Estimating the Escape of Hydrogen and Deuterium from the Atmosphere of Mars

John Clarke
Majd Mayyasi
Dolon Bhattacharyya
& the IUVS team

ESLAB Aeronomy Noordwijk
Determining the Global Escape Flux from Mars

- One of the primary goals of the MAVEN mission is to determine the escape rate of water and the controlling physical processes.

- To determine the escape fluxes of H and O we need to know their densities and velocity distributions at the “exobase”.

- The escape rate can also be limited by the flux of replacing atoms from below – need to understand diffusion from the lower atmosphere.

- To determine the global escape flux we need to average across the globe, i.e. a range of different temperatures and densities

- MAVEN’s long-term mission and moving orbit provide global coverage over a period of months to years
Determining H and D Densities and the D/H Ratio

- The D/H ratio relates to the historic loss of water into space - a higher D/H ratio results from higher total escape.

- We need to understand the detailed physics of the upward diffusion and escape of both D and H to be able to extrapolate into the past and find the history of water on Mars.

- The D/H ratio would be the same as HDO/H₂O in the lower atmosphere when the upward diffusion of H and D is slow.

- We now know that H and D both vary by an order of magnitude with martian seasons, peak near southern solstice.

- We are finding that the D/H ratio is strongly enhanced near perihelion, while close to the lower atmosphere at aphelion.
HST Observations of H Exosphere - Sept 2016 - Jan 2017

- Brightness of H Ly α emission from scattered solar photons
- Different observations are color-coded by time, max H was after perihelion
- See Bhattacharyya poster for more info

Altitude profiles put constraints on H population and escape fluxes, and the high degree of variability is clear

Bhattacharyya et al., 2017
Large changes in D that repeat with subsequent seasons (Mayyasi et al. 2016)

Note detection limit ~ 100 Rayleighs

Peak value is not at perihelion, and may be later than southern summer solstice
Challenges in Estimating H and D Densities and D/H Ratio

Need accurate absolute sensitivity calibration to obtain accurate H and D densities.

- New HST observations in Jan. 2018 established the cross-calibration of ACS and STIS instruments - now self-consistent and tied to MAVEN IUVS calibration (IPH)

Degeneracy between density (n) and temperature (T) in interpreting the emission brightness.

- Using MAVEN NGIMS and IUVS measurements to constrain the temperature, then set the density to fit the brightness

Variations in n and T with solar zenith angle (SZA) and local time

- Use averaged MAVEN measured T decrease from noon to midnight and theoretical SZA variation in H density
Challenges in Estimating H and D Escape Fluxes

Different rates of diffusion of atoms from below with time and solar zenith angle – thermospheric dynamics.

- This requires GCM’s and theoretical models for understanding

Presence and number of superthermal atoms strongly changes escape flux.

- New progress on the identification of hot H atoms from recent HST observations – see Bhattacharyya poster

Differences between H and D with all of the above.

- Will require future modeling
Different Rates of Upward Diffusion - Thermospheric Dynamics

GCM modeling of global atmosphere show complex dynamics and seasonal changes in H density and escape flux due to changing solar EUV flux (Chaufray et al., Icarus, 2015)

- Modulation is almost x10, and shape is close to sinusoidal (similar to $1/R^2$)
- Model also shows x5 change from solar min to solar max
- Plot shows global escape flux, but there are also complex dynamical effects - large variations with location
- Alternative is upward flux of water near perihelion, may lead to more narrow increase

New HST Observations Show Hot H in Martian Exosphere

- Bhattacharyya et al. poster shows new HST data from Jan. 2018
- Observations made near Mars aphelion (low temp and compact exosphere) when Mars was far from the Earth (see to high altitudes)
- Data (in black) show apparent 2 component scale heights in emission
- RT model (in red) shows expected profile for measured temp - does not fit the data!
- Difference is hot H
Preliminary H and D Densities and Ratio

- D densities based on MAVEN altitude profiles of D Ly α emission close to perihelion with non-symmetric atmosphere

- H densities based on HST observations at similar L_s range - used symmetric atmosphere but constrained by high altitudes

- D/H ratio is a factor of several times larger than the aphelion value (consistent with HDO/H_2O) observed earlier in HST spectra

<table>
<thead>
<tr>
<th>L_s bins</th>
<th>D density</th>
<th>H density</th>
<th>D/H ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>aphelion</td>
<td>1033 ± 110</td>
<td>254500 ± 17868</td>
<td>0.001 (global)</td>
</tr>
<tr>
<td>220 – 240</td>
<td>800 ± 100</td>
<td>180000 ± 13000</td>
<td>0.0044 ± 0.00077</td>
</tr>
<tr>
<td>240 - 260</td>
<td>1450 ± 70</td>
<td>250000 ± 30000</td>
<td>0.0058 ± 0.00087</td>
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<tr>
<td>260 - 280</td>
<td>3350 ± 143</td>
<td>500000 ± 73000</td>
<td>0.0067 ± 0.0011</td>
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<tr>
<td>280 – 300</td>
<td>1000 ± 206</td>
<td>289000 ± 42000</td>
<td>0.0035 ± 0.0011</td>
</tr>
</tbody>
</table>

- Framework for explanation
Possible Solution to Uncertainties in Global Escape Flux

Take a Global Average

Reasons for optimism:

- At low altitudes, atoms are mainly from local region
- At high altitudes, atoms come from all over

Also, at high altitudes there is a higher fraction of hot atoms - use highest altitudes to constrain superthermal population
Summary: Estimating H and D Escape

Progress is being made on several fronts in efforts to nail down global H and D escape fluxes and D/H ratio:

- Improved absolute calibration of IUVS and HST to get accurate densities for D and H
- Derive a model thermospheric T with SZA and L_s, then fit density - use combination of models and MAVEN data
- Need also to determine local time variations in H density - use theoretical formulation from R. Hodges
- Determine contribution of hot H from high altitude brightness distribution(s) - requires HST data and new observations
- Determine the minimum D brightnesses near aphelion - HST proposal will be submitted
Backup Slides
H and D Ly α Brightnesses over Time - Observing Coverage

May 2018
ESLAB Aeronomy Noordwijk
Differences Between H and D

D and H have different reaction rates, can lead to differences in D/H ratio at different altitudes:

- HDO has lower vapor pressure (solid to gas) than H$_2$O
- Water ice clouds are enriched in D compared with H
- Upward moving water clouds can enrich D/H ratio in middle atmosphere
- H$_2$O and HDO have different rates of photodissociation, also contributes to changes in upper atmosphere

Differences in Water Vapor:

Figure 16. Globally and annually averaged vertical distributions of water vapor (on the left) and of the D/H ratio (on the right).

Montmessin et al., JGR (2005)
Future Observations of D and H

Seasonal Changes:

- Keep looking with MAVEN IUVS and record the shape of the changes with $L_S$.
- We have applied for HST time to measure D brightness and H exosphere brightness distribution near aphelion.

Calibration:

- HST can observe Mars H with two different instruments, one (STIS) with a much better absolute calibration.
- We have applied for HST time to cross-calibrate the ACS and STIS sensitivities.