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DIURNAL VARIATIONS IN THE MARTIAN ATMOSPHERE FROM ENHANCED MAVEN/IUVS STELLAR OCCULTATION DATASET

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Introduction: Over the last five decades, diverse observations and theoretical models have provided a comprehensive account of thermal structure and composition for different regions of the Martian atmosphere. Nonetheless, there are still gaps in our interpretation when it comes to the study of day/night differences for the Martian upper mesosphere to lower thermosphere, a region that is critical in understanding atmospheric loss, coupling processes, global circulation patterns, energy balances, along with the influences of H_2O, CO_2, and dust cycles prevalent on Mars. Part of this region is explored by a few Martian missions, e.g., SPICAM onboard Mars Express observed the nighttime temperature and density profiles in the altitude range 70-130 km (Montmessin et al., 2017), NGIMS on MAVEN during its deep dip campaigns can retrieve in-situ density and temperatures for different local solar times, but altitudes from ~125 km (Stone et al., 2018), while ACS onboard TGO probes the lower mesosphere, resolving the diurnal cycle over a 54-sol period (Guerlet et al., 2022).

Stellar occultations, one of the observation modes of the Imaging Ultraviolet Spectrograph (IUVS) aboard the Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft, are being designed and executed in dedicated bimonthly campaigns for the last seven years to fill this gap (Jakosky et al., 2015; McClintock et al., 2014). This study presents a methodology for enhancing and expanding the usable mission-wide MAVEN/IUVS stellar occultation dataset to provide the first complete diurnal coverage of Martian upper mesosphere to lower thermosphere (~80-160 km) for a range of latitudes, longitudes, and Martian seasons. We here present the preliminary results of this study.

MAVEN/IUVS Stellar Occultations: As the stellar signal of UV bright star traverses the Martian middle atmosphere, it gets attenuated due to absorption by the atmospheric constituents. Information on the column abundances of CO_2, O_2, O_3, together with aerosol optical depth, can be obtained from the transmission spectra due to such absorption features, from which are retrieved the local densities and profiles of temperature and pressure by vertical inversion in the 20 – 160 km altitude range (Gröller et al., 2018). There have been forty-two stellar occultation campaigns from 24 March 2015 to 29 January 2022 (covering MY 32 to 36) that are executed every 2 to 3 months and last between 1 and 2 days.

*The limitation of the current dataset is that it contains only the nighttime events***.** Of the total 3003 stellar occultation events to date, ~53% of the observations correspond to the nightside while the remaining 47% are during dayside or bright terminator such that the sunlight is scattered to the MUV channel of IUVS and saturates it while part of this first-order stray light contaminates the second-order FUV channel. In the current stellar occultation data pipeline, dayside events (LT 6–18) with stray light contamination are not processed, therefore resulting in a data gap and significant loss of important information and science, especially on a diurnal scale.

The objective of this study is to expand and enhance the usable stellar occultation dataset by processing the daytime events. FUV (110 – 190 nm) is crucial for the retrieval of CO_2 and O_2 above 90 km and for examining the diurnal and seasonal variability of the O_2 mixing ratio. The majority of these unprocessed dayside cases have first-order stray light in the FUV confined to the altitude range where FUV starlight is fully attenuated. An example is shown in Figure 1. Ignoring the contaminated MUV spectrum and performing the retrievals on only the FUV spectrum for such dayside cases can rescue the daytime events and considerably expand the usable dataset.

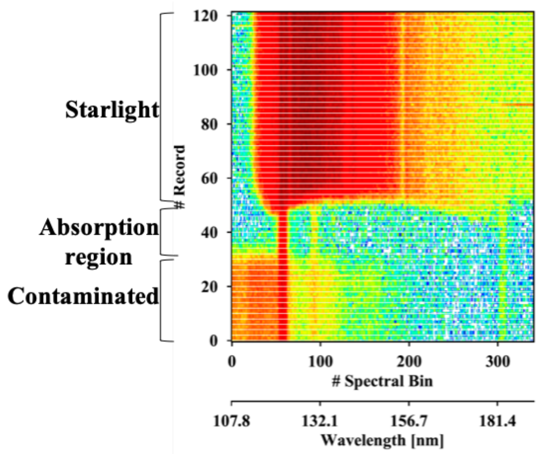

Figure 1. An example of a dayside FUV spectrum with the unattenuated stellar spectrum, rescuable finite absorption region, and stray light contaminated records.

Methodology: We have devised a stray light avoidance methodology to rescue at least the FUV spectrum for the dayside occultation measurements by 1) only considering λ=115-170 nm, 2) eliminating aerosol contribution in the spectral fits, 3) limiting the altitude range to where the retrievals are credible (restricting transmissions 0.1-0.95), and 4) testing the validity of these modifications on the nightside events that are processed by the current pipeline (using 115-300 nm). This is to eliminate any bias introduced due to considering only the FUV wavelengths. The criterion for choosing a retrievable altitude range is shown in Figure 2.

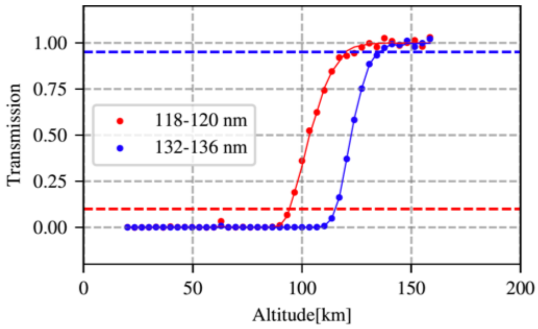

Figure 2. Limiting retrieved altitude range based on transmission at two different wavelength ranges. The retrievals in this example are credible between 95-130 km.

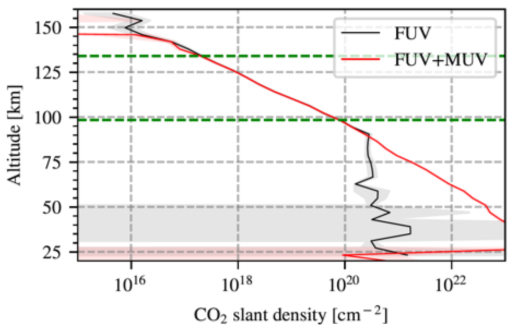

Figure 3. CO_2 column abundance for the nightside event retrieved from only the FUV spectrum (black), with pipeline retrieval from both FUV and MUV (red). The credible altitude range for the FUV analysis is given by green lines.

The stray light avoidance methodology has enabled the retrieval of ~1000 dayside events (LT 6–18). Based on this methodology, the nightside events are also reprocessed. To validate the stray light avoidance approach, these reprocessed nightside events are then compared to the pipeline retrievals that considers both FUV and MUV. An example is shown in Figure 3. It can be seen that the two profiles are consistent with each other. We have been able to successfully process 2300 events to date using only the FUV wavelengths, providing unprecedented day/night observations of retrieved CO_2 number density and temperature in the 80-160 km altitude range.

The enhanced and expanded usable dataset covers a wide range of local times, latitudes, longitudes, and the Martian seasons. The data coverage for these 2300 events is shown in Figure 4, covering three complete Martian years.

Observations and Results: Based on these dayside and nightside retrievals for the FUV, Figure 5 (a) shows the diurnal cycle for temperature variations on a vertical scale. It is to be noted that for each LT and pressure bin, the temperature values are averaged over corresponding Martian seasons, longitudes, and latitudes in the range 65°N – 65°S. There are temperature anomalies at the top side due to the assumption of an isothermal atmosphere in retrieving the upper boundary temperature from CO_2 number density before integrating downward following hydrostatic equilibrium.

Prominent day/night differences are seen with the dayside observations warmer than the nightside over all pressure levels. The lowest temperatures are seen in the midnight mesosphere, while the maximum temperatures reaching ~250 K are observed for LT 14-17 in the lower thermosphere. We also see evening terminator temperatures to be warmer than the dawn, especially in the lower thermosphere.

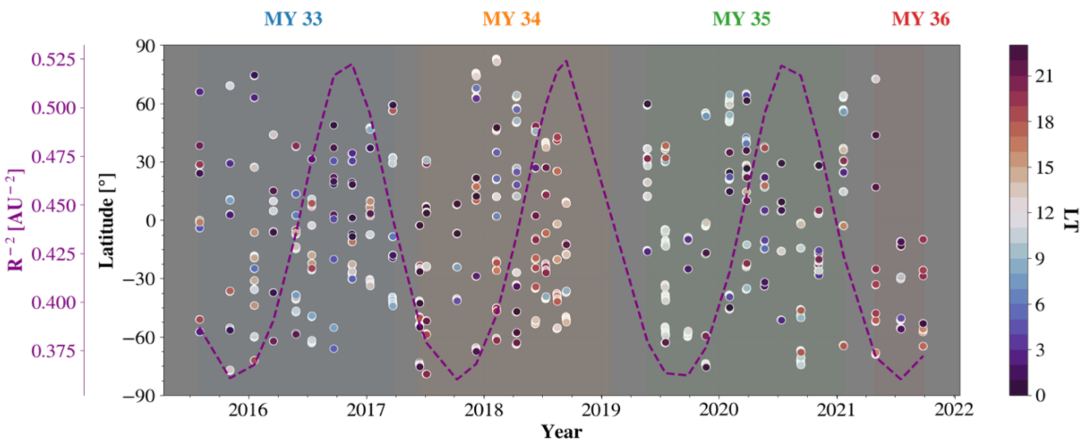

Figure 4. Data coverage for 2300 processed events considering only FUV with inverse square of heliocentric distance (R) for MY 33-36. Each data point represents median latitude and local time for all the orbits corresponding to a star in a campaign.

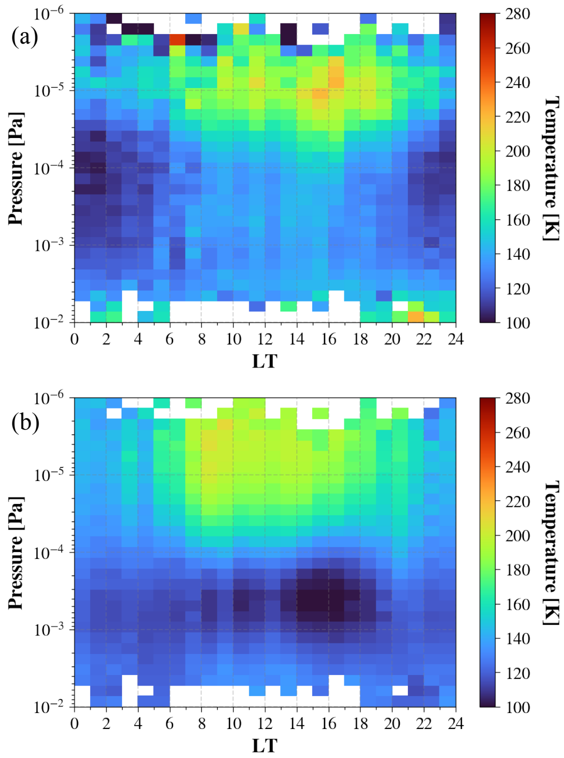

Figure 5. Diurnal variations in temperature (a) based on retrievals for FUV, and (b) corresponding MCD values. These observations are over all the Martian seasons, longitudes, and latitudes 65°N – 65°S.

The analysis of the enhanced dataset shows that the mesopause is significantly warmer in the daytime than nighttime. The dayside upper mesospheric temperatures (up to 10^{-4} Pa) do not show much variation (~140 K) with a warm and weak mesopause. This is in contrast with the nightside mesospheric temperatures, whereby mesopause is placed at 10^{-3} – 10^{-4} Pa with the minimum temperatures reaching ~100 K. This agrees well with the nightside mesopause reported by SPICAM (González-Galindo et al., 2009).

Comparison with the MCD reveals an opposite trend in the mesosphere with the nighttime mesopause warmer than daytime. We compare our retrievals with the predicted profiles from Mars Climate Database (MCD) v5.3 using its climatological dust scenario for average solar EUV conditions (Forget et al., 1999; Millour et al., 2018). A quite opposite trend is seen by MCD in Figure 5 (b) where values are taken corresponding to each of the observation conditions. This discrepancy between the retrievals and the MCD is also distinctly seen in Figure 6. While the MCD mesopause is quite stable at 10^{-3} – 10^{-4} Pa, it is colder by ~20 K during the dayside, resulting in a difference of ~40 K with the retrievals. On the other hand, it is warmer and lower in altitude for the nightside. This overestimation of cooling in the mesosphere during the daytime could be due to improper parametrization of CO_2 15 µm cooling and radiative balance in LMD-MGCM simulations (González-Galindo et al., 2015).

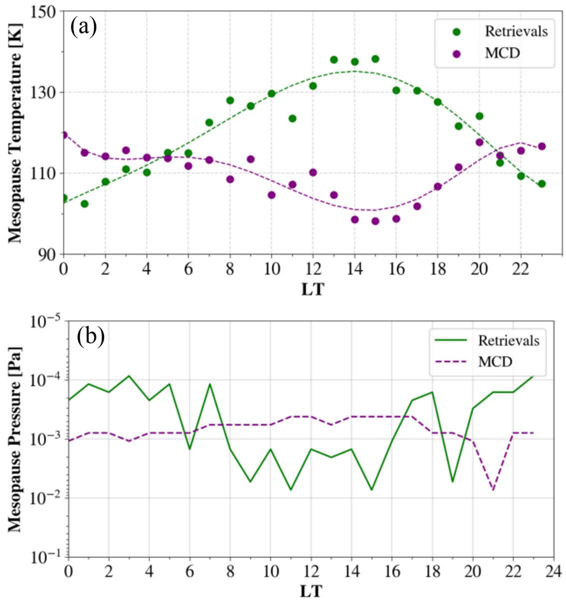

Figure 6. (a) Temperature and (b) pressure level at mesopause for different local times as given by the retrievals on FUV and the corresponding MCD values.

The day/night differences are predicted to be much lower by the MCD. Quantification of such diurnal differences between the retrievals and the MCD, for the entire altitude range of 80-160 km (5 km binning), is shown in Figure 7. The day/night differences become more relevant above 90 km as solar forcing imposes a strong diurnal cycle in the thermosphere. Further, the rapidly increasing temperatures seen at times lower in the atmosphere are not predicted by the MCD.

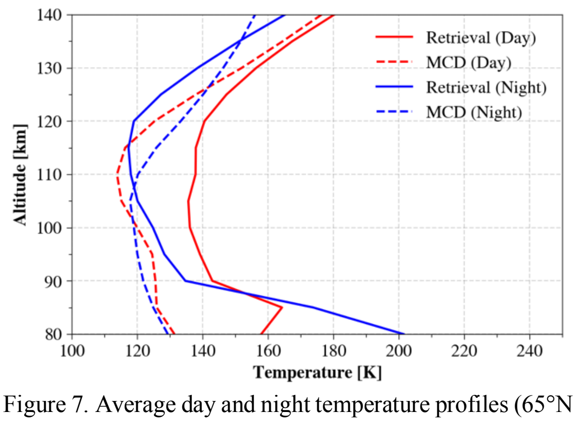

Figure 7. Average day and night temperature profiles (65°N – 65°S) for the retrievals on FUV (solid line) and corresponding MCD values (dashed lines).

The seasonal and latitudinal variations of the diurnal cycle exhibit expected characteristics. The retrieved temperature profiles will also be studied for varied combinations of seasons and latitude ranges to examine maximum and minimum day/night differences. Two examples are presented here in Figure 8 to show expected minimum nightside temperatures for northern low/mid-latitudes around aphelion and maximum dayside temperature for southern latitudes during dust storm season around perihelion. We have also seen nightside southern polar winter warming that is due to an enhanced interhemispheric circulation around solstice and downwelling at winter poles, but analogous warming for northern winter is not seen due to sparse observations for the northern winter high latitudes.

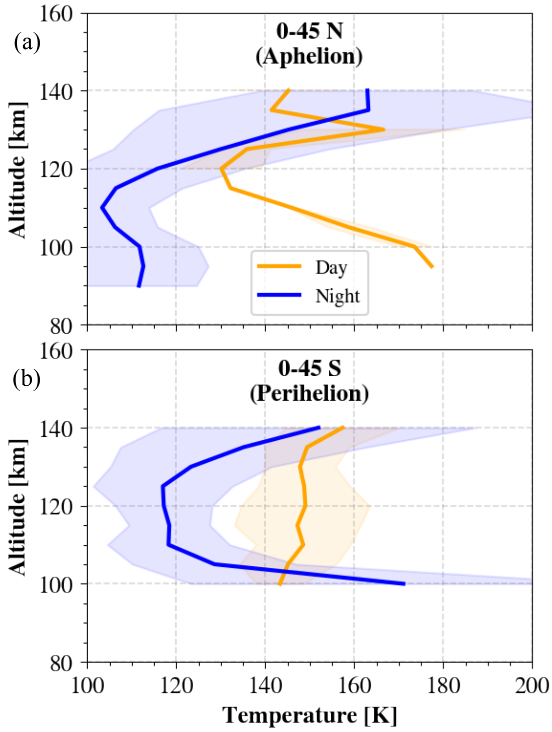

Figure 8. Day and night temperature profiles for low/mid-latitudes (a) in the northern hemisphere around aphelion, and (b) in the southern hemisphere around perihelion.

Conclusions: We have added ~1000 new dayside events to the stellar occultation dataset that were previously not processed due to the contamination by stray light. The formulated methodology to avoid stray light considering only the FUV spectrum gives consistent results when compared to the nightside test cases processed by considering both FUV and MUV spectra. Apart from considerably expanding and enhancing the usable dataset, this effort has enabled the first complete day/night study of the upper mesosphere/lower thermosphere (80-160 km). It is seen that the diurnal variations dominate any other variations. The temperature profiles so obtained demonstrate discrepancies with LMD-MGCM simulations, especially around the mesopause.

Though these are some of the preliminary results, our future endeavor would be focused on justifying these observations with the mechanisms responsible – the role of vertical winds and dynamics, heating rates, and radiative transfer. These observations have the potential to provide important inputs and constraints to the models to improve their predictions.

Data Availability: The L1B fits files for each of the stellar occultation events used in this study, along with the higher-level data products, are archived in the Planetary Atmospheres Node of the Planetary Data System (PDS).

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