Protonated Ions and the Seasonal Variation of Hydrogen Observed by MAVEN NGIMS

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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. (*Villanueva et al.* (2015), *Mahaffy et al.* (2015), *Krasnopolsky* (2015))

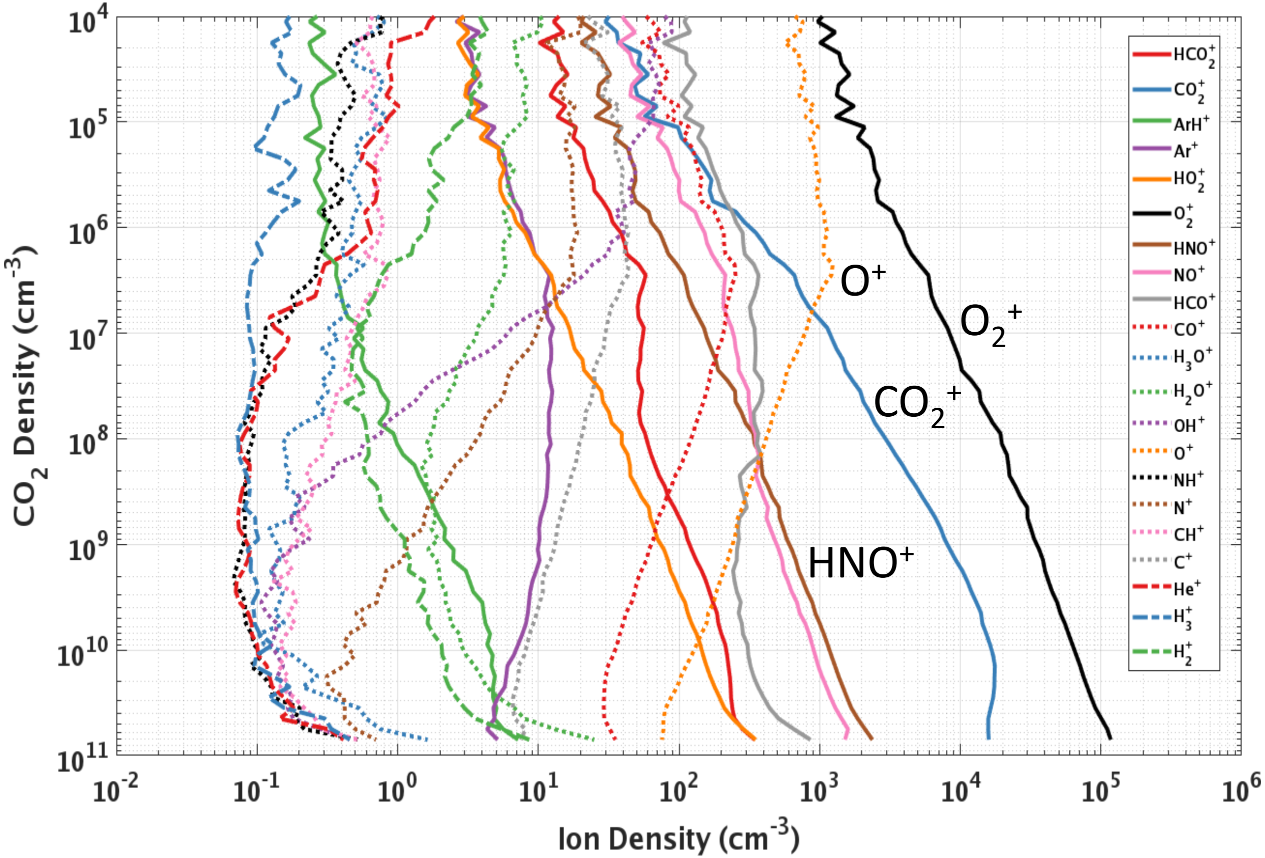
- Previous investigations have found temporal variations of an order of magnitude or more in the hydrogen density in the upper atmosphere of Mars, implying a similar variation in the hydrogen escape rate. (*Chaffin et al.* (2015), *Bhattacharyya et al.* (2015), *Clarke et al.* (2017))

- $\mathbf{H_2}$, a product of the photolysis of $\mathbf{H_2O}$ in the lower atmosphere, diffuses upward where it can react with ions to form protonated species such as $\mathbf{HCO_2^+}$, $\mathbf{HCO^+}$, $\mathbf{OH^+}$, $\mathbf{HNO^+}$, $\mathbf{H_2^+}$, and $\mathbf{H_3^+}$.
  - **H** is formed by these reactions and can then escape to space.

- The MAVEN spacecraft descends through the ionosphere every ~4.5 h, down to altitudes as low as ~125 km during Deep Dips (DDs), near the primary (F1) ionospheric peak.

- The Neutral Gas and Ion Mass Spectrometer (NGIMS) aboard MAVEN measures the abundance of 22 atmospheric ions with unit mass per charge (*m/z*) resolution.

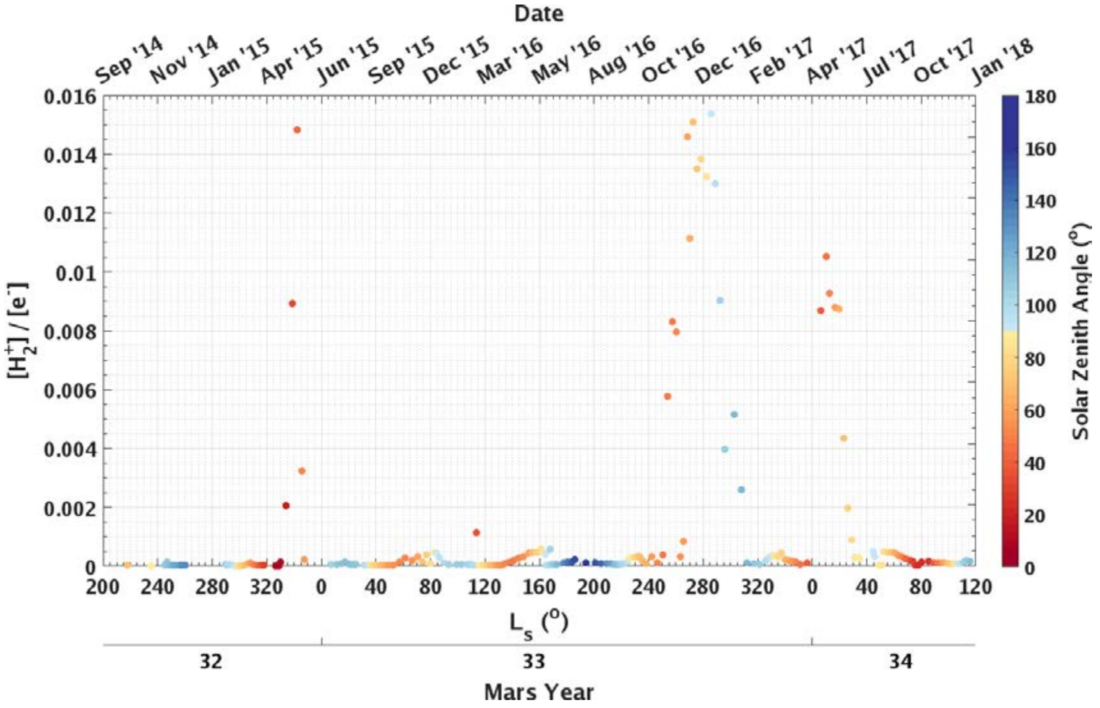
INTRODUCTION



- DD2 (subsolar) mean ion profiles from MAVEN NGIMS.
- HNO^+ is the most abundant protonated species in the NGIMS data; abundance is larger than predicted.
- Using protonated ion densities and simple photochemical equilibrium, we can calculate H and H_2 abundances.

Ion Variation

- We observe large variations in the abundances of some protonated species, e.g. H_2^+.
- At least one of these events correlates with the appearance of dust storms in the lower atmosphere near perihelion.
- Are the rapid increases in protonated ions indicative of a rapid increase in the thermospheric H and H_2 abundances?

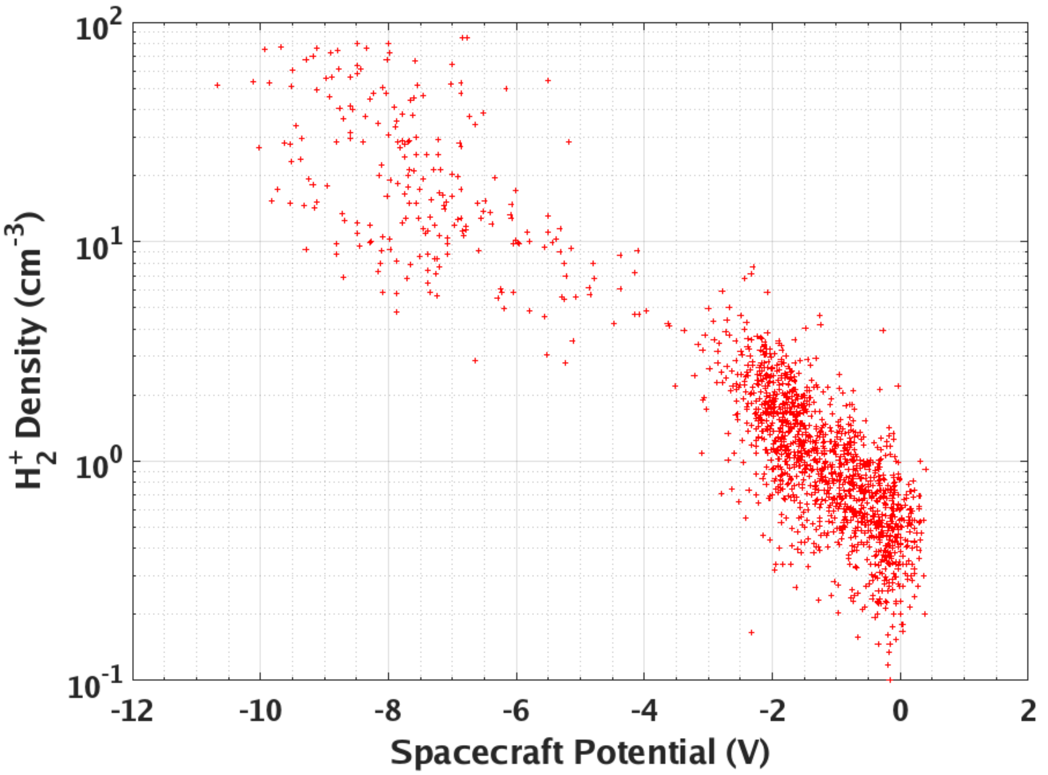


Effect of Spacecraft Potential

- The spacecraft infrequently charges to large negative voltages (–20 V) during a periapse pass; nominal is 0 to –2 V.

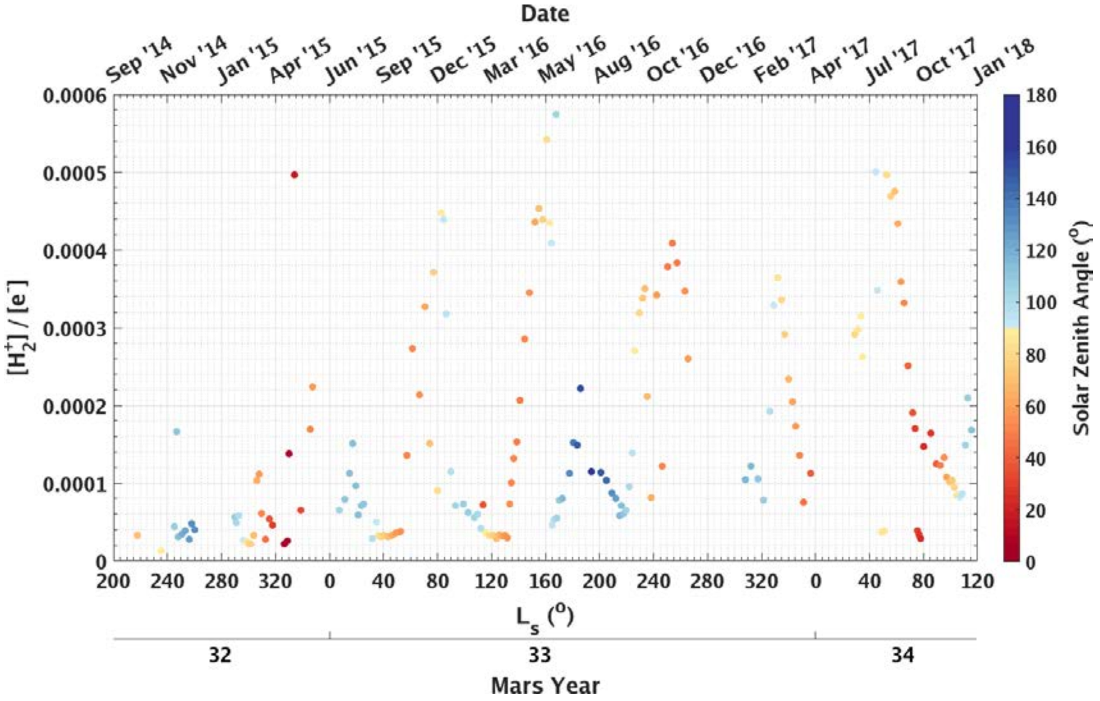
- The abundances of some protonated species, e.g. H_2^+, show a strong correlation with spacecraft potential.

- Dayside H_2^+ densities at a CO_2 density of 10^7 cm^{-3} (~250 km altitude) show a strong correlation with spacecraft potential.

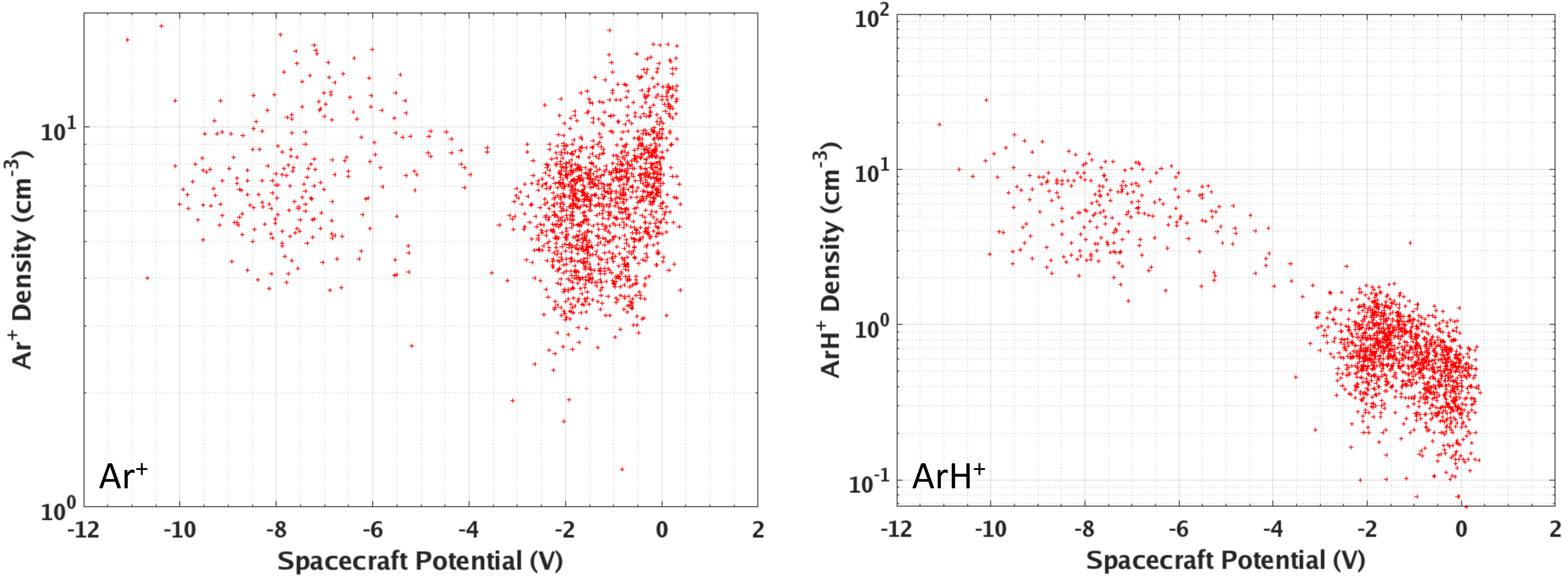


ION VARIATION

- The large peaks observed in protonated ion densities are removed if data from large negative spacecraft potentials are filtered out.
- Obvious variations in the H_2^+ density remain. Day-night variations appear to be the cause of predominant trends.
- What protonated ions are impacted by spacecraft potential?
- What protonated ions can give us reliable H_2 densities?

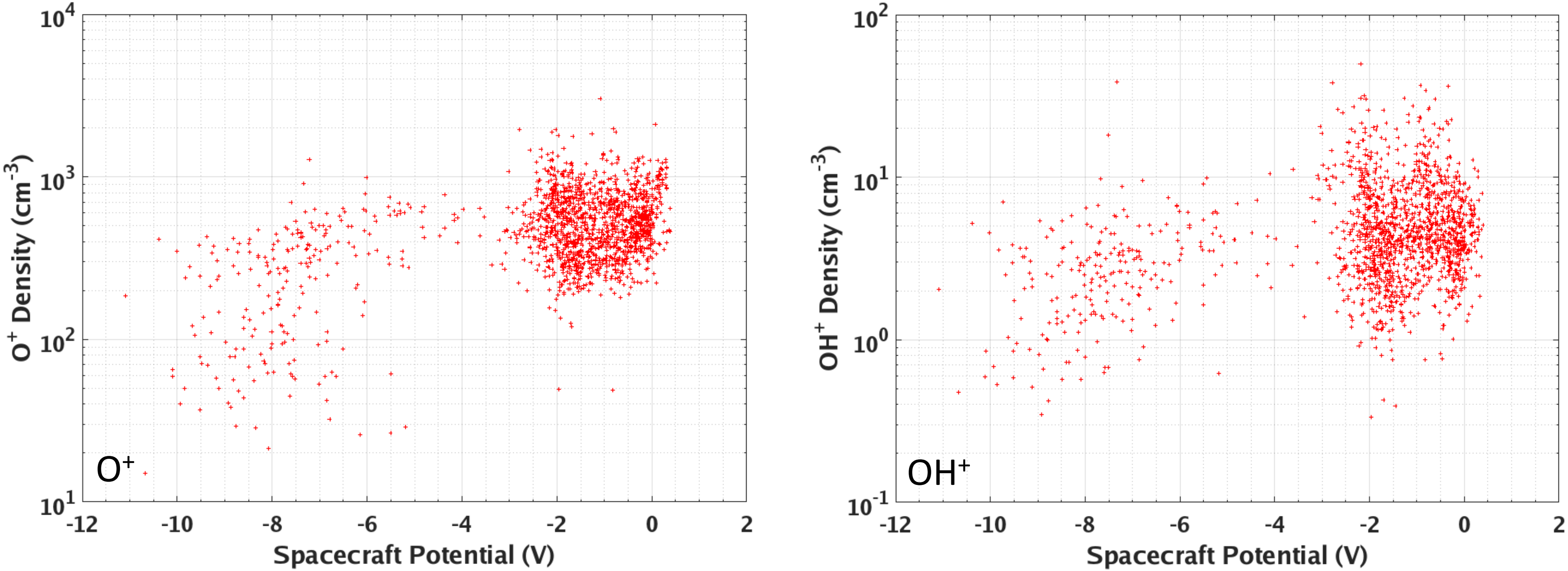


Effect of Spacecraft Potential



- Only some protonated ions are affected by spacecraft potential
- Related non-protonated ions seem to be unaffected by spacecraft potential

Effect of Spacecraft Potential



- Some protonated species and related ions are unaffected by spacecraft potential
- Can we use these ion abundances to calculate reliable H_2 densities?

H_2 Densities

$$O^+ + H_2 \xrightarrow{k_1} OH^+ + H$$

$$OH^+ + CO_2 \xrightarrow{k_2} HCO_2{}^+ + O$$

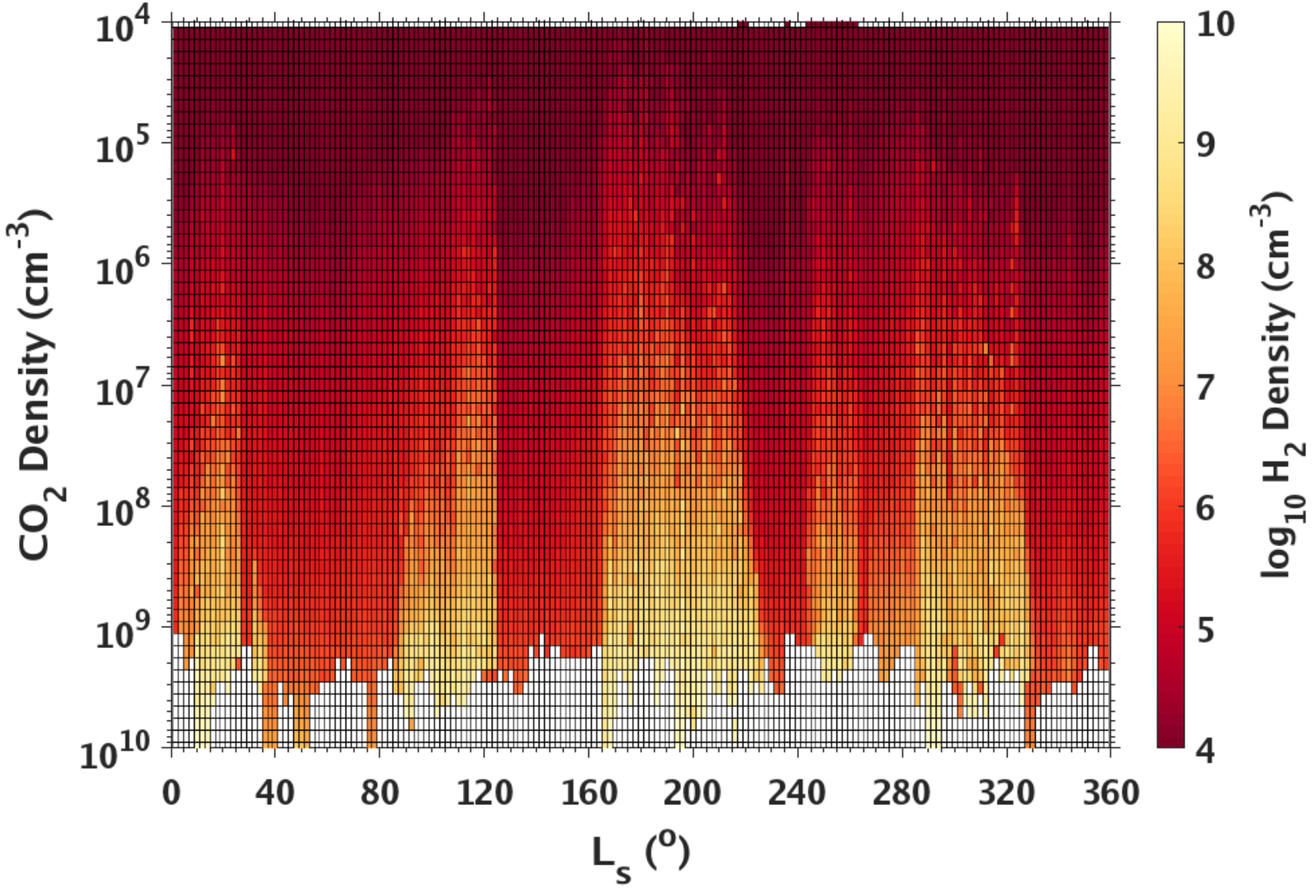
$$k_1[O^+][H_2] = k_2[OH^+][CO_2]$$

$$[H_2] = \frac{k_2[OH^+][CO_2]}{k_1[O^+]}$$

- Only O^+, OH^+, and CO_2 densities are required to calculate H_2 densities using the above equations.

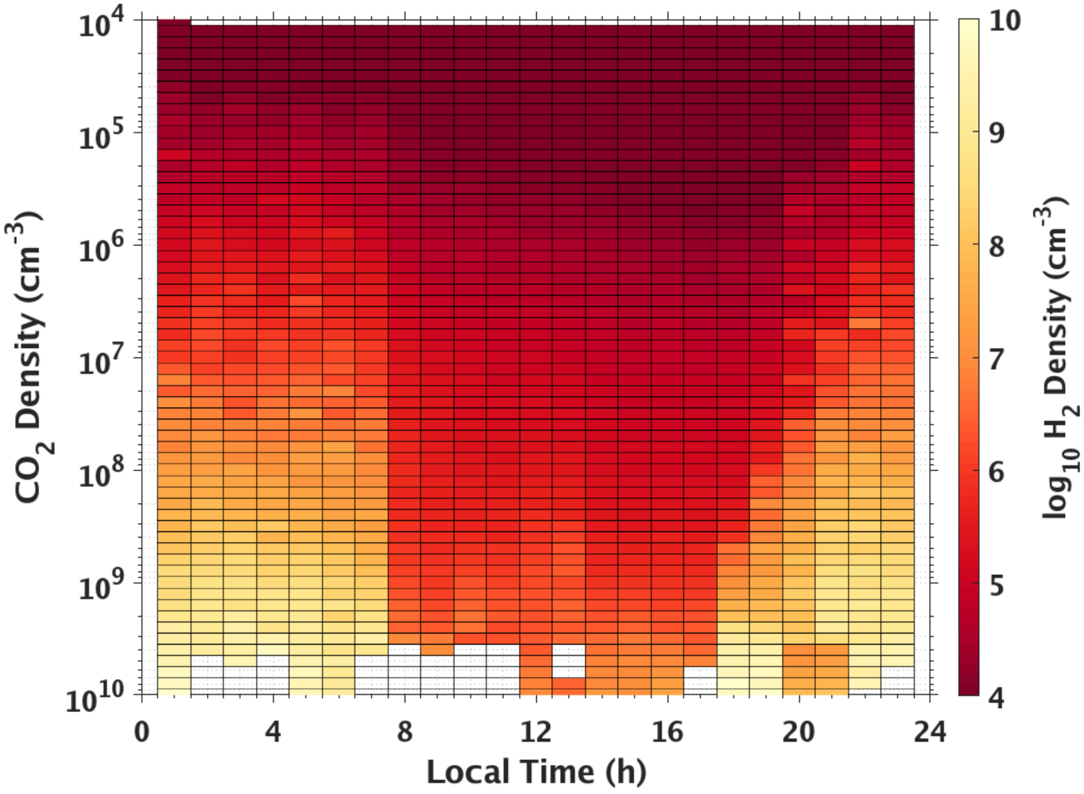
- This is a simple system, unaffected by spacecraft potential, which should give us reasonable H_2 densities.

H2 Densities



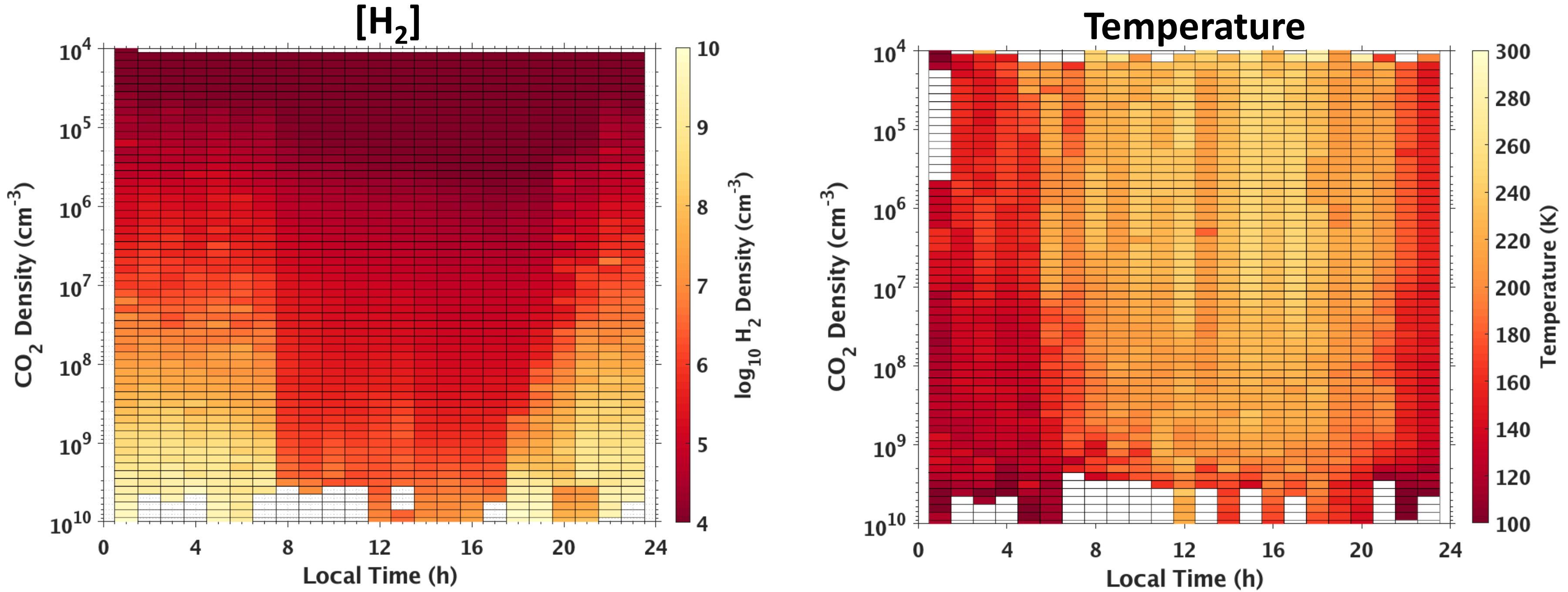
- H_2 densities vary with L_s, but MAVEN is precessing in latitude and local time.
- The observed variations must be largely diurnal.
- Are the effects of dust activity still apparent in the data?

DIURNAL VARIATION



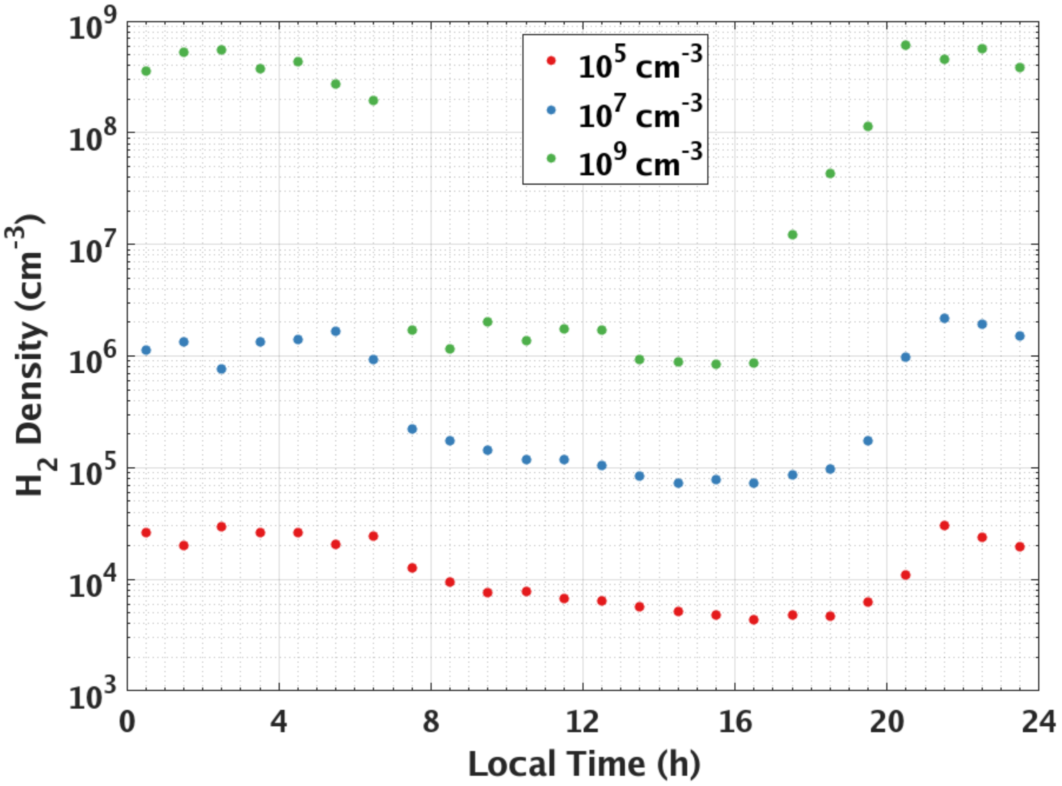
- Calculated H_2 densities from ±60° latitude binned on local time.
- Large diurnal variations are observed in the calculated H_2 abundances.
- We are seeing a nighttime "bulge" in the H_2 abundance.
- Similar phenomena have been observed for He at Mars by *Elrod et al.* (2017) and for H at Venus by *Brinton et al.* (1980).

H_2 Bulge



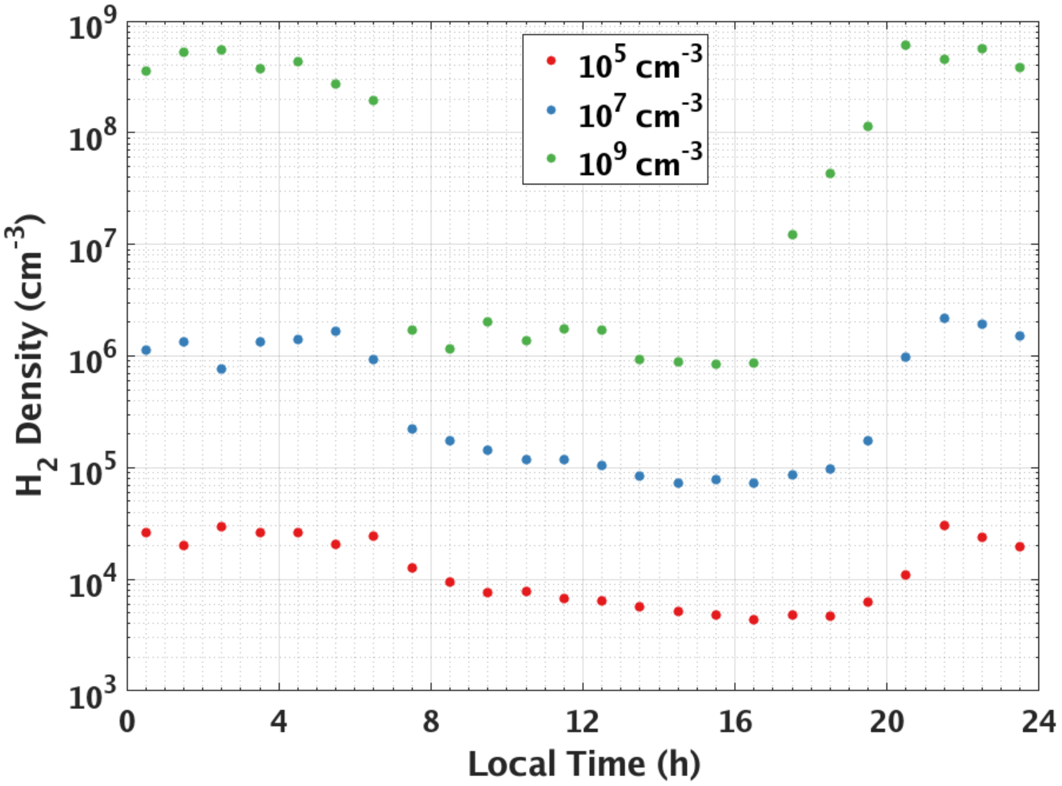
- H_2 abundance rises sharply across either terminator, and the nightside distribution is asymmetric.
- Using temperatures derived from NGIMS neutral Ar measurements (right), it is clear that H_2 accumulates in the coldest regions of the thermosphere.

H_2 Bulge



- On the dayside, H_2 densities are ~10^6 cm^{-3} near the nominal periapsis of MAVEN (150 km altitude; CO_2 densities of 10^9 cm^{-3}).
- The H_2 abundance rapidly increases on either side of the terminator, up to densities of a ~10^9 cm^{-3}
- These are very high H_2 abundances on the nightside.
- We will continue to investigate the absolute values of the calculated densities.

H_2 Bulge

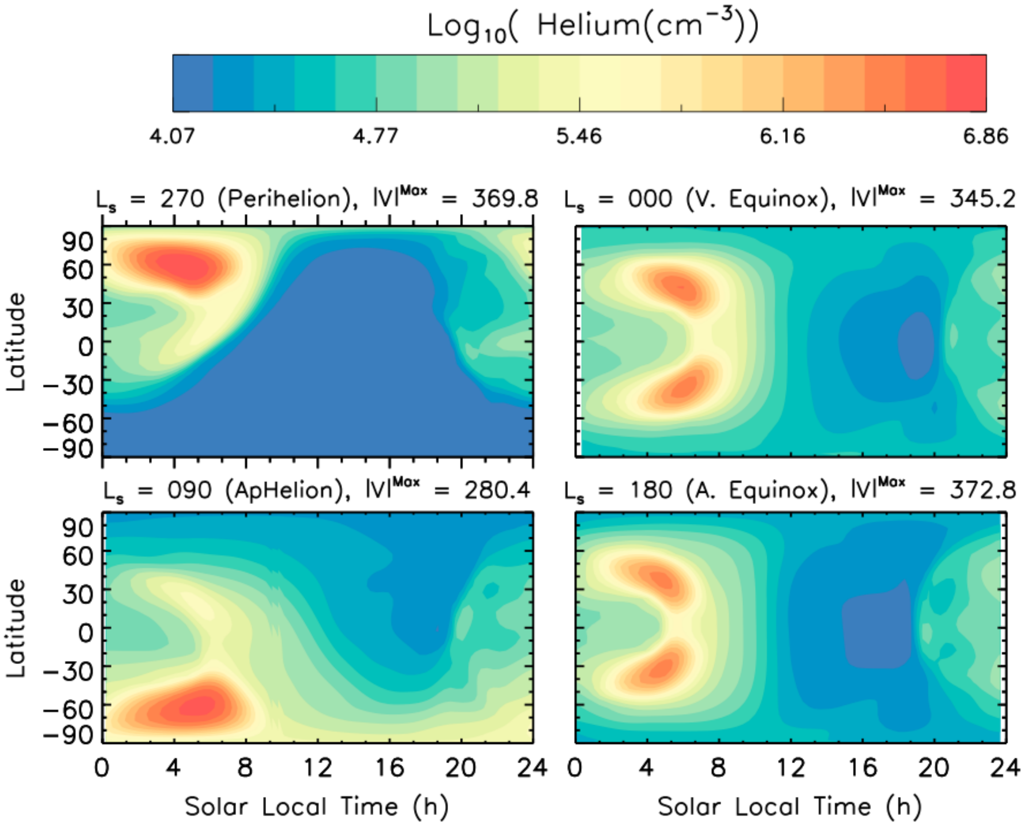


- Dayside abundances agree well with, e.g., *Krasnopolsky* (2002) and *Fox et al.* (2015), who calculate H_2 densities of ~10^6 cm^{-3}.
- Nightside abundances are more than a factor of 100 higher:
  - Similar variations in the He abundance have been observed and modeled (*Elrod et al.* (2017), next slide)
  - H abundance calculated to vary by a factor of 300 on Venus (*Brinton et al.* (1980))
- Diurnal, latitudinal, and seasonal (dust?) effects may be convolved.

He Bulge

- Simulations from the Mars Global Ionosphere-Thermosphere Model (M-GITM) predict a factor of ~600 increase in the predawn He abundance during perihelion.

- Diurnal variation is largest near perihelion



Elrod et al. *J. Geophys. Res.* **2017**, *122*, 2564.

SUMMARY

- Large variations in some protonated ion abundances are correlated with very low spacecraft potentials (down to –20 V).
- Not all protonated ions are affected by spacecraft charging. Non-protonated species appear to be unaffected by spacecraft charging.
- We calculate H_2 densities from NGIMS OH^+, O^+, and CO_2 densities.
- Large diurnal variations are observed in the calculated H_2 densities.
- Variations in the H_2 abundance due to dust activity may be masked by the relatively large diurnal variations.

Future Work

- Characterize fully the effects of spacecraft potential on all protonated species.
- Calculate H_2 abundances, where possible, using other simple photochemical equilibrium assumptions.
- Calculate H and H_2 abundances using a sophisticated photochemical model which includes NGIMS ions and neutrals and an extensive list of photochemical reactions.
- Characterize the seasonal or dust-storm dependence of observed variation in protonated ions and H_2.
- Investigate, broadly, the photochemical questions that have arisen from the NGIMS data.