rate
 If $\tau_H(t)$ is large, the escape is not efficient \rightarrow no fractionation

- $f(t)$: fractionation factor
 If $f(t) = 1$ then D and H escape in proportion to their atmospheric abundance \rightarrow no fractionation

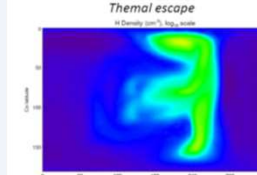
Recent measurements of MAVEN/IUVS suggest important temporal variation of the D escape, and the need of non-thermal escape to explain the observed variation (Clarke et al. 2017, Mayyasi et al. 2017).



Method and processes

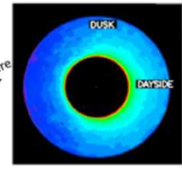
Goal : Estimate the escape rate of H (H, H2) and D species (D, HD) at Mars for present conditions.
Method : 3 models (Atmosphere/Ionosphere ; Exosphere ; Induced magnetosphere)

PCM-Mars : Atmosphere/ionosphere : Thermal escape



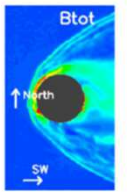
Conditions
 Spring equinox (Ls=0); solar average conditions ; nominal solar wind

Hot neutrals exosphere: Photochemical escape



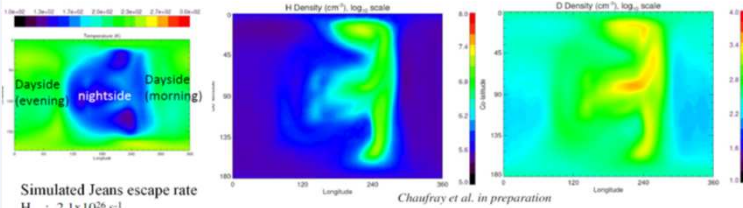
Adapted from Leblanc et al. 2017

Solar wind interaction : Ions escape



Thermal escape

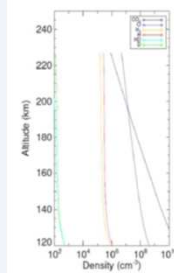
Martian-PCM : 3D Atmosphere of Mars from the surface to the exobase (Forget et al. 1999, Gonzalez-Galindo et al. 2009, Chaufray et al. 2015)
 New species included : deuterated species (HDO cycle : Vals et al. 2022, Rossi et al. 2022, photoproducts and ions)



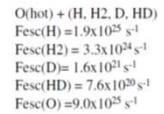
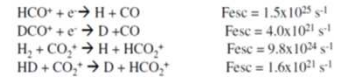
Simulated Jeans escape rate
 H : $2.1 \times 10^{26} \text{ s}^{-1}$
 D : $1.3 \times 10^{20} \text{ s}^{-1}$
 H2 : $1.9 \times 10^{23} \text{ s}^{-1}$
 HD : $1.8 \times 10^{17} \text{ s}^{-1}$

Photochemical escape

Input : 3D atmosphere/ionosphere



Main channels only (Krasnopolsky 2002, Gregory et al. 2023)



HCO⁺ RD : production and loss rate in good agreement with low solar activity scenario of Gregory et al. 2022 (1.3×10^{23} at low solar activity)

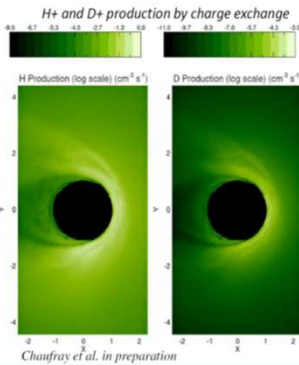
Photochemical escape : important source of D escape (> 10 thermal escape) but much lower than thermal escape for H.

Solar wind interaction

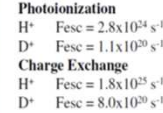
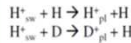
Lathys model (Modolo et al. 2016) to describe the EM environment.
 Test particle code to follow ions in EM

Solar wind parameters :
 Density = 2.7 cm^{-3}
 $V_{sw} = 480 \text{ km/s}$
 $B_{IMF} : 3 \text{ nT}$ (Parker spiral)

Kinetic hybrid model
 Electron = massless fluid
 Ions = Test particles
 Spatial resolution (EM) = 80 km



Two source of planetary ions
 - Photoionization of H and D above 200 km (no production in the shadow)
 - Charge exchange with solar wind protons



Summary of the results and discussion

Hydrogen escape (H and 2xH₂)

Hydrogen dominated by thermal escape (as expected)
Thermal escape : $2 \times 10^{26} \text{ s}^{-1}$
Total photochemistry : $5.0 \times 10^{25} \text{ s}^{-1}$
Solar wind : $2.1 \times 10^{25} \text{ s}^{-1}$
Total = $2.7 \times 10^{26} \text{ s}^{-1}$

Deuterium escape (D and HD)

Deuterium dominated by non-thermal escape (collisions with hot O ~ 30% of photochemical escape).
Thermal escape : $1.3 \times 10^{20} \text{ s}^{-1}$
Total photochemistry : $8.0 \times 10^{21} \text{ s}^{-1}$
Solar wind : $9.1 \times 10^{20} \text{ s}^{-1}$
Total = $9.0 \times 10^{21} \text{ s}^{-1}$

- Hydrogen dominated by thermal escape (as expected)
- Deuterium dominated by non-thermal escape (collisions with hot O ~ 30% of photochemical escape).
- Ions escape << neutral escape for both H and (~10% for H and D species)

$$f = \frac{\Phi(D)/\Phi(H)}{[D]/[H]} \approx 0.04$$

$\tau_H = \frac{N(H)}{\Phi_H} \approx 11000 \text{ yrs}$
 If atmospheric H only (10 μm pr)
But expected much larger when considering the unknown size of exchangeable reservoir (ice caps, ...)

Our simulated f value in agreement with recent estimate (Cangi et al. 2023)

Conclusion and perspectives

Summary :

- We perform a detailed modeling of the most important escape processes (thermal, photochemistry, solar wind) for H, H₂, D and HD at Mars by coupling 3 different models.
- As expected H is dominated by thermal escape, while D is dominated by photochemical processes.
- Ion escape for H and D represents ~ 10% of the total escape, dominated by charge exchange with solar wind protons
- Our derived fractionation factor $f \sim 0.04$ is in very good agreement with Cangi et al. 2023

Next steps :

- Estimate uncertainties due to different parameters (e.g. elastic collisions cross sections)
- Simulation at other seasons, solar activity, especially $L_s = 270^\circ$ where H and D escape are maximum ($\tau_H(t)$ is shorter)
- Simulations of ion escape during solar events
- Extrapolations to past conditions to derive $f(t)$ along the Martian history,...

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