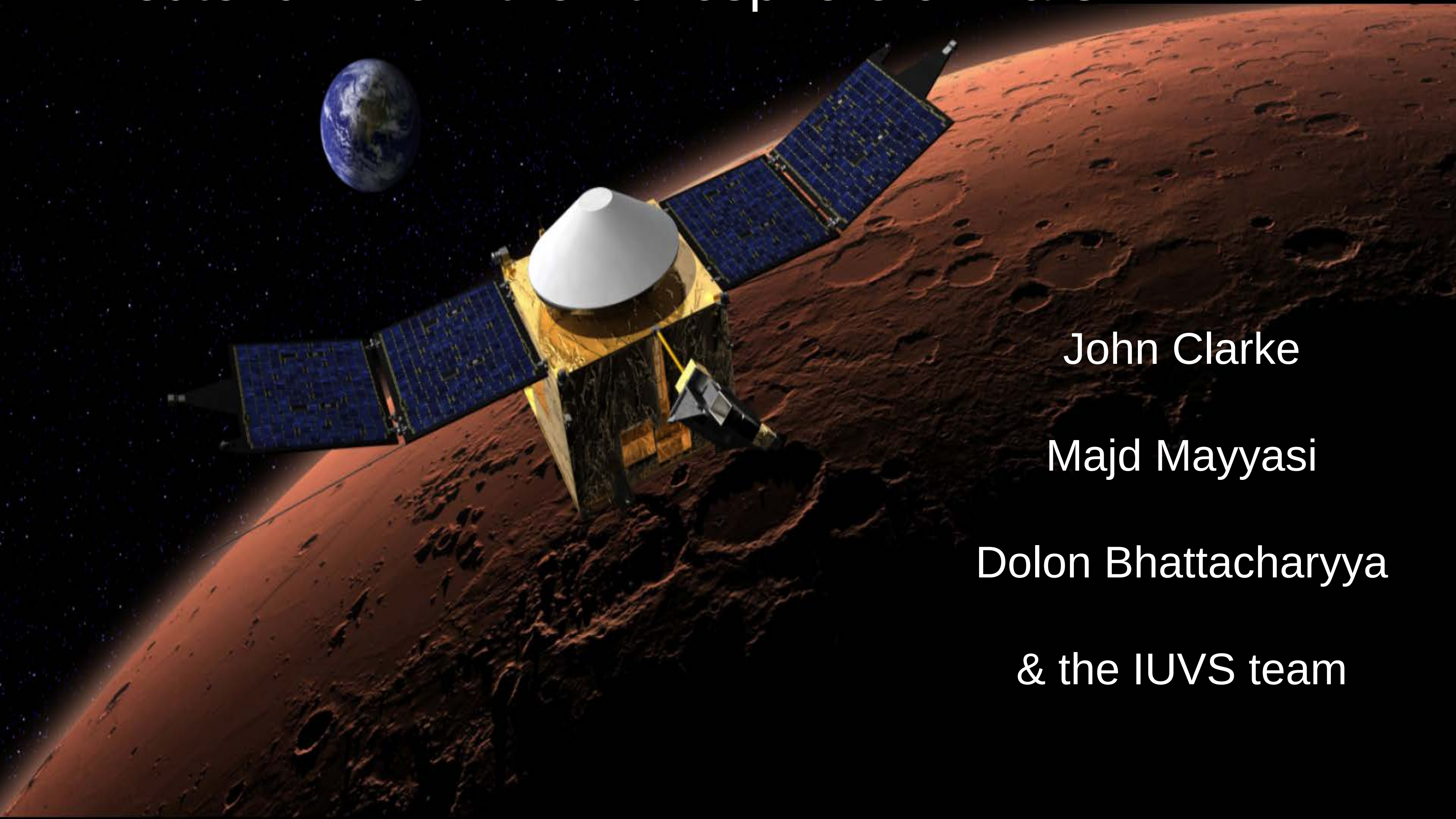
Estimating the Escape of Hydrogen and Deuterium from the Atmosphere of Mars



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Determining the Global Escape Flux from Mars

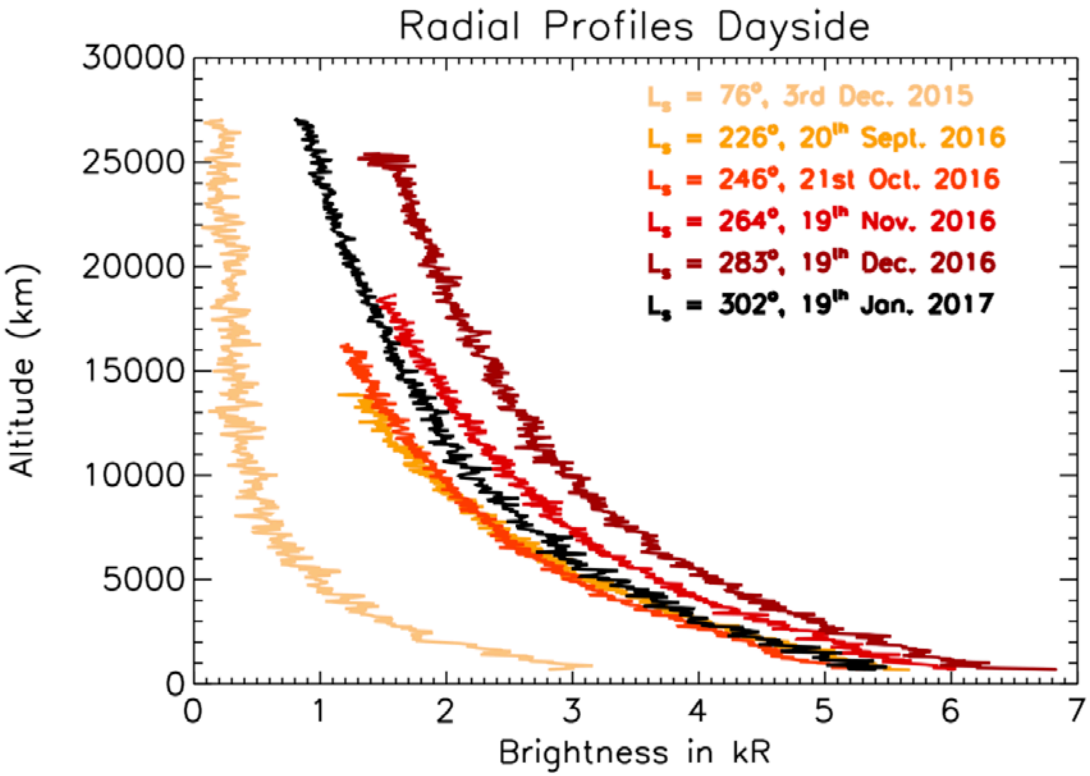
- One of the primary goals of the MAVEN mission is to determine the escape rate of water and the controlling physical processes.
- To determine the escape fluxes of H and O we need to know their densities and velocity distributions at the "exobase".
- The escape rate can also be limited by the flux of 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/H_2O 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

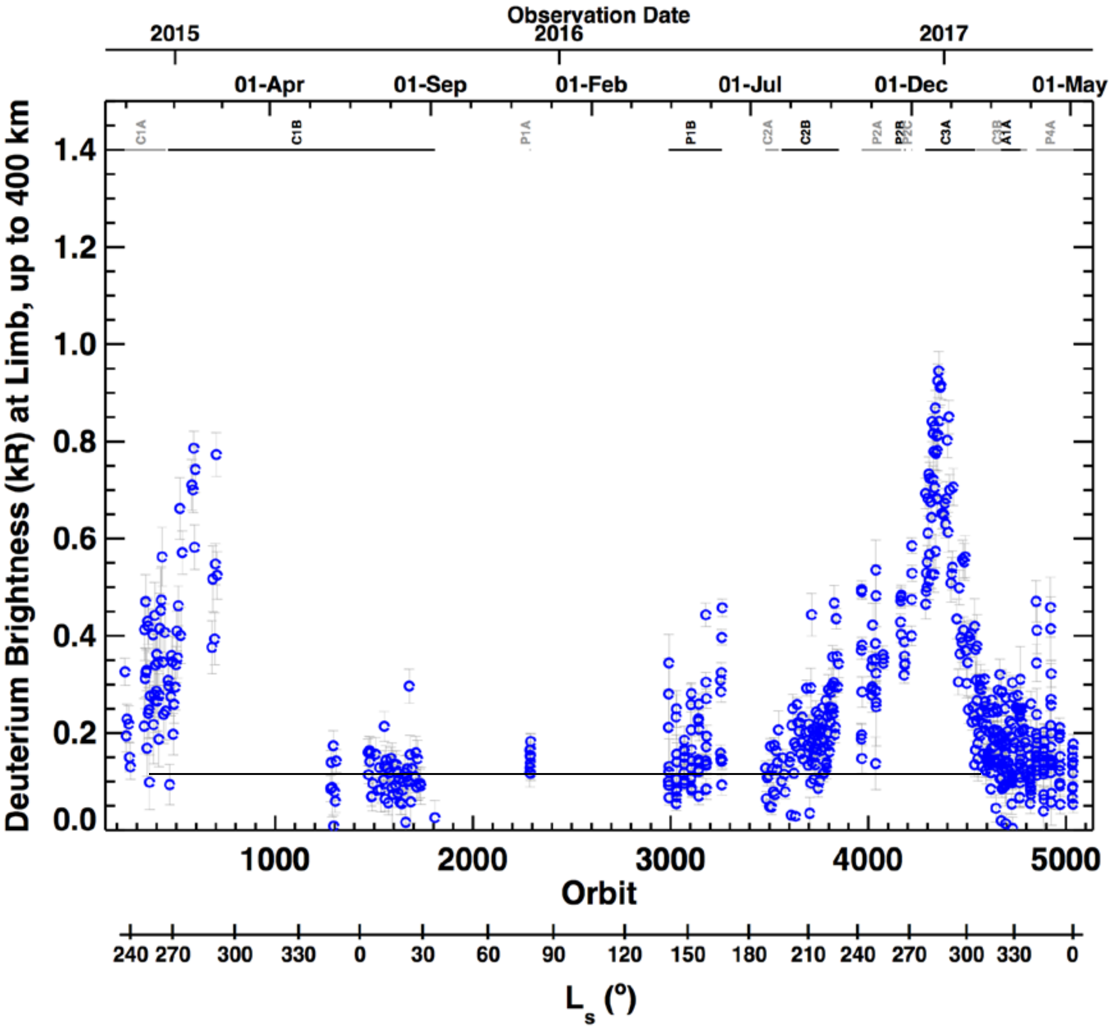


Bhattacharyya *et al.*, 2017

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

D Ly α Brightness Variations with Mars Seasons from MAVEN IUVS Echelle Data

- 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

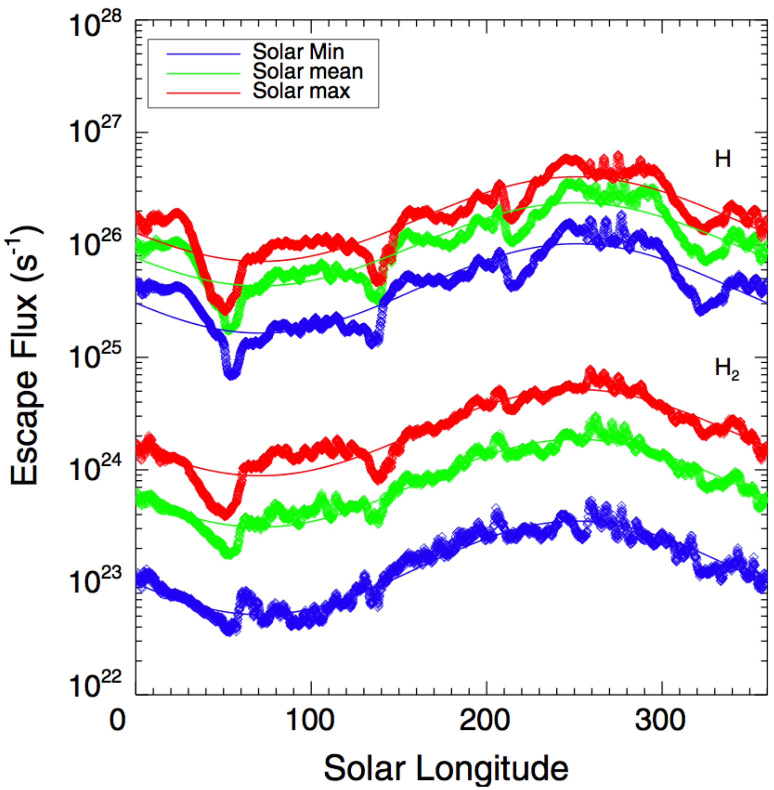
Differences between H and D with all of the above.

- 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

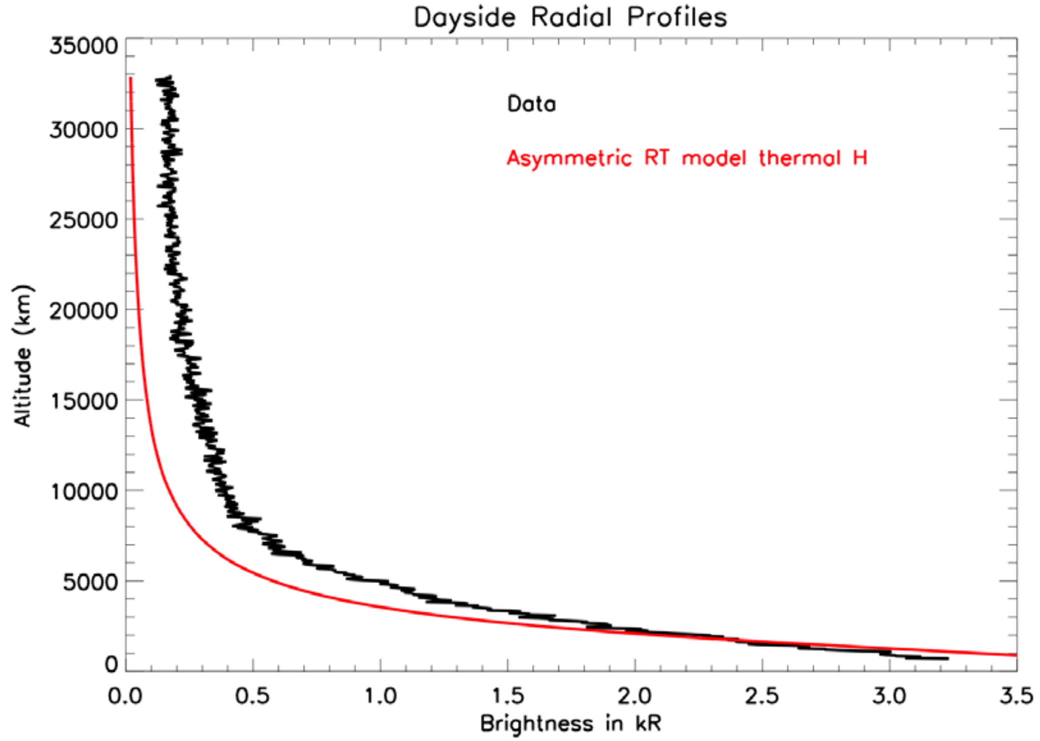


Chaufray *et al. Icarus* (2015)

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

L_s bins	D density	H density	D/H ratio
aphelion			0.001 (global)
220 – 240	1033 ± 110	254500 ± 17868	0.0041 ± 0.00073
240 - 260	800 ± 100	180000 ± 13000	0.0044 ± 0.00077
260 - 280	1450 ± 70	250000 ± 30000	0.0058 ± 0.00087
280 – 300	3350 ± 143	500000 ± 73000	0.0067 ± 0.0011
300 - 320	1000 ± 206	289000 ± 42000	0.0035 ± 0.0011

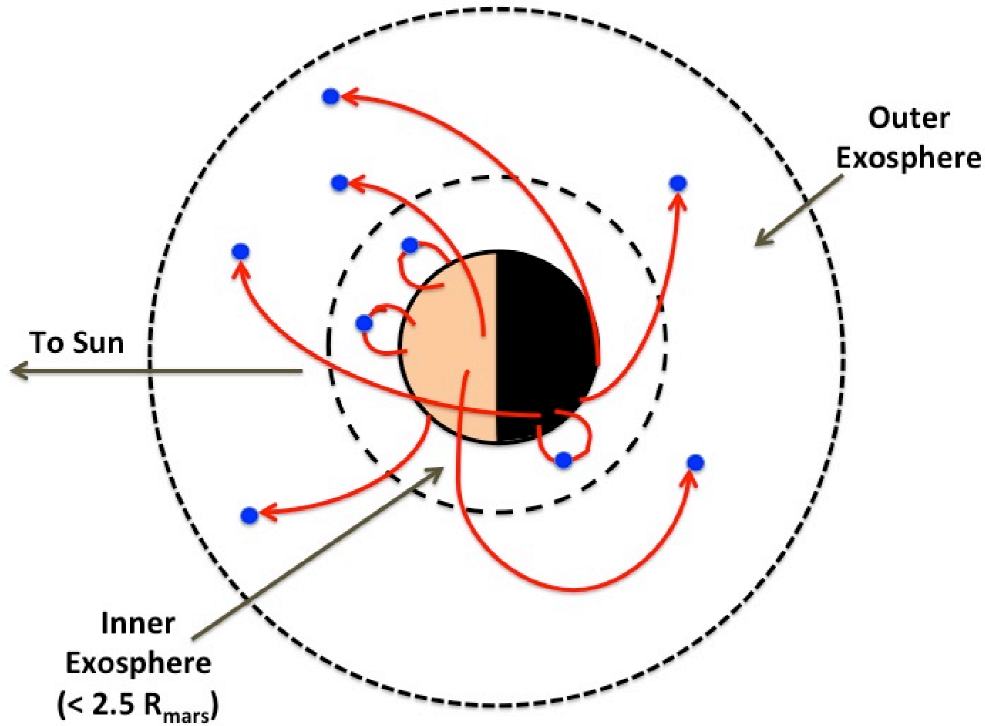
- Framework for explanation

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

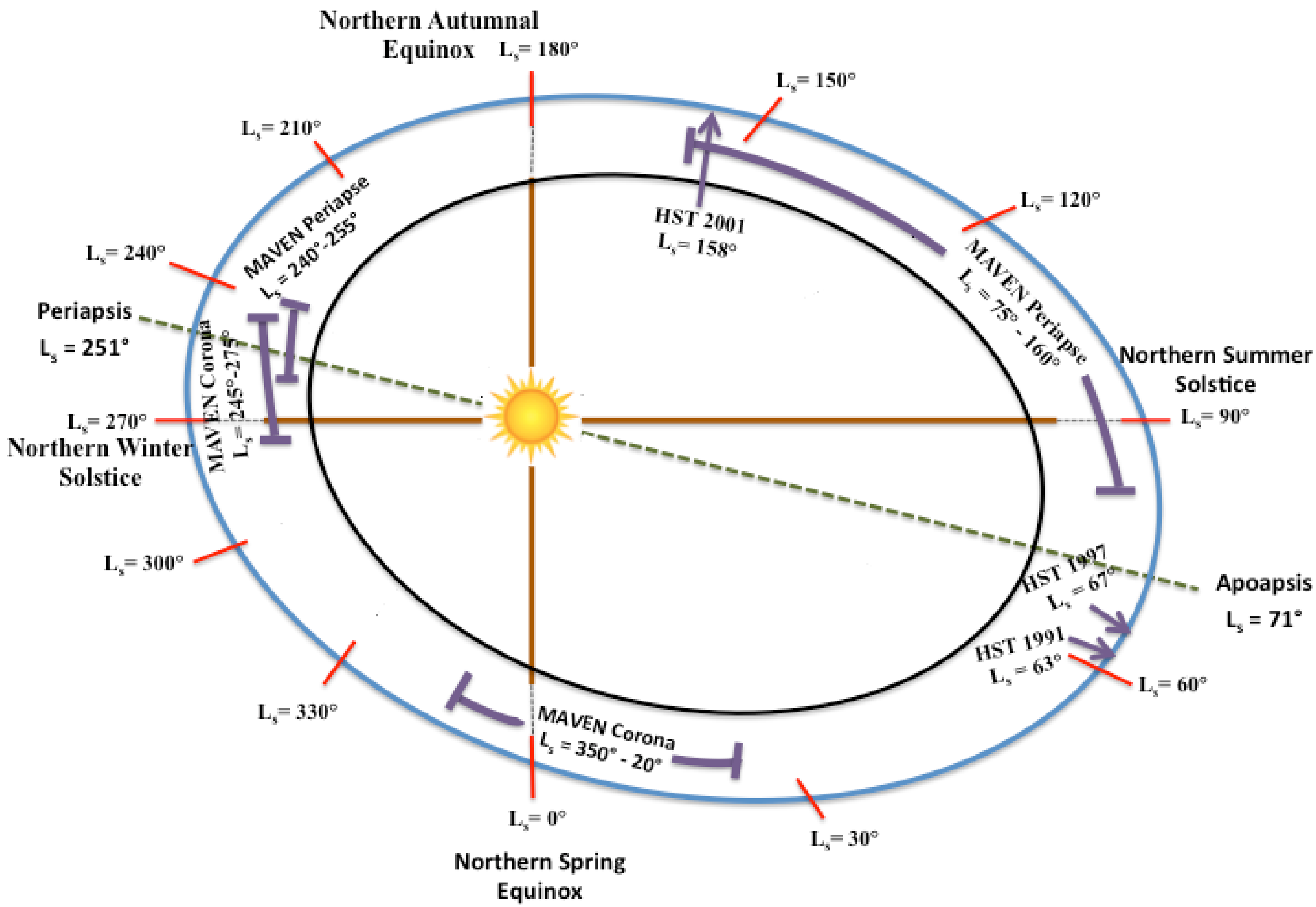
Summary: Estimating H and D Escape

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 a Brightnesses over Time – Observing Coverage



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_2O
- Water ice clouds are enriched in D compared with H
- Upward moving water clouds can enrich D/H ratio in middle atmosphere
- H_2O and HDO have different rates of photodissociation, also contributes to changes in upper atmosphere

Differences in Water Vapor:

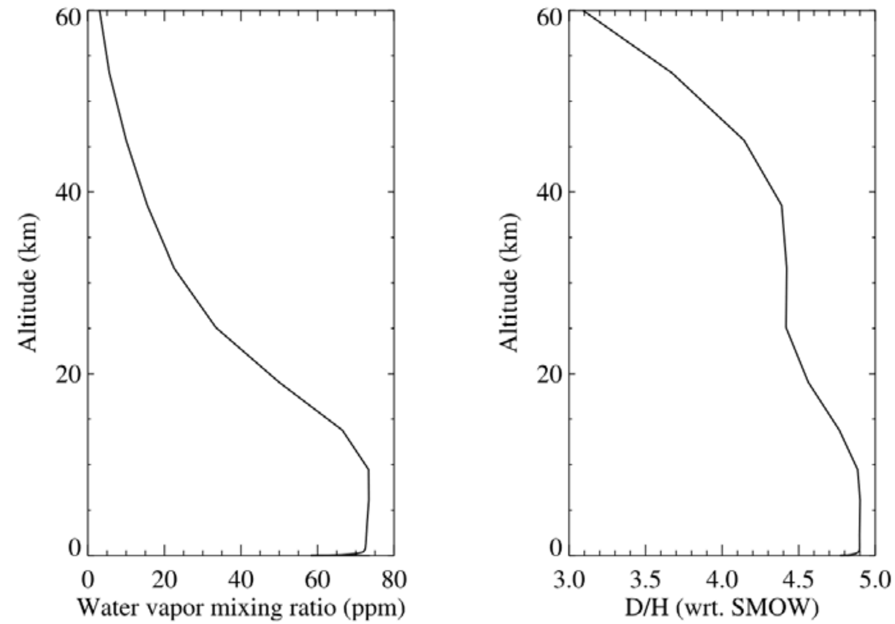


Figure 16. Globally and annually averaged vertical distributions of water vapor (on the left) and of the D/H ratio (on the right).

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.