Seasonal enhancement in upper atmospheric D/H at Mars driven by both thermospheric temperature and mesospheric water

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Key Points:

- Seasonal increases in exobase temperature or mesospheric water can enhance the upper atmospheric atomic D/H ratio up to 25 times VSMOW.
- The enhancement occurs due to dynamical differences, leading to similarities in D/H ratio but differences in abundance and escape.
- Concurrent measurements of temperatures, water vapor, and the D/H ratio will enhance our understanding of atmospheric escape from Mars.

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Abstract

The D/H ratio in water on Mars, R_{water}, is 4–6$\times$ the Earth ratio, signifying past water loss to space. Recently, measurements have revealed high values of the D/H ratio in hydrogen, R_{atomic}, in the thermosphere during southern summer. Here, we use a photochemical model to explore the potential drivers of R_{atomic}, testing three: thermospheric temperatures, excess mesospheric water, and changing insolation. We find that R_{atomic} can achieve values between 15$\times$ the Earth ratio (due to water) and 25$\times$ the Earth ratio (due to temperature). The effects arise because H escape is diffusion-limited, while D escape is energy-limited. Our results underscore how R_{atomic} reflects mesospheric dynamics, and the need for concurrent measurements of mesospheric water, thermospheric temperatures, and R_{atomic} to understand seasonal changes in the martian water cycle and atmospheric loss.

Plain Language Summary

The high ratio of deuterium (D) to hydrogen (H) measured in water molecules on Mars indicates that much of Mars' past water has escaped to space. Recent measurements of the D/H ratio in the atoms themselves using data from the MAVEN spacecraft have revealed a ratio as high as 100 times the Earth value. In this work, we use a computational model of the Mars atmosphere to explore whether the large values could be caused by seasonal changes in three atmospheric parameters: the upper atmospheric temperature, the presence of extra water vapor in the middle atmosphere, and the incoming solar radiation. We find that temperature and water vapor have comparable effects, with each leading to an atomic D/H ratio similar to those found by MAVEN observations. We also explain how temperature and water affect the dynamics of H and D in the atmosphere to cause the change in the ratio.

1 Background and Motivation

Isotope ratios in planetary atmospheres encode a history of atmospheric escape. On Mars, the argon isotope system reveals how sputtering has affected atmospheric loss (Jakosky et al., 2017; Slipski & Jakosky, 2016); nitrogen is used to reconstruct potential past atmospheric compositions (e.g. Pieris & Jakosky, 2022; Hu & Thomas, 2022); and hydrogen probes long-term water loss (Owen et al., 1988; Yung et al., 1988; Carr,

1990, and many others). Because of the interest in water loss from Mars, the isotopic ratio of deuterium (D) and hydrogen (H) is typically measured in water as:

$$R_{water} = \frac{[HDO]}{2[H_2O]},$$ (1)

where square brackets represents a number density (abundance). R_{water} is 4–6 × VSMOW (Vienna Standard Mean Ocean Water, the ratio measured in Earth's oceans) (Owen et al., 1988; Bjoraker et al., 1989; Krasnopolsky et al., 1997; Encrenaz et al., 2018), with local variations between 1–10× VSMOW (Villanueva et al., 2015, 2021, 2022). This enhancement relative to Earth is thought to be driven by escape to space of H and D, which on Mars are primarily sourced from the water molecules H_2O and its isotope HDO.

Despite the key role of the atomic species in the parching of the planet, few measurements exist of the atomic D/H ratio,

$$R_{atomic} = \frac{[D]}{[H]}.$$ (2)

This is mainly due to measurement difficulties: a high resolution is required to resolve the H and D Lyman α emissions. Some measurements have been made using the Hubble Space Telescope's Goddard High Resolution Spectrograph and Space Telescope Imaging Spectrograph (Bertaux et al., 1992; Krasnopolsky et al., 1998; Clarke et al., 2006) during Mars aphelion. Combined with these, new results obtained with the MAVEN (Mars Atmosphere and Volatile EvolutioN) IUVS (Imaging UltraViolet Spectrograph) throughout the Mars year suggest a strong seasonal variation in H and D brightness and the derived R_{atomic} (Clarke et al., 2022; Chaufray et al., 2021), distinct from effects of individual dust storms, suggesting a repeatable, seasonal driver. Because the emission brightness of Lyman α directly probes the escaping atomic species, these measurements enable additional insight into atmospheric escape.

In this work, we study the sub-annual response of R_{atomic} due to seasonal perturbations and the driving dynamical or chemical processes. We use a 1D photochemical model (E. M. Cangi et al., 2023) to explore three options for the driver of R_{atomic} enhancements: greater thermospheric temperatures, which have a significant effect on the D/H fractionation factor (E. M. Cangi et al., 2020); changing insolation, which affects

photodissociation and ionization and atmospheric chemistry; or increased mesospheric water, demonstrated to enhance H escape (e.g. Chaffin et al., 2021; Stone et al., 2020; Chaffin et al., 2017). To simulate an annual cycle and examine the time-dependent photochemistry of the atmosphere, we simulate one Mars season per model run, using the output of one run as input for the next. We find that the thermospheric temperature and mesospheric water can both cause significant variations in R_{atomic}, while insolation changes are negligible.

Our present work demonstrates how subtle differences in the underlying dynamics of H and D lead to similarities in their thermospheric ratio, but differences in their abundances in the upper atmosphere and escape to space. This suggests the possibility of using measurements of D/H in atoms in the thermosphere as a probe for mesospheric dynamics. We thus highlight a need for concurrent observations of D/H, thermal structure, and atmospheric water abundances from surface to space to enable new insights into atmospheric escape and water loss from Mars.

2 Modeling methods

We use the same modeling approach as E. M. Cangi et al. (2023). Full details of the model, bluejay, are available in that paper and the archived code (E. Cangi & Chaffin, 2023), and the model parameters are summarized in Table S1. The three variable atmospheric parameters of thermospheric temperature, mesospheric water, and solar input are handled by the model in the following ways:

1. **Thermospheric temperature**: Past work has shown that the thermospheric temperature strongly affects D/H fractionation (E. M. Cangi et al., 2020) and Jeans escape. Our model prescribes temperature as a function of altitude, controlling it by modifying T_{exo}, the temperature at top of the model (250 km). T_{exo} can take on the values 175 K ("winter"-like conditions), 225 K ("spring"/"fall"), or 275 K ("summer").

2. **Mesospheric water abundance**: Water can enter the mesosphere due to dust activity (Villanueva et al., 2021; Chaffin et al., 2021; Holmes et al., 2021; Stone et al., 2020; A. A. Fedorova et al., 2020; Vandaele et al., 2019; Aoki et al., 2019; Heavens et al., 2018; Chaffin et al., 2021) or other seasonal effects (Shaposhnikov et al., 2019; Neary et al., 2020), driving H escape (Chaffin et al., 2021; Stone et

al., 2020). In our model, we prescribe water abundance below 72 km, allowing the model to solve or the abundance above that level. We define three scenarios: a dry mesosphere ("aphelion" conditions), a mesosphere with average moisture, and a wet mesosphere ("perihelion").

3. **Insolation**: Mars' orbit is eccentric, which affects the amount of UV insolation available to drive photodissociation and ionization of atmospheric molecules. We use the solar spectra for at 1.67 AU, 1.524 AU, and 1.38 AU.

As mentioned, the effect of the insolation variation was negligible (see Figure S2), and will not be discussed. We also explored a set with extra water added in the lower atmosphere (see Figure S7), but this also had a negligible effect on R_{atomic}.

Timesteps in the model are logarithmic; they start small ($dt \approx 10^{-3}$ seconds) and become larger near the end ($dt \approx 10^7$ seconds). The model state is saved in quasi-logarithmically spaced points from 1 second to 1 day, then once per week after. This scheme is shown in Figure S1.

We use the best available photodissociation cross sections for HDO (Cheng et al., 1999, 2004; Chung et al., 2001). We also ran several simulations in which both H_2O and HDO use the H_2O cross sections, resulting in a $2.5\times$ larger ratio around 60 km, consistent with Alday et al. (2021), but a negligible change to the D/H ratio above 80 km (see Figures S4 and S10).

We run three sets of simulations: "Temperature", "Water", and "Insolation". For each set, we model an annual cycle by imposing the appropriate seasonal input parameters on the model, running it for one "season" (1/4 of a Mars year, $\sim 1.48 \times 10^7$ seconds), and then using the atmospheric state at the end of each simulation as the initial conditions for the next season in the cycle. In all simulations, there are no sub-seasonal changes in the temperature profile, the water profile below 72 km, or the insolation profile, in order to clearly separate the atmospheric response to a forcing impulse.

3 Two controls on escape to space: energy and supply

Two major variables affect the escape of light atoms like H and D to space: the amount of energy available to these atoms, and their total abundance in the upper atmosphere.

130   In order to escape from the atmosphere, atoms must do two things: reach the escape re-

131   gion (exobase), and gain enough energy to exceed escape velocity.

132   The importance of energy is fairly straightforward. Atoms with velocities in the

133   high-energy tail of the Maxwell-Boltzmann distribution have enough energy to escape

134   in the thermal Jeans escape regime; other atoms do not, but may gain excess energy through

135   non-thermal processes, mostly involving ions or the solar wind in some way (Hunten, 1982).

136   Previous work has shown that the mass difference of H and D leads to H escape being

137   mostly thermal, while D escape is mostly non-thermal (E. M. Cangi et al., 2023; Krasnopol-

138   sky, 2002).

Supply is slightly more complex, and requires us to consider the atmosphere as an

integrated whole. Water is the main reservoir of H and D at Mars, and is primarily present

in the lower atmosphere. This means that the lower atmosphere is a source region for

H and D, which are freed when water dissociates and then transport up toward the exobase.

As temperatures rise and the atmosphere expands, the density of heavier species at a

given altitude near the homopause increases, making it more difficult for H and D to dif-

fuse upward due to more frequent collisions (Mayyasi et al., 2018), thus limiting the sup-

ply of atoms to the thermosphere. There is thus some maximum vertical flux of light gases.

The limiting flux (Hunten, 1973) has been used to describe the maximum upward flux

of a species possible in an isothermal atmosphere, defined as follows (Hunten, 1973):

$$\phi_\ell \cong \frac{D_i n_i}{H_a} \left(1 - \frac{m_i}{m_a} \right) \tag{3}$$

$$\cong \frac{b f_i}{H_a} \quad \text{(for minor species)}, \tag{4}$$

139   where D_i, n_i and m_i are the diffusion coefficient, density, and mass of species i, and H_a

140   and m_a are the mean scale height and molecular mass of the background atmosphere.

141   Equation 4 is valid for minor species like H and D; here b is the binary diffusion param-

142   eter, and f_i is the mixing ratio of species i. When the actual vertical flux of a species

143   equals the limiting flux, $\phi_{\text{esc}} = \phi_\ell$, the mixing ratio of that species is constant with height

144   and its escape to space is described as diffusion-limited (Hunten, 1973).

145   The limiting flux does not apply perfectly throughout real atmospheres, which are

146   typically not isothermal and have complex chemistry and transport. In studies of Mars,

147   the limiting flux is typically evaluated at the homopause, near the top of the mesosphere,
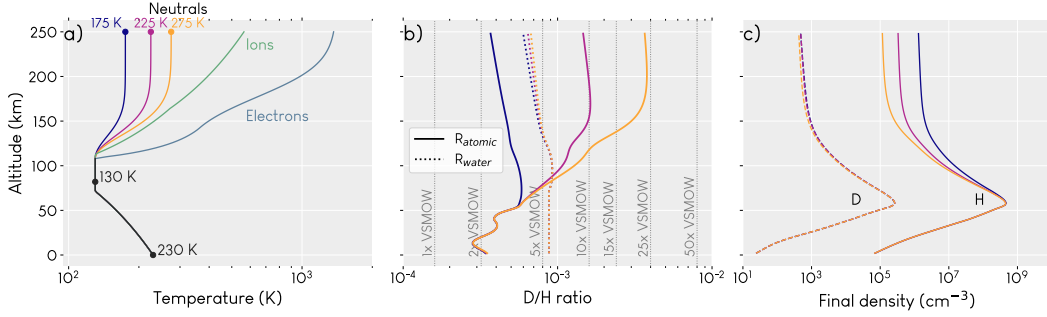
Figure 1. a) Model input: Temperature profiles adopted to simulate seasonal variation. b) Model output: Response of the D/H atmospheric profile (at the end of the associated simulation)/season. c) Associated D & H density profiles. Note that in panels b and c, the colors of the lines map to the neutral temperatures in panel a.

which separates the lower atmospheric source of H and D and the escape region (e.g. Zahnle et al., 2008). The mesosphere is also the only part of the atmosphere that is at all close to isothermal. Using our model, we can calculate representative limiting fluxes using equation 4 and compare to typical escape values. For H, $\phi_{\mathrm{esc,H}} = 1\text{--}1.1 \times 10^8$ cm^{-2}s^{-1}(Jakosky et al., 2018), but the representative limiting flux is $\phi_{\ell,H} = 4\text{--}6 \times 10^8$ cm^{-2}s^{-1}. The similarity in $\phi_{\ell,H}$ and $\phi_{\mathrm{esc,H}}$ means that supply to the upper atmosphere is the most significant barrier to H escape. On the other hand, for D, the typical escape rate is $\phi_{\mathrm{esc,D}} = 5\text{--}14 \times 10^3$ cm^{-2}s^{-1}(E. M. Cangi et al., 2023), and the representative limiting flux is $\phi_{\ell,D} = 4\text{--}5 \times 10^5$ cm^{-2}s^{-1}. The limiting flux being larger than the escape flux means that upper atmospheric supply is not a barrier to escape for D; rather, due to D's higher mass, its energy is the more important controlling factor of its escape. Essentially, on Mars, H escape is diffusion-limited (or supply-limited), while D escape is energy-limited (sometimes also called kinetically limited).

For the remainder of this paper, we will discuss energy-limited escape mostly in reference to D, and diffusion-limited escape in reference to H.

4 Warmer exospheric temperatures increase R_{atomic} by driving H escape and throttling resupply from below

Figures 1 and 2 show the model results from variation of the exobase temperature (which also changes the overall thermospheric temperature, due to the functional form we use for temperature), with altitude profiles of R_{atomic} and H and D densities shown

168   in Figure 1 and time evolution of R_{atomic}, the densities, and their escape fluxes shown

169   in Figure 2.

170   Figure 1a shows the temperature profiles adopted. Ion and electron profiles are held

171   fixed due to limited new data available to constrain them (E. M. Cangi et al., 2023; Han-

172   ley et al., 2022) and the fact that due to observing geometries and instrument pointing

173   requirements, it is difficult to obtain simultaneous temperature measurements of differ-

174   ent populations such as neutrals and ions (Gupta et al., 2022). Panel 1b shows how R_{atomic}

175   and R_{water} respond; R_{water} is mostly unaffected, while R_{atomic} ranges from 2 to nearly

176   $25\times$ VSMOW in the upper atmosphere. This response is largest in the atoms; D/H ra-

177   tios in other species are less pronounced (see Figure S3). Figure 1c shows a minimal change

178   to upper atmospheric D, whereas a higher temperature leads to a $10\times$ rarefaction of H,

179   the same amount by which the D/H ratio increases.

180   Figure 2 shows the same information over the full annual cycle by placing time on

181   the horizontal axis. Panel 2c shows even more clearly that the primary driver of the in-

182   crease in R_{atomic} is the large decrease of the H density.

183   The responses of D and H escape to temperature perturbations are dissimilar, as

184   shown in panels 2d and e. As explained previously, H escape is diffusion-limited, and es-

185   cape depends on both energy available to the escaping atoms and supply of said atoms.

186   Thus, when the temperature rises, a larger fraction of upper atmospheric H suddenly has

187   enough energy to escape, creating the spikes in flux in panel 2d. However, the resupply

188   of H from below is mostly unchanged, so after a short time, the thermospheric H den-

189   sity decreases and H escape returns to its prior value, but the density of H at the exobase

190   is depleted (as discussed by Mayyasi et al., 2018). A similar effect occurs when the tem-

191   perature drops: less energy available means the escape rate suddenly drops, allowing the

192   H abundance near the exobase to rebound, later returning the escape rate to its prior

193   value. The net effect to the seasonally-integrated escape rate is negligible.

194   On the other hand, as long as the temperature is enhanced, so too is D escape, which

195   is energy-limited. There was already plenty of D in the escape region that only needed

196   some extra energy (which is made available by the temperature increase) to escape.

197   The uniqueness of H as a diffusion-limited species on Mars is important in under-

198   standing D/H variations and escape; the D/H ratio of other isotopologue pairs (see Fig-
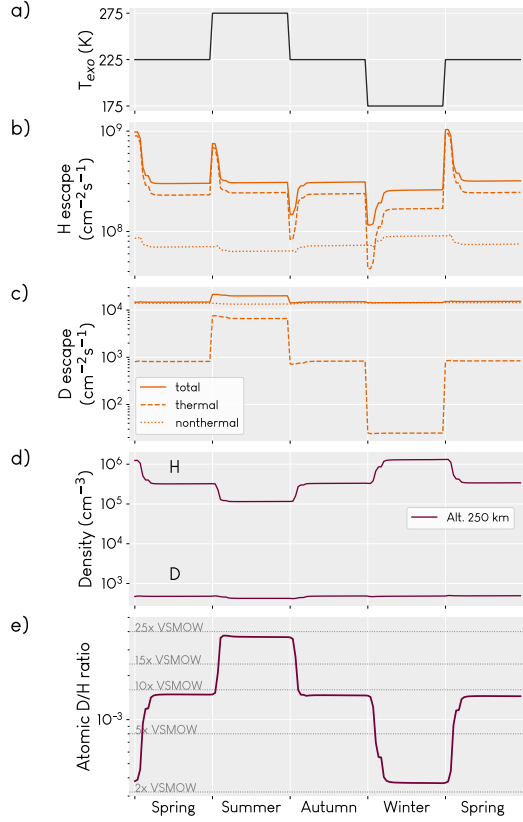
Figure 2. Atmospheric behavior over one Mars year. a) Model input: Exobase temperature. b) H and c) D escape to space (total, thermal, and non-thermal) in response to the temperature changes of panel a). d) Changes to H and D densities as a result of escape and vertical transport. e) The resulting effects on R_{atomic}.
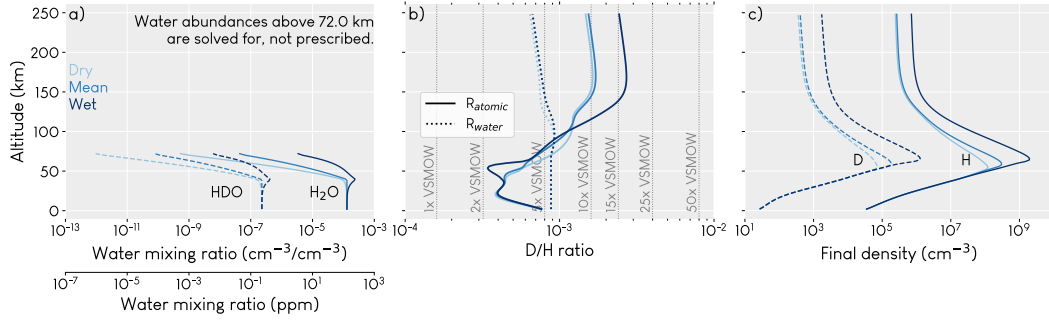
Figure 3. The same as Figure 1, but for different initial mesospheric water abundances (panel a). In panel a, which shows the initial state, we do not include the upper atmosphere (which is solved for in the model). The profile with the most water has a peak mixing ratio of nearly 300 ppm of water at its peak, which is comparable to what has been observed during dust storms (e.g. Vandaele et al., 2019).

ure S3) do not show such dramatic temperature dependence, as heavier molecules in these other isotopologue pairs are less abundant and do not escape as readily as H or D.

5 Extra mesospheric water increases R_{atomic} by supplying more H above the mesosphere

Figure 3 shows the altitude profiles of R_{atomic} and D and H densities that result from varying the mesospheric water abundance. Changing the water abundance in the mesosphere makes only a small difference in the total amount of water in the atmosphere (in precipitable micrometers, it is 10.4, 10.5, and 10.9 pr μm for the low, mean, and high water cases respectively).

Our "perihelion" water profile has nearly 300 ppm at its peak in the mesosphere, which is similar to observations during dust storms, (e.g. Vandaele et al., 2019) and was chosen to demonstrate an edge case of high water conditions. Perturbations of this magnitude to the water profile can also spur an enhancement of R_{atomic} (Figure 3b), but with a smaller magnitude (to 10-15× VSMOW, compared with 2-25× VSMOW in Figure 2c). Figure S8 also shows the D/H ratio in other species.

When water is introduced into the mesosphere, D and H respond differently. The abundances of both species peak at a higher altitude as mesospheric water increases, which is logical given the greater abundance of source water molecules at higher altitudes. The
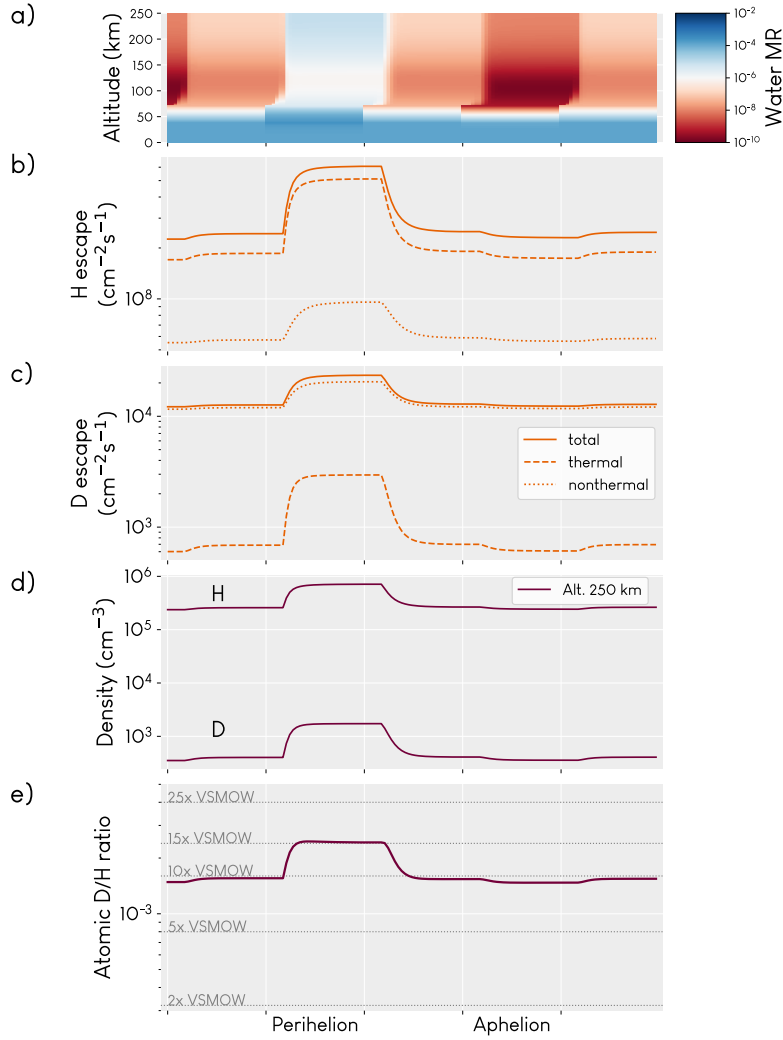
Figure 4. The same as Figure 2, but in response to changing water abundance in the mesosphere, which also propagates upwards. Because the water is supplied above the cold trap, both H and D escape in this scenario are sustained throughout the perihelion season, and the D/H ratio also increases because H escape increases relatively more than D escape.

increase in upper atmospheric D density also exhibits a stronger response to the perturbation than H. This is because no additional energy has come into the system, only supply; thus, D escape does increase somewhat, but not as much as H escape.

The relative changes in escape and density of H and D as a result of mesospheric water are shown in Figure 4. Adding water into the mesosphere has two main effects. First, the dissociated water supplies both D and H to the upper atmosphere. This additional supply enables a greater enhancement of H escape (150% increase) than D es-

cape (85% increase). This is because diffusion-limited H escape is most strongly controlled by the supply of escape-capable atoms, while the main control on D escape is the energy available. We have not changed the temperature (and therefore the energy) in this scenario, so the overall change to D escape is smaller than for H escape. Second, this preferential enhancement of H escape means that the increase of H (a 145% increase) in the upper atmosphere is less pronounced than for D (a 282% increase).

Because of the greater relative enhancement of H escape, we should also expect to see a decreased fractionation factor of escape (E. M. Cangi et al., 2020) when the mesosphere has extra water; this expectation is confirmed in Figure S9.

6 Discussion

The key takeaway is: both thermospheric temperature variations and mesospheric water abundance variations can affect the value of R_{atomic} in the upper atmosphere with similar efficacy, but differ in the effects on escape and raw abundance.

Seasonal periods of high thermospheric temperatures increase R_{atomic} by depleting the upper atmosphere of H. This depletion occurs due to a brief enhancement of H escape (Figure 2d) and reduced, diffusion-limited re-supply from below. At the same time, D escape is enhanced slightly, but not enough to meaningfully deplete the upper atmosphere of D (Figures 1 and 2), and the elevated, energy-limited escape can be sustained as long as the temperature perturbation lasts (Figure 2e). A similar effect on H has been observed during space weather events with MAVEN. In September 2017, heightened solar activity briefly enhanced thermospheric heating caused a 25% decrease in H density and a temporary $5\times$ increase in H escape (Mayyasi et al., 2018), comparable to seasonal variations in H escape.

Seasonal mesospheric water releases extra H and D atoms, increasing the supply of atoms that can more easily reach the escape region. This means that escape of both H and D is sustained while the water perturbation is present. Because of the diffusion-limited nature of H escape, a relatively greater proportion of the H supplied to the upper atmosphere will escape compared to the supplied D. This leads to a build-up of D in the upper atmosphere and an enhanced R_{atomic}.

Close examination of Figure 4 will reveal that while thermal H escape increases by a factor of $\sim 2.5\times$ after the introduction of mesospheric water, non-thermal escape only

increases by a factor of ~ 2. This is likely because the dissociation of water leads directly to the creation of neutral H (D), which can then escape thermally. On the other hand, non-thermal escape occurs when hot H (D) is created in ionospheric reactions, most importantly HCO^+ (DCO^+) dissociative recombination (E. M. Cangi et al., 2023; Gregory et al., 2023). HCO^+ (DCO^+) is a terminal ion (Fox, 2015), so neutral H (D) in the upper atmosphere must first be incorporated into HCO^+ (DCO^+) and then later be freed through dissociative recombination before it can escape non-thermally; evidently, these chemical pathways are already saturated. Along the way, neutral H (D) may also find its way into a number of other species; in essence, the path for H (D) to non-thermal escape is less direct than to thermal escape.

Not all atoms escape. Some H and D may also mix downwards, which is required for the exchangeable reservoir of water to attain its present D/H ratio. It is difficult to quantify the exact amounts which mix down, as we do not track individual atoms, but we can estimate the amount of escape relative to the total H and D columns. Figures S5 and S11 show the same information as Figures 2 and 4, but with an additional plotted line showing the fraction of the total H or D column which escapes; for H, this is $\sim 4 \times 10^{-5}\%$ (0.4 ppm) on average, and for D, $\sim 3 \times 10^{-6}\%$ (0.03 ppm, 30 ppb). The D/H ratio of escaping atoms is also rarely higher than $1\times$ VSMOW (see Figures S6 and S12), consistent with the notion that even in periods of elevated D escape, most D is retained on the planet.

Apart from the drivers of R_{atomic} discussed here, other fractionating processes may add nuance to the mobilization or retention of D. One is the preferential condensation of HDO over H_2O (Bertaux & Montmessin, 2001; Lamb et al., 2017), which may temporarily reduce D escape by sequestering it in the seasonal water ice polar caps (Fisher, 2007; Vos et al., 2022) and clouds (Moores, Osinski, et al., 2011). On the other hand, adsorption fractionation of water on dust grains has a fractionation factor of 1.97 ± 0.74, leading to a D/H ratio up to $21\times$ VSMOW in adsorbed water (Moores, Smith, & Boynton, 2011). Little dust has been observed above 60 km, so dust adsorption/desorption is not thought to be a direct delivery method for water above that altitude (Neary et al., 2020; Vandaele et al., 2019; A. Fedorova et al., 2018), but the process may enable D to reach the bottom of the mesosphere; at present, dedicated studies in this area are not available in the literature.

Similarly large values of R_{atomic} have been observed at Mars with the MAVEN IUVS instrument. Using the low resolution mode, Chaufray et al. (2021) calculated R_{atomic} at 200 km and T= 220 K up to $1.7 \pm 0.4 \times 10^{-2}$, or $106\times$ VSMOW; other values range as low as $1\times$ VSMOW, but frequently fall between 20–$40\times$ VSMOW. Through observations of the H corona, Chaffin et al. (2018) calculated $R_{atomic}=20$–$91\times$VSMOW. Measurements of R_{atomic} using the echelle channel (higher resolution) are also currently underway, with initial results hinting at a strong seasonal response in both D and H brightness and R_{atomic} (Clarke et al., 2022). Past work by the same team has also revealed seasonal enhancement of atomic D brightness without a concurrent atomic D/H ratio calculation (Mayyasi et al., 2019). Our results generally agree with these measurements while also adding the important context of the two distinct drivers of R_{atomic}.

7 Conclusion

Our results demonstrate that thermospheric R_{atomic}, rather than R_{water}, is more sensitive to short-term perturbations in the atmospheric system due to its sensitive dependence on both thermospheric temperature and mesospheric water. Seasonal changes to these two parameters lead to similar effects on R_{atomic}, but affect the thermospheric abundances of D and H and their escape rates differently. The cause of these variations in the thermosphere is differences in the dynamics of H and D in the mesosphere; H escape is diffusion-limited, while D escape is energy-limited.

Mars is unique in the fact that its gravity, atmospheric pressure and thickness, and presence of water vapor combine to create a situation where the diffusion and escape behaviors of H and D are so different. Since other planets in the solar system have either much higher gravity, thicker atmospheres, or much less water, the same situation may not arise for H and D on other bodies. However, the lessons learned here may be potentially applied to other isotope systems on other terrestrial planets with atmospheres.

Cross-correlation of martian datasets containing upper atmospheric R_{atomic}, thermospheric temperatures, and mesospheric water would enhance our understanding of the martian climate and water cycle. Concurrent measurements could be ingested into photochemical and climate models, providing realistic constraints, refining estimates of atmospheric escape, and helping to identify knowledge gaps. Such an approach could also

provide insight into the dynamics of water, H, and D in the relatively difficult-to-observe upper mesosphere and lower thermosphere ($\sim$ 80-110 km).

In our quest to understand the long-term evolution of the stability of water on terrestrial planets, we must continue working both to understand the specific effects of individual processes and to develop synoptic-scale understanding of the complex ways that surfaces and atmospheres interact and alter one another.

8 Open Research

Our model, bluejay, is available on Zenodo (E. Cangi & Chaffin, 2023); the working copy is available in the linked Github repository. bluejay is written for Julia 1.8.5 (Bezanson et al., 2017).

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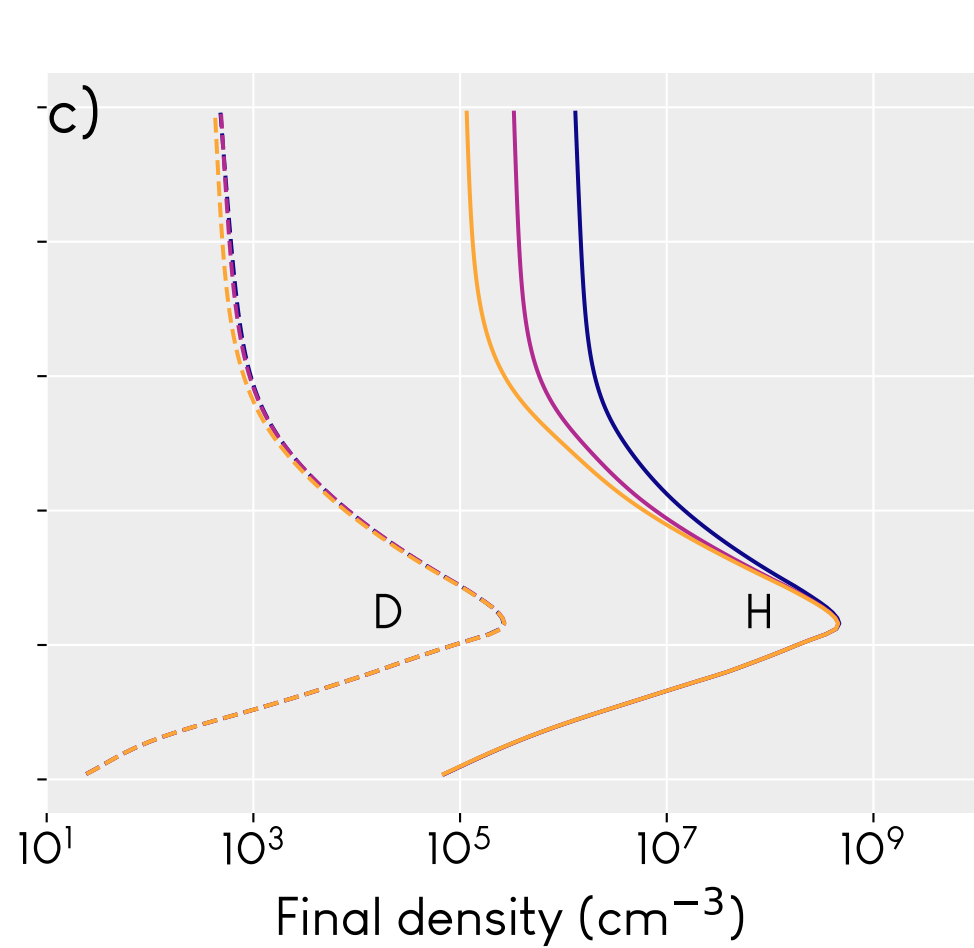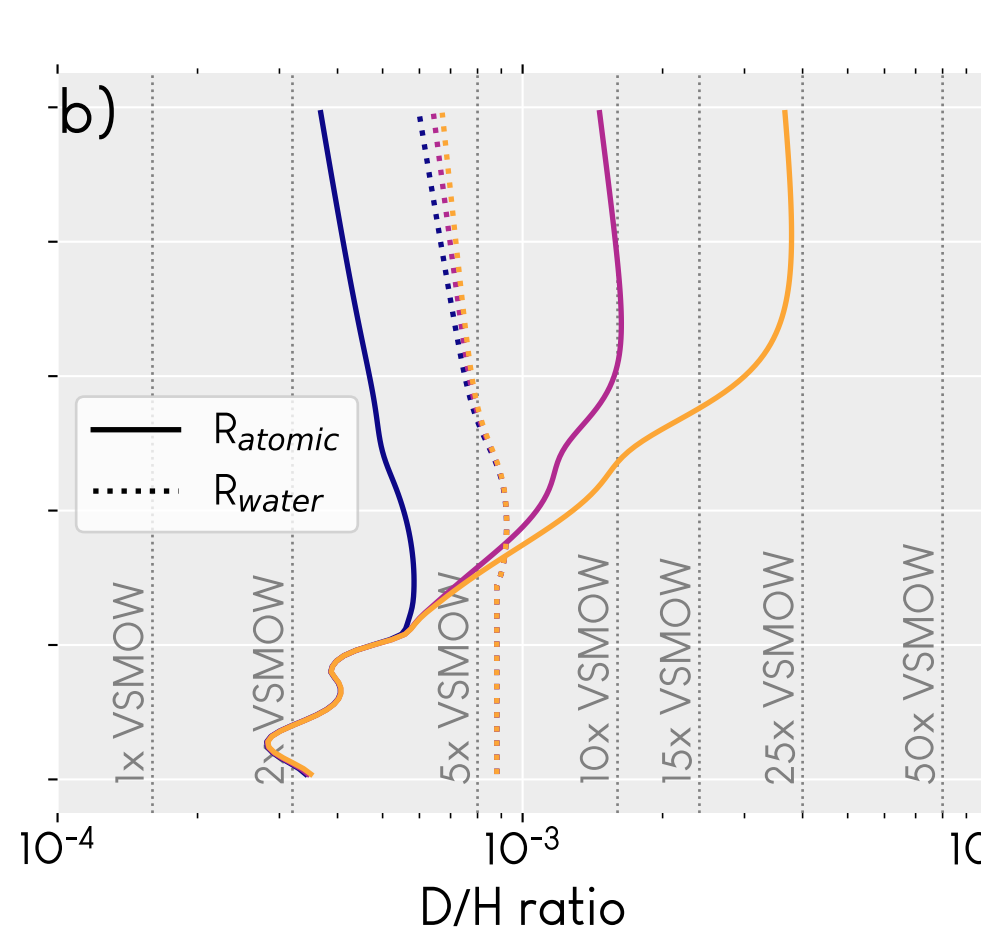
Figure 2.

a) Neutrals — 175 K, 225 K, 275 K; Ions; Electrons; 130 K; 230 K

b) R_{atomic} (solid), R_{water} (dotted); 1x VSMOW, 2x VSMOW, 5x VSMOW, 10x VSMOW, 15x VSMOW, 25x VSMOW, 50x VSMOW

c) D, H

Figure 4.

a)

Altitude (km)

Water MR

b)

H escape (cm^{-2}s^{-1})

c)

D escape (cm^{-2}s^{-1})

total
thermal
nonthermal

d)

Density (cm^{-3})

H

D

Alt. 250 km

e)

Atomic D/H ratio

25x VSMOW

15x VSMOW

10x VSMOW

5x VSMOW

2x VSMOW

Perihelion

Aphelion

Figure 3.

a)

Water abundances above 72.0 km are solved for, not prescribed.

Dry
Mean
Wet

HDO

H_2O

Altitude (km)

Water mixing ratio (cm^{-3}/cm^{-3})

Water mixing ratio (ppm)

b)

R_{atomic}
R_{water}

1x VSMOW
2x VSMOW
5x VSMOW
10x VSMOW
15x VSMOW
25x VSMOW
50x VSMOW

D/H ratio

c)

D

H

Final density (cm^{-3})

Figure 1.

a) T_{exo} (K)

b) H escape $(cm^{-2}s^{-1})$

c) D escape $(cm^{-2}s^{-1})$

- total
- thermal
- nonthermal

d) Density (cm^{-3})

H

D

Alt. 250 km

e) Atomic D/H ratio

25x VSMOW

15x VSMOW

10x VSMOW

5x VSMOW

2x VSMOW

Spring   Summer   Autumn   Winter   Spring