DENSITY RETRIEVALS OF THE MARS HYDROGEN EXOSPHERE FROM MAVEN SOLAR LYMAN-ALPHA OCCULTATIONS

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Introduction: Although its primary mission is to characterize the solar Extreme Ultraviolet (EUV) input into the Mars atmosphere, the MAVEN-EUVM [1] instrument has proven sufficiently sensitive to characterize the Mars hydrogen (H) exosphere from 200 km to above 6000 km via solar H Lyman-α occultation measurements. In 2015, we presented early results of EUVM solar occultations which did not conclusively constrain the absolute density values but did suggest solar or seasonally driven variability [2]. Here, we present absolute density retrievals of the Mars H exosphere spanning the first year of the MAVEN mission.

Because the Mars H exosphere originates from dissociated water molecules, it carries information about the history of water at Mars [3]. Past surface water levels can be directly estimated from the contemporary H exosphere if the sources of variability and escape to space are adequately constrained; and the historical space environment is properly accounted for. Regular occultation measurements of the H exosphere made by MAVEN EUVM can provide a present-day baseline for the absolute magnitude of H contained in the exosphere, and characterize relative changes due to both seasonal factors and solar influences.

Previous Observations: The Martian H exosphere was first characterized by the Mariner 6 and 7 fly-by missions which showed a single population of H with a temperature of 350 K and a density of 3 x 10^4 cm^-3 at 250 km [4]. It took over three decades for the H exosphere to be further characterized with independent H density retrievals from the SPICAM and ASPERA instruments on-board Mars Express [5,6]. The H exosphere has also been characterized using the Hubble Space Telescope (HST) during campaigns in 2007 and 2014 [7,8]. And currently, the MAVEN IUVS instrument is making regular measurements of the H exosphere, revealing new structure [9], with absolute density retrievals pending final instrument calibration. The previous H exosphere measurements have measured the optically thick H Lyman-α emissions directly; and radiative transfer models, with inherent density and temperature degeneracy, are needed to invert the measured brightnesses. Unlike the initial Mariner results, the SPICAM and HST measured and model-predicted brightnesses are improved if a hot component is added. And the HST retrievals, in particular, show a seasonal dependence on the hot component. However, unlike Venus, which has a population of hot H in its exosphere [10], the source of a hot H population at Mars has yet to be conclusively explained. Further, both the SPICAM and HST campaigns have revealed unexpected variability in the exospheric H density [7,11] which can have substantial implications for escape of H to space and past surface water estimates based on current conditions. Given that the latest measurements yield new questions in addition to answers, it is clear that the H exosphere is still poorly understood and a need for additional measurements exists.

MAVEN-EUVM Solar Occultations: When accounting for signal loss due to atmospheric absorption and/or scattering, the local irradiance, \( E(r, \lambda) \), incident on an EUVM channel is related to the irradiance at the top of the atmosphere, \( E(\lambda, r_{\text{top}}) \), as

\[
E(r_{\text{sc}}, \lambda) = E(\lambda, r_{\text{top}}) e^{-\Sigma \sigma_i(\lambda) n_i(r)}.
\]

Here, \( \sigma_i(\lambda) \) is the wavelength dependent absorption and/or scattering cross-section for the \( i^{th} \) species and the corresponding column density, \( N_i \), is given by

\[
N_i = \int_{\text{los}} n_i(r) dz',
\]

where the integral is over line-of-sight defined by the \( z' \) axis and \( n(r) \) is a spherically symmetric density function of radial coordinate, \( r \).

We can rewrite equation ?? in terms of the measured counts, \( N \), and instrument solar Lyman-α response function, \( R(\lambda) \), as

\[
N(r_{\text{sc}}) = \int_{\lambda} R(\lambda) N(r_{\text{top}}, \lambda) e^{-\Sigma \sigma_i(\lambda) n_i(r)} d\lambda,
\]

where we assume all signal loss is due to resonant scattering with cross-section, \( \sigma_H \).

Onion peeling inversion of an occultation scan discretizes the atmosphere into layers of constant \( n(r) \) to solve equation ?? for successively deeper layers while feeding back the computed density of the upper layers. Figure ?? shows the onion peel inversion geometry and should be referred to in the discussion that follows.

\[
N(r_{\text{sc}}, r_h) \text{ can be shown to be related to } n(r_i) \text{ as }
\]

\[
N(r_{\text{sc}}, r_h) = 2 \int_{r_h}^{r_{\text{max}}} \frac{n(r) r dr}{\sqrt{r^2 - r_h^2}} + N_{\text{top}}(r_{\text{sc}}, r_h),
\]

(4)
$z' = \frac{47}{sc}$


Figure 1: Onion peel inversion geometry.

$$\mathcal{N}_{top}(r_{sc}, r_h) = 2 \int_{r_{h,max}}^{r_{sc}} \frac{n(r)rdr}{\sqrt{r^2 - r_h^2}} + \int_{r_{sc}}^{\infty} \frac{n(r)rdr}{\sqrt{r^2 - r_h^2}}.$$ (5)

$\mathcal{N}_{top}(r_{sc}, r_h)$ represents the column density above which EUVM is capable of measuring in any given scan and approaches zero as $r_{h,max}$ becomes large.

We can discretize the integral over $r$ with the line-of-sight matrix element,

$$L_{h,i} = \left( \sqrt{r_{i+1}^2 - r_h^2} - \sqrt{r_i^2 - r_h^2} \right) \quad \in \quad i \geq h$$

$$L_{h,i} = 0 \quad \in \quad i < h,$$ (6)

where the matrix rows correspond with line-of-sight tangent heights, $r_h$, and the columns correspond with the radial coordinate of the number density, $r_i$. Using $L_{h,i}$, we can write the matrix equation for the column densities at each line-of-sight,

$$\tilde{N}(r_{sc}, r_h) - \mathcal{N}_{top}(r_{sc}, r_h) = \tilde{L}n(r_i)$$ (7)

which can be inverted for the $n(r)$ using standard methods.

In practice, equation (7) is first solved by finding the value of $N(r_h)$ which minimizes the difference between the predicted and measured counts where $N(r_{top}, \lambda)$ is taken to be the maximum signal in an occultation scan. Once $N(r_{sc}, r_h)$ is known for every value of $r_h$, equation (7) can be solved iteratively to correct for $\mathcal{N}_{top}(r_{sc}, r_h)$. Because equation (7) depends on the H temperature, $T_H$, through $\sigma_H$, solving for $n(r)$ requires additional iteration. Once a solution for $n(r)$ converges on a stable $T_H$, a numerical Monte-Carlo simulation of the H exosphere is run initialized with the retrieved densities and temperatures to compute the final $\sigma_H(r_h, r_{sc})$ which are in turn used for a final iteration of the density retrieval.

As an example, the initial inversion steps are shown in Figure 2, where densities corresponding with assumed H temperatures of 275 and 375 K are shown for MAVEN orbit 927. Unlike inversion from emission spectroscopy, no model for the shape of the exosphere is needed to retrieve the density profiles aside from spherical symmetry, allowing temperature and density to be decoupled. Tuning the assumed cross sections results in a higher order refinement of the density profile, but not order-of-magnitude changes. In our study, we explore the inversion’s sensitivity to assumed inputs, namely the solar spectral shape and $\sigma_H$, to quantify the retrieval uncertainty. We then report absolute density retrievals with uncertainties for over a year of EUVM measurements at Mars and discuss possible causes of observed variability.

References