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

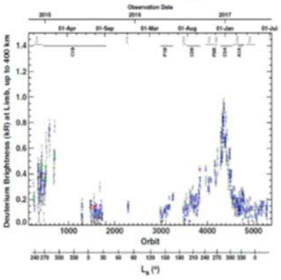
$$\frac{d(D/H)}{dt} = (D/H)\frac{1-f(t)}{\tau_H(t)} \qquad f(t) = \frac{\Phi(D)/\Phi(H)}{D/H}$$

2 important parameters:

- **τ_H(t)** : time scale of escape = hydrogen abundance/escape rate
If τ_H(t) is large, the escape is not efficient → no fractionnation

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

Mayyasi et al. 2017

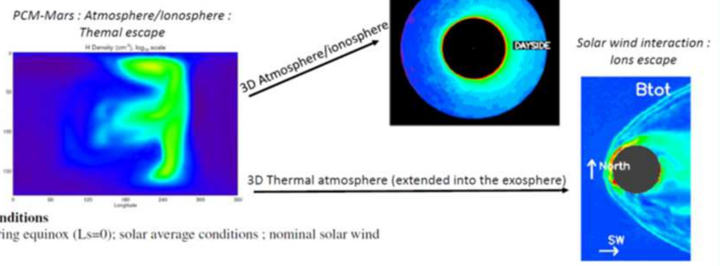


Recent measurements of MAVEN/IUVS suggest important temporal variation of the D escape, and the need of non-thermal escape to explain the observed variation (Clarke et al. 2017, Mayyasi et al. 2017).

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)

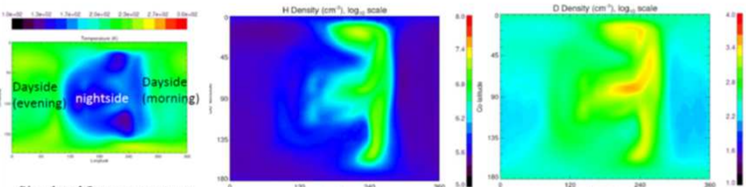
Adapted from Leblanc et al. 2017



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

Thermal escape

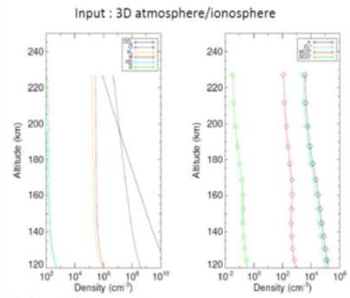
Martian-PCM : 3D Atmosphere of Mars from the surface to the exobase (Forget et al. 1999, Gonzalez-Galindo et al. 2009, Chaufray et al. 2015)
New species included : deuterated species (HDO cycle : Vals et al. 2022, Rossi et al. 2022, photoproducts and ions)



Chaufray et al. in preparation

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

Photochemical escape



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

$HCO^+ + e^- \rightarrow H + CO$	Fesc = 1.5×10^{25} s^{-1}
$DCO^+ + e^- \rightarrow D + CO$	Fesc = 4.0×10^{21} s^{-1}
$H_2 + CO_2^+ \rightarrow H + HCO_2^+$	Fesc = 9.8×10^{24} s^{-1}
$HD + CO_2^+ \rightarrow D + HCO_2^+$	Fesc = 1.6×10^{21} s^{-1}

O(hot) + (H, H2, D, HD)
Fesc(H) = 1.9×10^{25} s^{-1}
Fesc(H2) = 3.3×10^{24} s^{-1}
Fesc(D)= 1.6×10^{21} s^{-1}
Fesc(HD) = 7.6×10^{20} s^{-1}
Fesc(O) = 9.0×10^{25} s^{-1}

HCO^+ RD : production and loss rate in good agreement with low solar activity scenario of Gregory et al. 2022 (1.3×10^{25} at low solar activity)

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

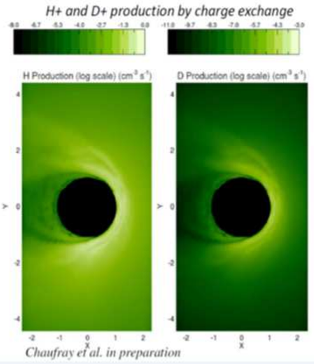
Solar wind interaction

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 km/s
B_{IMF} : 3 nT (Parker spiral)

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

H+ and D+ production by charge exchange



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

$H^+_{sw} + H \rightarrow H^+_{pl} + H$
$H^+_{sw} + D \rightarrow D^+_{pl} + H$

Photoionization
H^+ Fesc = 2.8×10^{24} s^{-1}
D^+ Fesc = 1.1×10^{20} s^{-1}
Charge Exchange
H^+ Fesc = 1.8×10^{25} s^{-1}
D^+ Fesc = 8.0×10^{20} s^{-1}

Summary of the results and discussion

Hydrogen escape (H and 2xH_2)

Thermal escape : 2×10^{26} s^{-1}
Total photochemistry : 5.0×10^{25} s^{-1}
Solar wind : 2.1×10^{25} s^{-1}
Total = 2.7×10^{26} s^{-1}

Deuterium escape (D and HD)

Thermal escape : 1.3×10^{20} s^{-1}
Total photochemistry : 8.0×10^{21} s^{-1}
Solar wind : 9.1×10^{20} s^{-1}
Total = 9.0×10^{21} 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)

$$f = \frac{\Phi(D)/\Phi(H)}{[HDO]/2\,[H_2O]} \approx 0.04$$

$$\tau_H = \frac{N(H)}{\Phi_H} \approx 11000 \text{ yrs}$$

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 fractionnation factor f ~ 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 Ls = 270° where H and D escape are maximum (τ_H(t) is shorter)
- ❑ Simulations of ion escape during solar events
- ❑ Extrapolations to past conditions to derive f(t) along the Martian history,…

References

- Cangi et al. (2023), Fully coupled photochemistry of the deuterated ionosphere and its effects on escape of H and D, JGR: Planets, 128, e2022JE007713
- Chaufray et al. (2015), Variability of the hydrogen in the Martian upper atmosphere as simulated by a 3D atmosphere-exosphere coupling, Icarus, 245, 282-294
- Clarke et al., (2017), Variability of D and H in the Martian upper atmosphere observed with the MAVEN IUVS echelle channel, JGR : Space Physics, 122, 2336-2344
- Forget et al. (1999), Improved general circulation models of the Martian atmosphere from the surface to above 80 km, JGR, 104, 24155-24175
- Gonzalez-Galindo et al. (2009), A ground-to-exosphere Martian general circulation model: 1. Seasonal, diurnal, and solar cycle variation of thermospheric temperatures, 114, E04001
- Gregory et al. (2023), Nonthermal hydrogen loss at Mars: contributions of photochemical mechanisms to escape and identification of key processes, JGR: Planets, 128, e2023JE007802
- Krasnopolsky (2002), Mars' upper atmosphere and ionosphere at low, medium, and high solar activities: Implication for evolution of water, JGR, 107, E12, 5128
- Leblanc et al. (2017), On the origin of Mars' exospheric nonthermal oxygen component as observed by MAVEN and modeled by HELIOSARES, JGR : Planets, 122, 2401-2428
- Mayyasi et al. (2017), The variability of atmospheric deuterium brightness at Mars: Evidence for seasonal dependence, JGR : Space Physics, 122, 10811-10823
- Modolo et al. (2016), Mars-solar wind interaction: LatHyS, an improved parallel 3D multispecies hybrid model, JGR: Space Physics, 121, 6378-6399
- Rossi et al. (2022), The HDO cycle on Mars: Comparison of ACS observations with GCM simulations, JGR: Planets, 127, e2022JE007201
- Vals et al. (2022), Improved modeling of Mars' HDO cycle using a Mars' global climate model, JGR: Planets, 127, e2022JE007192