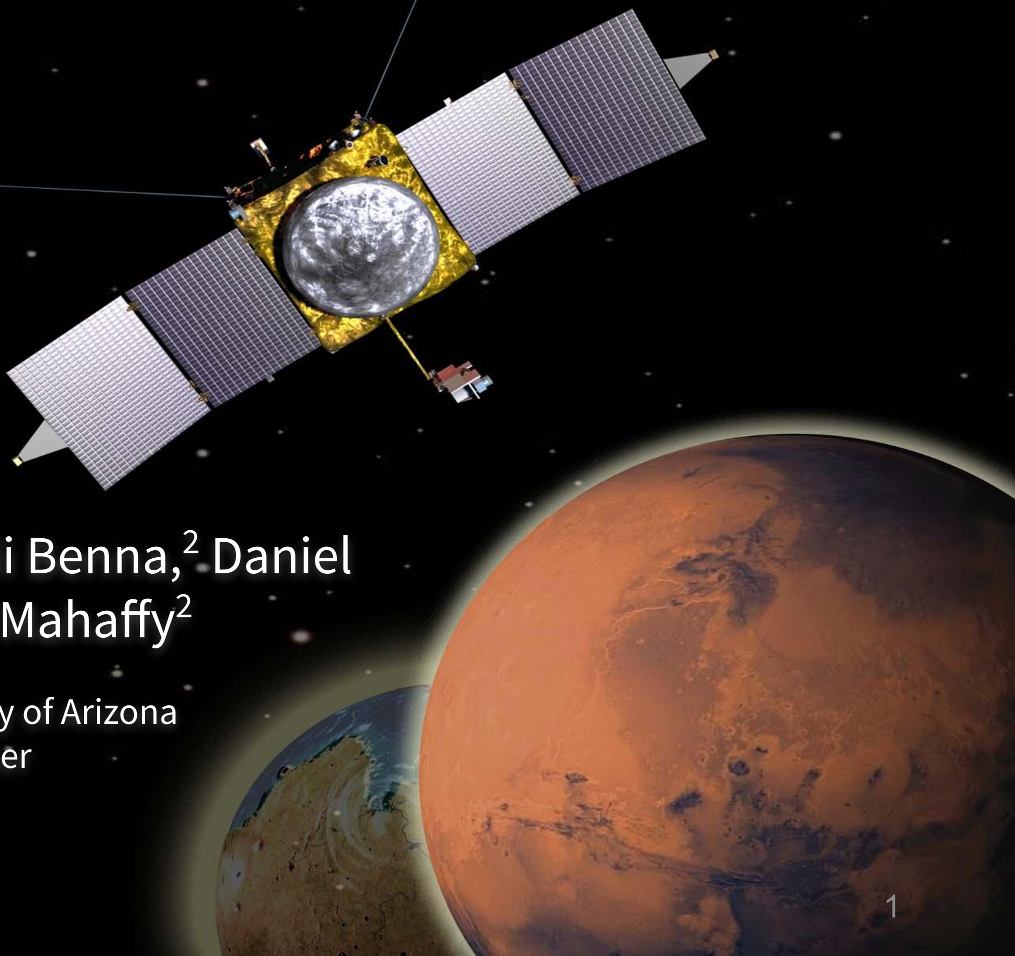
Hydrogen Escape from Mars is Driven by Seasonal and Dust Storm Transport of Water



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Introduction

- H escape to space could account for the loss of 85% of the initial water inventory of Mars over the last 4 billion years.

- Previous investigations have found seasonal variations of an order of magnitude or more in the upper atmospheric H density, implying a similar variation in the H escape rate. *Chaffin et al.* (2014), *Clarke et al.* (2014), *Bhattacharyya et al.* (2015), *Clarke et al.* (2017)
  - These variations are too rapid to be explained by the slow and steady delivery of H_2 from the lower atmosphere by diffusion. This is the "classical" source of H.

- Rapid seasonal and dust-storm-induced changes in the vertical distribution of H_2O have now been observed by MCS, SPICAM, ACS, and NOMAD. *Heavens et al.* (2018), *Fedorova et al.* (2018, 2019), *Vandaele et al.* (2019)

- H_2O transported to the upper atmosphere is rapidly destroyed and the H produced can escape efficiently. MAVEN Neutral Gas and Ion Mass Spectrometer (NGIMS) is uniquely positioned to collect *in situ* measurements of neutral and ionic species in the upper atmosphere.

Classical Source of H

4) Jeans escape of H

Upper Atmosphere

3) $CO_2^+ + H_2 \longrightarrow HCO_2^+ + H$

Hygropause

2) Diffusion of H_2

$H_2O\,(g) \longrightarrow H_2O\,(l)$

Lower Atmosphere

1) $H + HO_2 \longrightarrow H_2 + O_2$

New Source of H

4) Jeans escape of H

Upper Atmosphere

3)

$CO_2^+ + H_2O \longrightarrow H_2O^+ + CO_2$

$HCO^+ + H_2O \longrightarrow H_3O^+ + CO$

$H_3O^+ + e^- \longrightarrow H_2O + H$

Weak Hygropause

2) Transport of H_2O

Lower Atmosphere

1) $H_2O\,(s) \longrightarrow H_2O\,(g)$

Direct Transport of Water

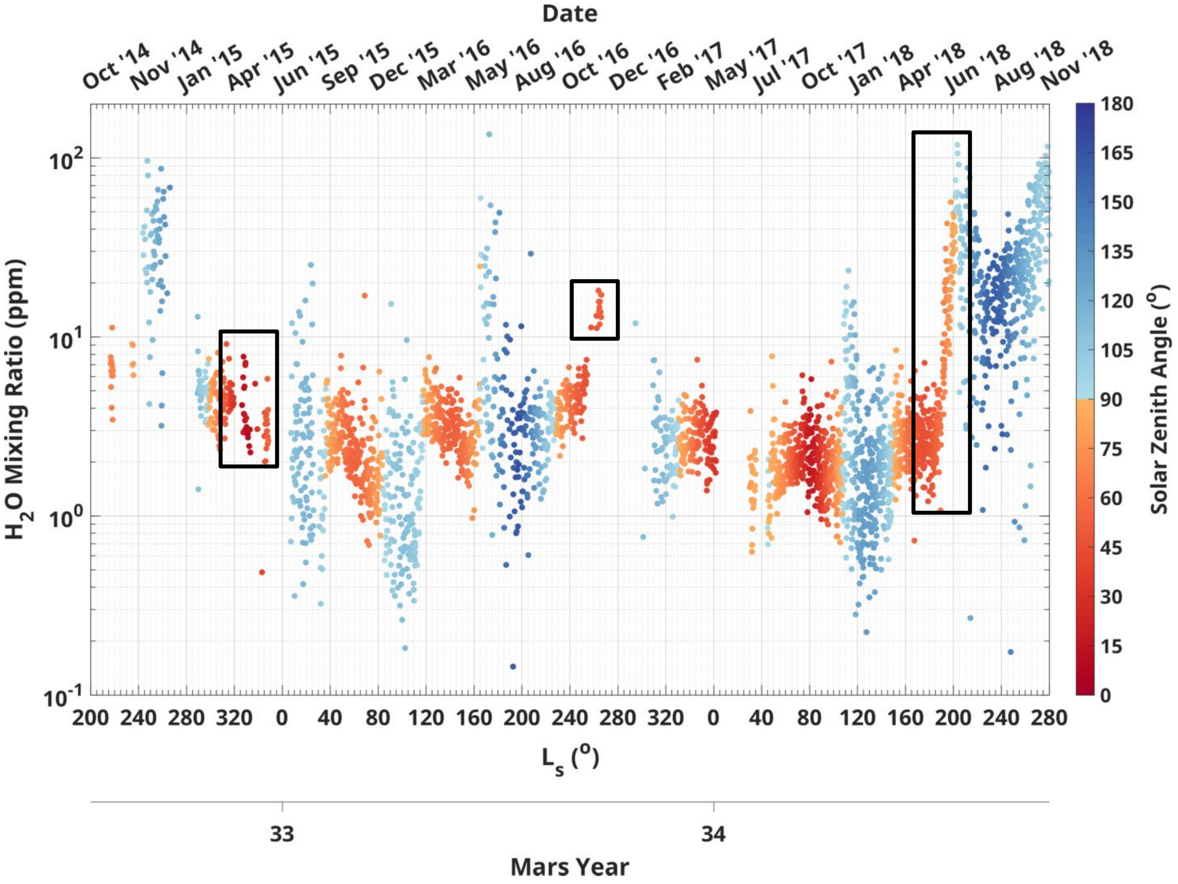
- Diffusion of H_2 is slow and steady, too slow to explain observed rapid order-of-magnitude variations in the exospheric H abundance.

- Transport of H_2O from the lower atmosphere, however, is fast enough. *Fedorova et al.* (2018, 2019), *Heavens et al.* (2018), *Vandaele et al.* (2019)

- NGIMS data can be used to investigate the diurnal, seasonal, and dust-related variation of water and water-related ions in the upper atmosphere of Mars.
  - We measure abundances of H_2O^+ and H_3O^+.
  - We calculate H_2O abundances from NGIMS measurements assuming photochemical equilibrium and use direct measurements of H_2 from the NGIMS neutral mode.

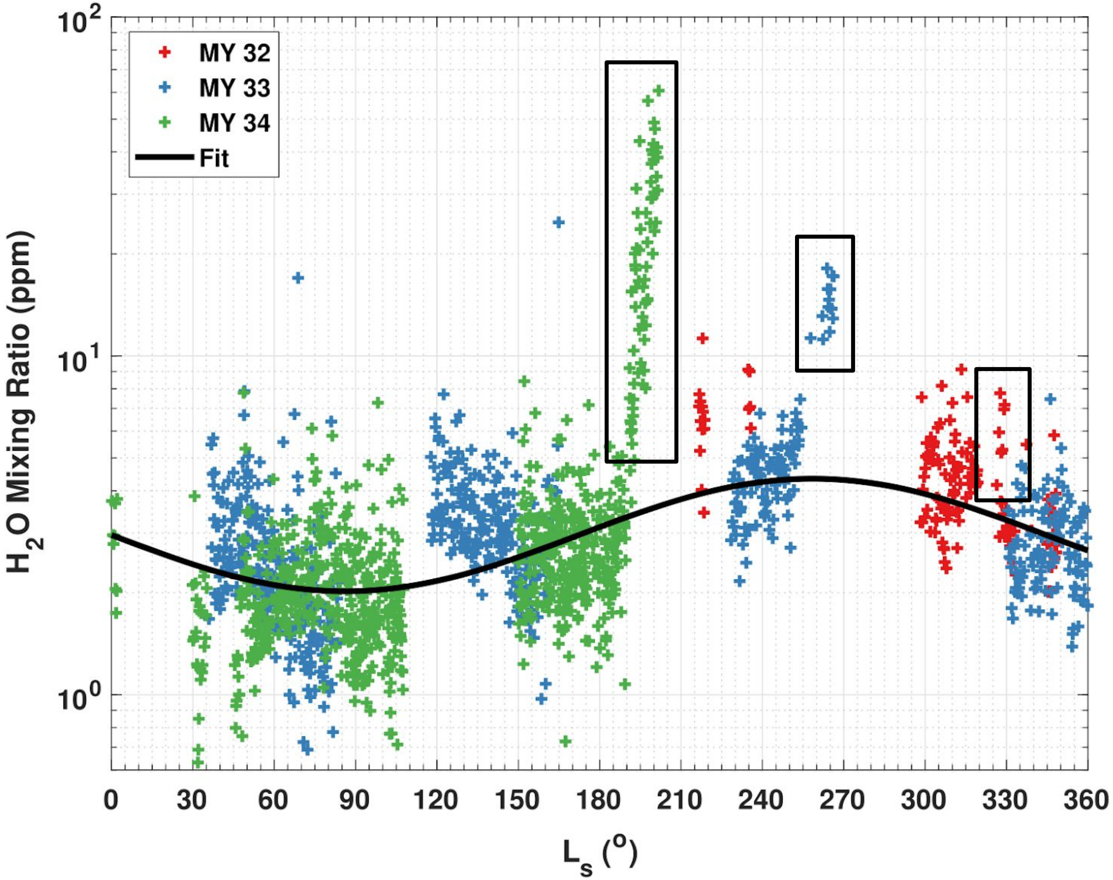
- This allows us to differentiate between the transport of H_2O and H_2 to the upper atmosphere.

VARIATION OF WATER



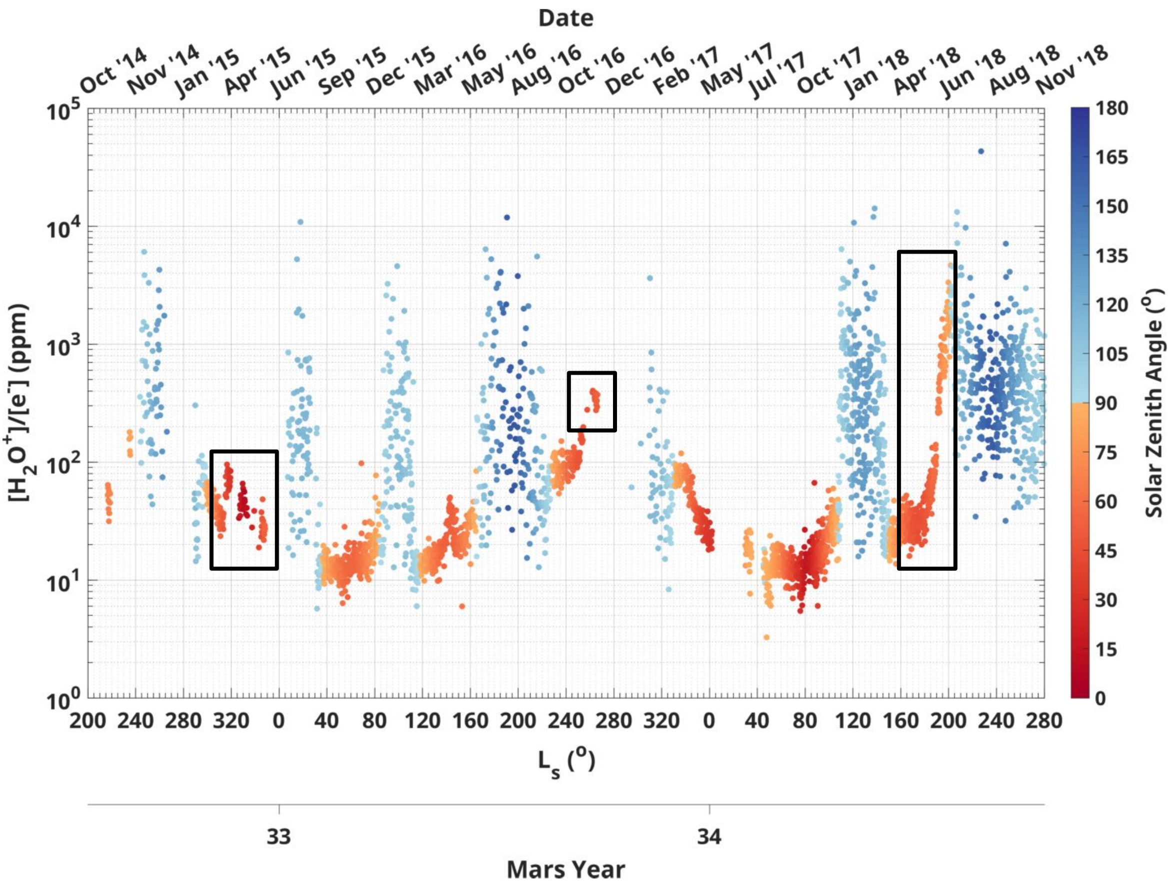
- The sinusoidal seasonal variation is apparent in the H_2O mixing ratio.
- Dust storms lead to a significant increase in the H_2O mixing ratio over a short time period.
- There are no strong seasonal or dust-storm-induced variations in measured H_2 abundances.

Variation of Water



- The upper atmosphere (~150 km) contains >1 ppm H_2O throughout the Martian year.
- The transport of water into the upper atmosphere is seasonal, peaking in southern summer.
  - The largest water vapor maximum in the lower atmosphere occurs during northern summer.
- Southern summer occurs near perihelion and this is the season of high dust activity.

Variation of Water Ions



- H_2O^+ is a chemical intermediate that lies between an injection of H_2O from below and H escape from the top of the atmosphere.
- There are clear diurnal and seasonal variations in the relative abundance of H_2O^+.
- We observe an abrupt, marked increase in H_2O^+ immediately following the onset of dust activity during 3 dust storms.
- Similar, but smaller, variations are observed in H_3O^+.

Calculating Water Densities

- Assuming photochemical equilibrium, we construct simple equations for the calculation of **H_2O** abundance from NGIMS ion and CO_2 measurements:

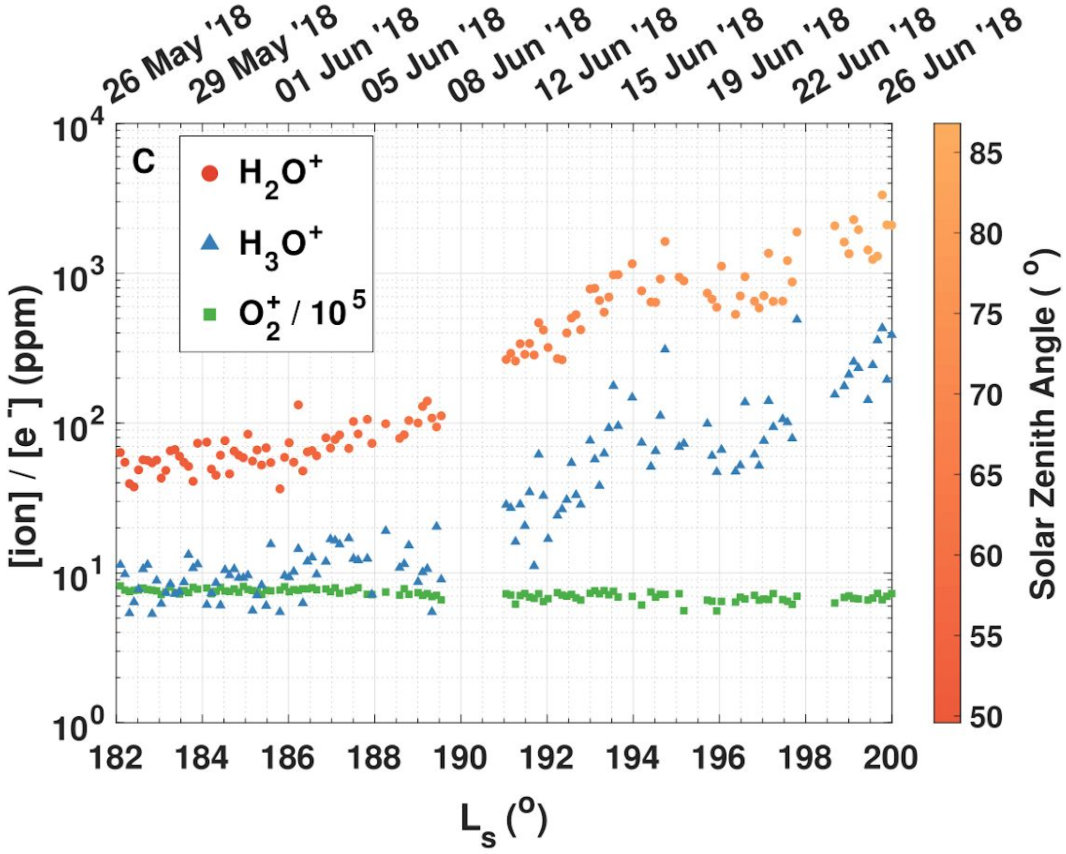
$$\mathrm{HCO^+ + H_2O \xrightarrow{k_1} H_3O^+ + CO}$$

$$\mathrm{H_2O^+ + H_2O \xrightarrow{k_2} H_3O^+ + OH}$$

$$\begin{aligned} \mathrm{H_3O^+ + e^-} &\xrightarrow{\alpha_1} \mathrm{OH + H + H} \\ &\xrightarrow{\alpha_2} \mathrm{H_2O + H} \\ &\xrightarrow{\alpha_3} \mathrm{OH + H_2} \\ &\xrightarrow{\alpha_4} \mathrm{O + H_2 + H} \end{aligned}$$

$$\boxed{[\mathrm{H_2O}] = (\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4) \frac{[\mathrm{H_3O^+}][\mathrm{e^-}]}{k_1[\mathrm{HCO^+}] + k_2[\mathrm{H_2O^+}]}}$$

DUST EVENTS

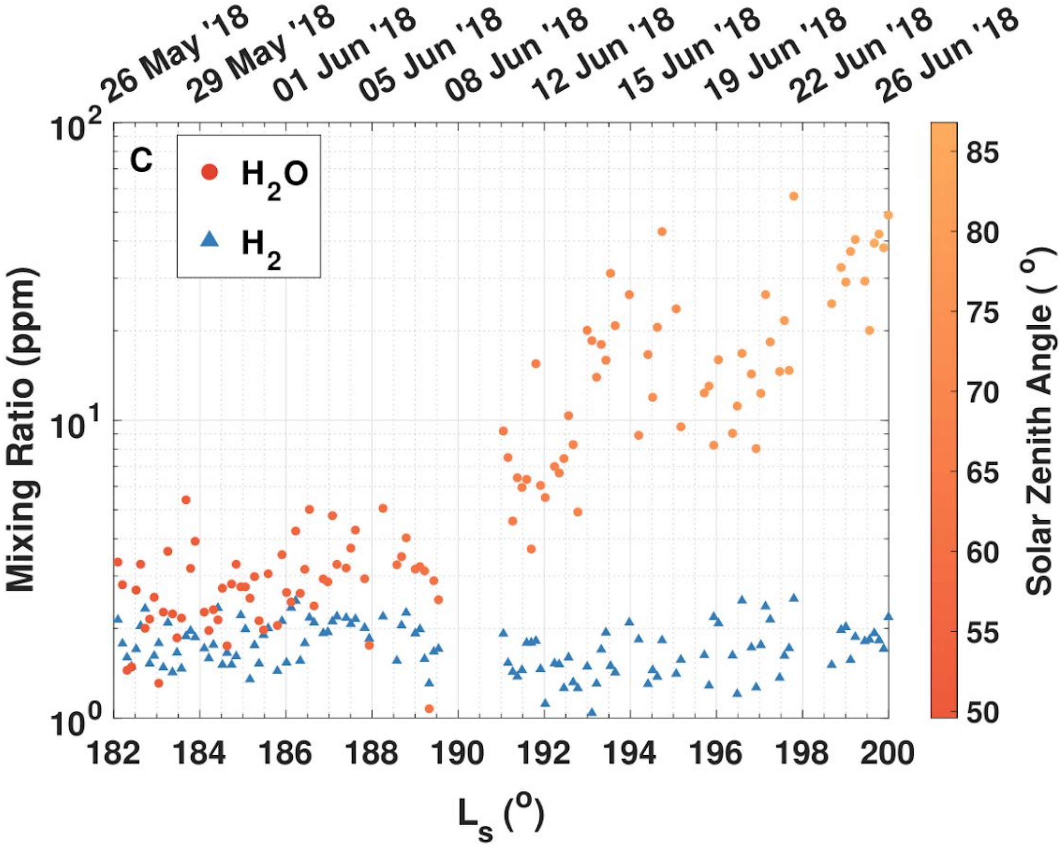


- Looking at the MY 34 global storm in greater detail, we observe a…
  - — 3.1x increase in [$\mathbf{H_2O^+}$]/[e^-]
  - — 2.5x increase in [$\mathbf{H_3O^+}$]/[e^-]

  …over ~2 days.

- We do not observe significant change in [O_2^+]/[e^-], indicating that the storm did not perturb the entire ionosphere, but only the abundances of these water-related ions.

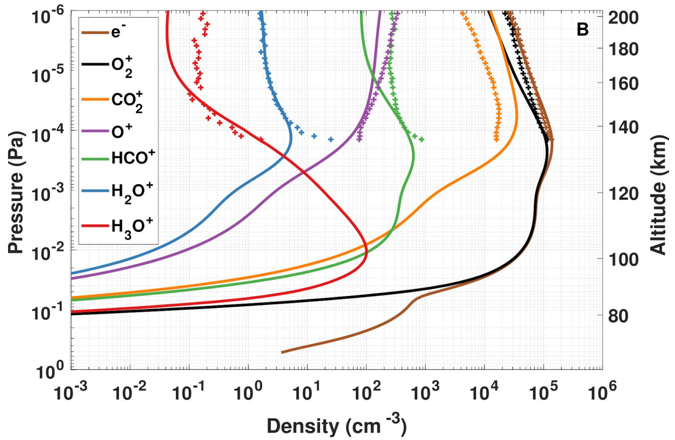
Dust Events

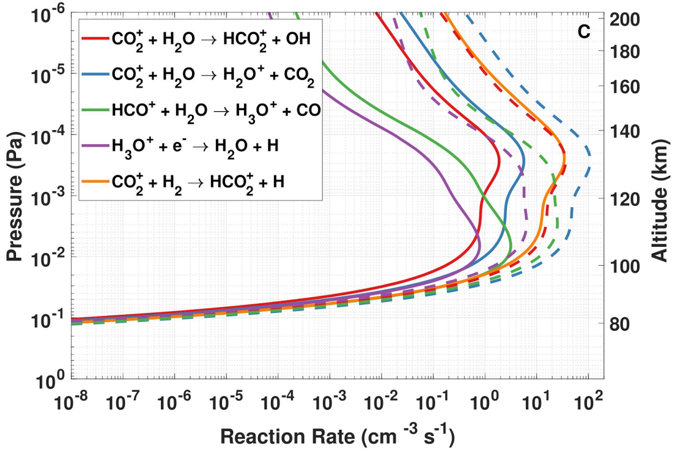


- During the MY 34 global storm, we observe a 2.4x increase in X(**H_2O**) over ~2 days.

- No change in the **H_2** mixing ratio is observed, indicating that **H_2O**, not **H_2** is responsible for the observed perturbations in the ionosphere.

H Production from Water





- 1D photochemical models were constructed for low H_2O and high H_2O cases.

	Low H_2O	**High H_2O**
H_2O Mixing Ratio at 80 km (ppm)	2	430
Net H_2O Destruction ($cm^{-2}\ s^{-1}$)	2.6×10^7	1.6×10^9
H Production (H_2O) ($cm^{-2}\ s^{-1}$)	5.0×10^7	2.9×10^9
H_2 Destruction Rate ($cm^{-2}\ s^{-1}$)	9.6×10^7	9.6×10^7

- H produced from H_2O in the ionosphere can escape efficiently since it is produced close to the exobase.

Conclusions

- We observe diurnal, seasonal, and dust-storm-induced variations in upper atmospheric H_2O^+ and H_3O^+ abundances using data from NGIMS onboard MAVEN.

- These variations are due to the upward transport of H_2O past the hygropause and into the middle and upper atmosphere.

- **The upper atmosphere contains >1 ppm H_2O throughout the Martian year**.
  — Dust storms rapidly increase the upper atmospheric H_2O abundance by up to a factor of 2 over a few sols.

- Escaping H atoms are produced from H_2O near the exobase *via* reactions with ions.

- **The contribution of H_2O to H escape is likely comparable to or greater than that of H_2.**
  — A global dust storm leads to more than a Martian year's worth of H production and escape in just 45 days.