Mapping the D/H of water on Mars using high-resolution spectroscopy

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Introduction: We mapped HDO and H_2O on Mars using high-resolution infrared spectroscopy in March 2003 and March/April 2008.

The preferential escape of the lighter isotope of hydrogen controls the global $(D/H)_{H2O}$ abundance ratio and comparison of the present abundance ratio with escape models provides an estimate of the amount of water lost over time. Earlier measurements reported a global atmospheric enrichment (D/H) of five times the mean terrestrial ocean value (VSMOW). Because of HDO and H_2O different vapor pressures, the local $(D/H)_{H2O}$ is strongly dependent on the local temperature. Therefore, in order to locate the sources of water on Mars and their true D/H spatially resolved measurements are needed.

Methodology: We mapped H_2O and HDO on Mars in March/April 2008 and March 2003 using high-resolution infrared spectroscopy with CSHELL at NASA-IRTF. We oriented the spectrometer slit North-South on the planet and took spectra of HDO and H_2O at 9 slit-positions across the Mars' disk. We extracted 43 spectra along the slit sampling a total of 8.6 arcsec North-South, and leading to a disk-map consisting of 387 points for each isotope (see Figures 1 and 2).

At each footprint, we estimated the local atmospheric conditions by querying the Mars Climate Database v4.2 [1], a highly realistic general-circulation-model (GCM). These parameters were fed to a multi-layer planetary radiative transfer model (CODAT package [2]), and the Martian column densities were derived from the measured spectral line intensities (HDO, H_2O) using a Levenberg-Marquardt (LM) algorithm. At each iteration of the LM algorithm, a new model was constructed and numerical derivatives were computed for each parameter. This process was repeated until convergence was achieved, and the difference between data and the model was minimized. The mean statistical variation of the residual spectra (RMS or chi-square) was used to quantify the uncertainty in the retrieved column densities (sigma). Most of the RMS is induced by the intrinsic photon noise of the measurement, which is equal to the square root of the average collected photons, i.e. the sum of Mars continuum (> 80%) and telluric radiance. In addition, systematic errors introduced by imperfect removal of the instrumental effects, like scattered-light and variable resolving power, affected the quality of the spectra and thus the resulting sensitivity.

The retrieved column densities were subsequently mapped onto Mars by convolving with a weighting 2D spatial kernel. The statistical weight of the retrieved column density is maximum at the center of the footprint, and its significance decreases spatially following the PSF distribution. Multiple observations at the similar location on Mars were added following a weighted mean, with points with smaller error having a higher weight.

Results: The combined map shows important differences in $(D/H)_{H2O}$ between the afternoon (East) and the morning hemispheres (West), with an important correlation between temperature and $(D/H)_{H2O}$ indicative of Rayleigh distillation (see Figure 3). In addition, we observe important enrichments of deuterated water in certain regions of the southern (winter) hemisphere. The weighted mean of all points shows a global atmospheric $(D/H)_{H2O}$ enrichment of 5.75 relative to Earth's oceans. But, if we compensate the measurements for Rayleigh distillation, the true $(D/H)_{H2O}$ ratio in the permanent cap is expected to be considerably higher, suggesting a wetter climate in the past.

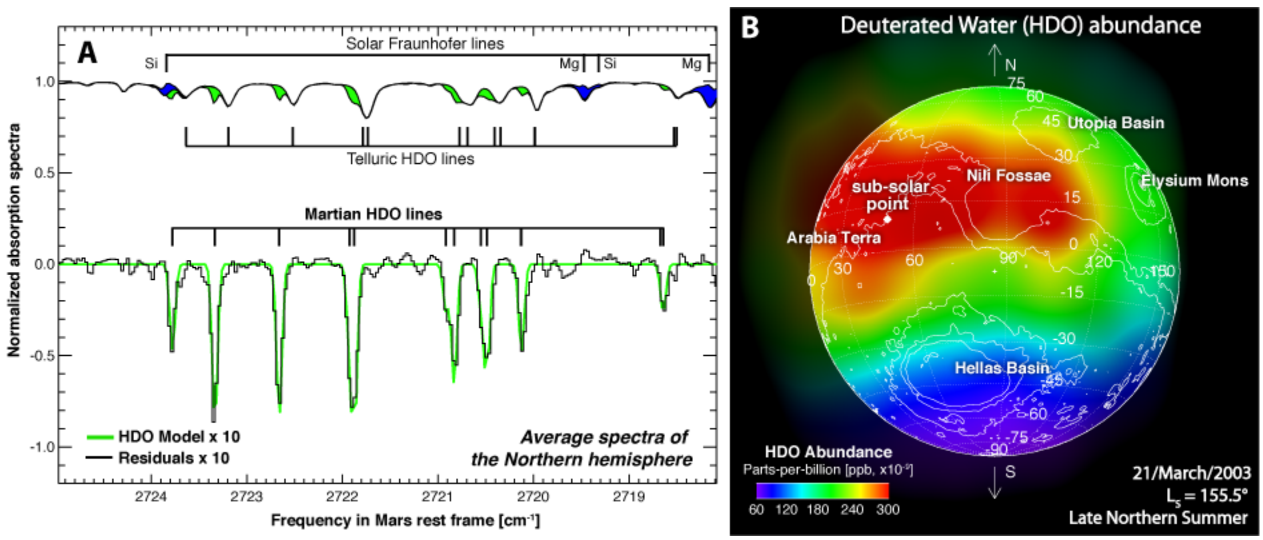

Figure 1: Measurement of Martian deuterated water (HDO) on 21/March/2003 using CSHELL at IRTF. Panel 'A' shows the average spectrum of the Northern hemisphere. The normalized spectral extract contains telluric HDO and CH_4 absorption lines, Solar Fraunhofer lines (marked in blue) and Doppler shifted Martian HDO lines (marked in green). Mars was 7.00 arc-seconds in diameter and the topocentric Doppler shift was –15.7 km/s. By removing the non-Martian spectral features we isolated multiple HDO lines, which are shown in the figure multiplied by 10 and have not been corrected for telluric atmospheric extinction. A synthetic spectrum of Martian HDO has been over-plotted in green. Panel 'B' shows a map of deuterated water obtained by orienting the spectrometer's slit North-South and by taking samples of HDO at 9 slit-positions across the Mars' disk. We extracted 43 spectra along the slit sampling a total of 8.6 arcsec North-South, and leading to a disk-map of 387 points.

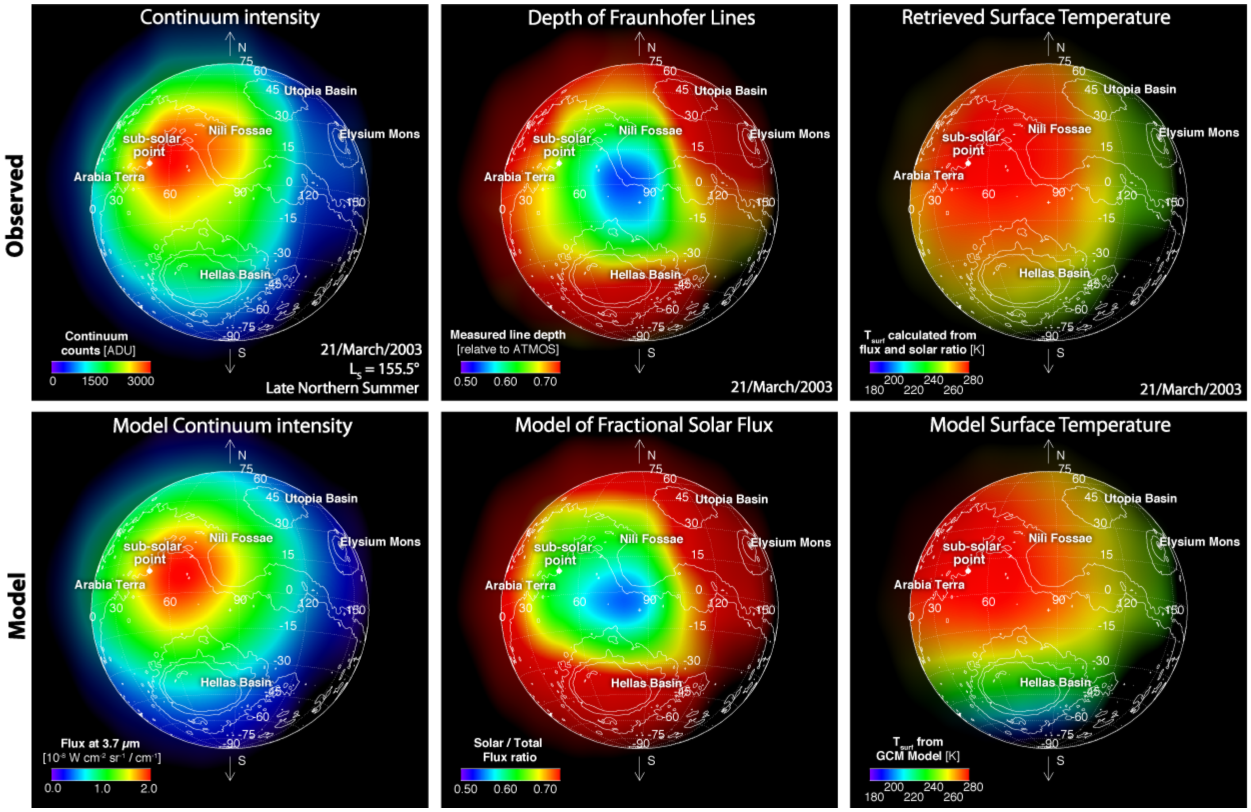

Figure 2: Comparison between observed and modeled parameters, and validation of the mapping method. The observations were performed on 21/March/2003 using CSHELL at IRTF and sample the HDO region at 3.7 μm (2725–2718 cm^{-1}). The map was obtained, as presented on Fig. 1B, by orienting the spectrometer's slit North-South and by taking samples of HDO at 9 slit-positions across the Mars' disk. We extracted 43 spectra along the slit sampling a total of 8.6 arcsec North-South, and leading to a disk-map of 387 points. For each extract, we retrieved the continuum intensity and the depth of the Solar Fraunhofer lines (see Fig. 1A). At these wavelengths, the radiation received from Mars is a combination of reflected-sunlight (with Fraunhofer lines) and planetary thermal emission (featureless continuum). The varied surface temperatures and albedos across the Mars surface lead to differences in the apparent thermal/solar ratio, and thus in the apparent equivalent width of the observed Fraunhofer lines. The observed surface temperature was inferred from the thermal/solar ratio and the continuum intensity. The modeled intensity and thermal/solar ratio were calculated using a "Lambertian" model that computes the two components of the emergent intensity: reflected sunlight and thermal emission from the surface. The model surface temperature was calculated using the LMD-AOPP-IAA general circulation model [1] for this season and local time. For comparison purposes, we convolved the synthetic maps with the spatial point-spread-function (PSF) of the telescope.

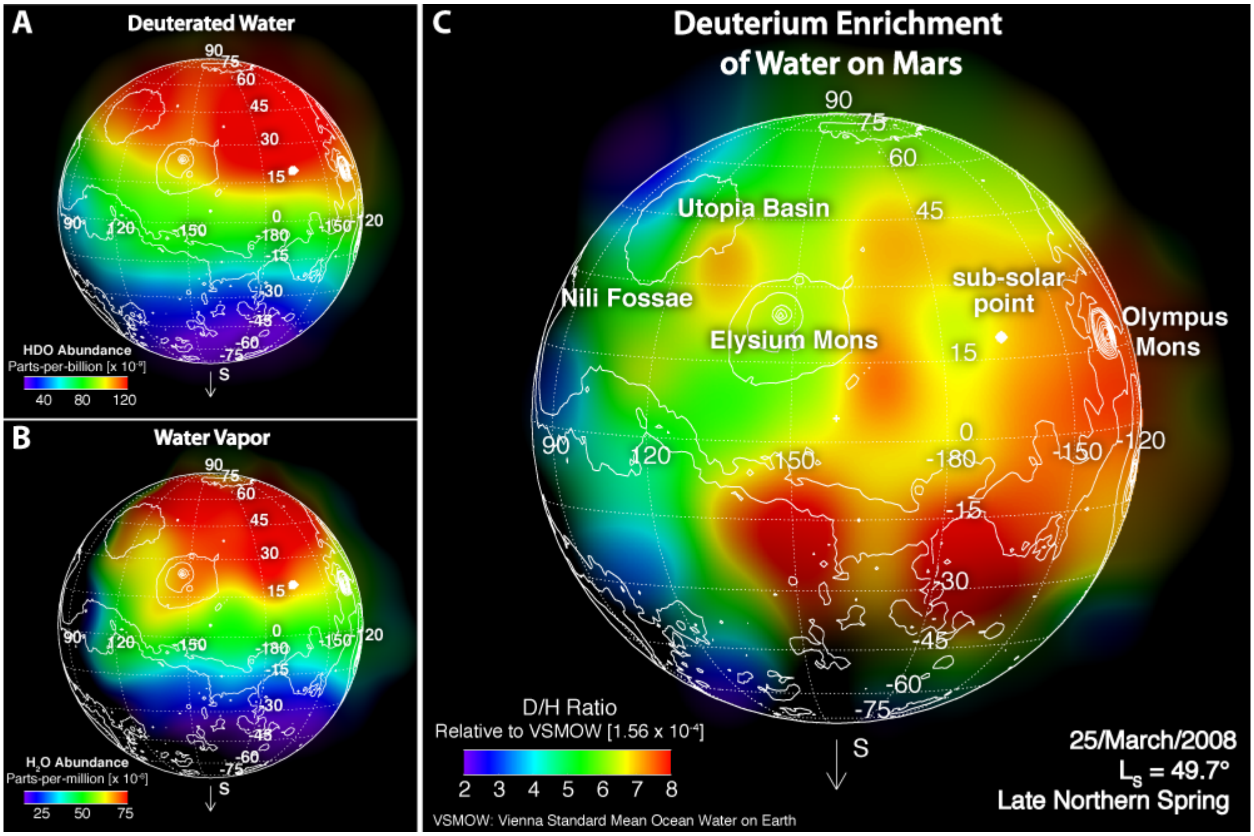

Figure 3: Maps of deuterated water (HDO), water vapor (H_2O) and $(D/H)_{H2O}$ on Mars as measured using CSHELL at IRTF on 25/March/2008. The measurement required two spectral settings, which were alternated across the planet's disk in 9 positions. For each setting and position, we acquired one ABBA (4 x 1 minutes) with a total of 36 frames per setting, or a total of 72 frames, requiring 2 hours of observation. We extracted 43 spectra along the slit (North-South), leading to a map of 387 points for each gas. The map shows important differences between the afternoon (East) and the morning hemispheres (West). In addition, we observe important enrichments of deuterated water at certain regions of the southern (winter) hemisphere. The weighted mean of all points show a $(D/H)_{H2O}$ enrichment of 5.75 relative to Earth's oceans (VSMOW).

References

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[2] T. Hewagama, *J. Quant. Spectrosc. Radiat. Transfer* **109** (2008)