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Diffusion and Day-Night Transport of Molecular Oxygen in Martian Upper Atmosphere. S. Gupta¹, R. V. Yelle², N. M. Schneider¹, S. K. Jain¹, A. S. Braude³, L. Verdier⁴, F. Montmessin⁴, H. Nakagawa⁵, M. Mayyasi⁶, J. Deighan¹, and S. M. Curry¹

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Introduction: Molecular oxygen in the martian atmosphere is produced photochemically and behaves like an inert trace gas due to its long photochemical lifetime (~ 60 Earth years) [1]. This implies that O_2 in the martian atmosphere is a long-lived and non-condensable species, such that its distribution is determined by the interplay between advection and diffusion. Its variations are therefore indicative of the changes in atmospheric mixing and circulation.

Due to limited spatial and temporal coverage, none of the previous studies give information on the vertical variation of O_2 [2], separately for day and night, to examine how it depends on diffusion as well as on day/night transport. Stellar occultations by the Imaging Ultraviolet Spectrograph (IUVS) aboard the Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft provide the first complete diurnal coverage of Martian upper mesosphere to lower thermosphere for a range of latitudes, longitudes, and seasons to help fill this knowledge gap [3].

Data: There have been 3459 IUVS stellar occultations from March 2015 to March 2024, covering both the dayside (LT=6-18) and the nightside (LT=18-6). This study implements an improved stray light filtering algorithm that allows the previously stray light affected dayside IUVS observations of O_2 to be studied for the first time [4], therefore providing the first quantification of the diurnal variation in O_2 mole fraction for ~ 90 -130 km altitude range.

Observed Day-Night Differences: As shown in Figure 1 (a), the measured O_2 mole fraction remains nearly constant around 10^{-3} at altitudes below ~ 105 km but is enhanced at higher altitudes.

Prominent day/night differences are seen above 105 km with nightside abundances several times larger than dayside values. From the local time averages shown in Figure 1 (b), the maximum mole fraction is measured at LT 4 and the minimum is at LT 14. The average nightside mole fraction is larger than the dayside by a factor of 1.75 in the altitude bin 120-125 km.

There is a strong detection of vertical gradients as expected from molecular diffusion and these are the first measurements to show this variation separately for day and night. The day and night average profiles in Figure 1 (c) are nearly identical below 105 km and equal to the value of 1.6×10^{-3} derived from MSL/SAM measurements near Gale crater [5]. However, as the altitude increases, the day/night differences become prominent with the nightside value a factor of 1.37 ± 0.04 larger than the dayside at ~ 125 km.

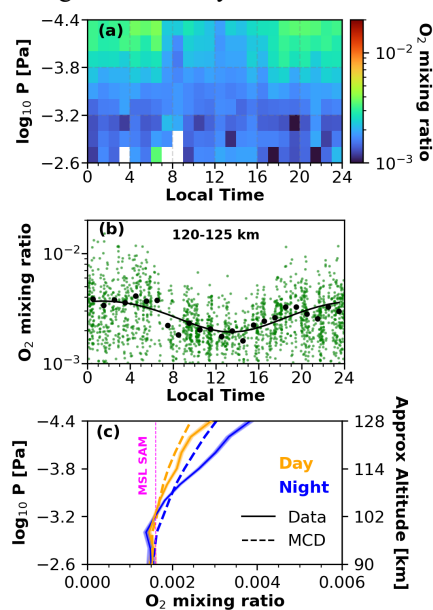


Figure 1. (a) Measured O_2 mole fraction averaged for each local time-log pressure bin over latitudes $65^\circ N$ - $65^\circ S$ and all seasons, longitudes, and martian years. (b) Measured O_2 mole fraction in the altitude bin 120-125 km, along with the average at each local time and its sinusoidal fit. (c) Average vertical dayside (orange) and nightside (blue) profiles as given by the data (solid) and MCD (dashed), along with the near-surface O_2 mixing ratio reported by [5] from MSL/SAM measurements.

Diffusion and Day-Night Transport: Since O_2 is a lighter species with larger scale height compared with CO_2 , it is enhanced at higher altitudes under molecular diffusive separation. As a result, the O_2 mole fraction should increase above the homopause. This variation and plausible mechanism with and without

including the effect of changing solar insolation and the resultant horizontal transport or diffusive flux, is illustrated in Figure 2.

There should be a depletion of minor lighter species on the dayside and its enhancement on the nightside as compared to the diffusive equilibrium profiles. This is explained in terms of the relative role of rapid horizontal transport at high altitudes and slower vertical diffusion resulting in net downward (upward) diffusive flux on the nightside (dayside). The observed day-night differences shown in Figure 1 are therefore consistent with the expectation depicted in Figure 2.

The 1-D vertical diffusion model is used to calculate day and night mole fraction profiles that are consistent with the measurements. It uses the diffusive flux $\Phi = 3.5 \times 10^8 \text{ cm}^{-2}\text{s}^{-1}$ and vertical eddy diffusion coefficient $K = 3.5 \times 10^6 \text{ cm}^2\text{s}^{-1}$. The equations used are described in [6]. Φ is estimated to be negative on the nightside and positive on the dayside. This implies downward diffusive flux on the nightside and upward diffusive flux on the dayside (day to night diffusive flux), thereby verifying the mechanism depicted in Figure 2 that results in observed day-night differences.

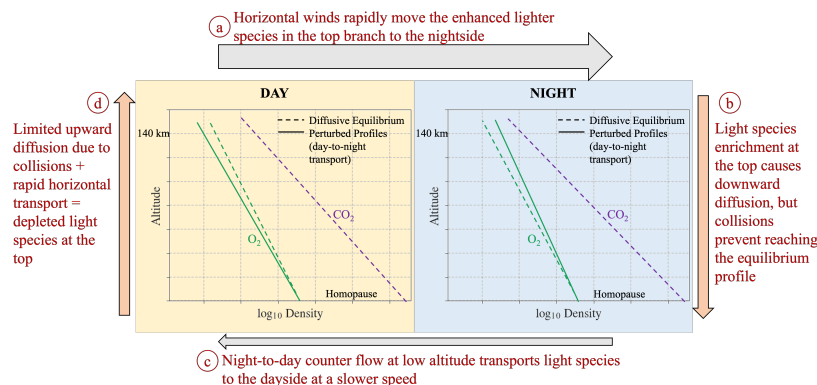


Figure 2. Schematic to represent diurnal circulation of lighter minor species O_2 in the martian atmosphere above the homopause that results in the nightside enhancement and dayside depletion of O_2 mole fraction with respect to the diffusive equilibrium profiles.

Data-Model Discrepancies: We also compared our results with the 3-D model. For this, we used the Mars Climate Database (MCD v6.1), which is based on the output of Mars Planetary Climate Model (M-PCM) [7]. This comparison shown in Figure 1 (c) suggests that the data and MCD are consistent in the well-mixed atmosphere with values in agreement with the MSL/SAM measurements. However, the data-model discrepancies arise above ~ 105 km in the molecular diffusion dominant region.

While the day/night trend is predicted to be similar to the observations with a nightside enhancement, the magnitudes are predicted to be smaller than the

measured mole fraction. Computing the 1-D model profiles corresponding to the MCD, the vertical eddy diffusion coefficient used is $K = 7.0 (\pm 1.0) \times 10^6 \text{ cm}^2\text{s}^{-1}$ which is approximately twice of that used for the data, $K = 3.5 (\pm 1.5) \times 10^6 \text{ cm}^2\text{s}^{-1}$ [8].

The data-model discrepancies are shown to be due to the overestimation of mixing in the martian atmosphere by the M-PCM, or due to overestimation of any proxy to denote mixing. This overestimation is likely to affect the diffusion of species through the martian atmosphere and the escape to space.

Conclusions: The UV stellar occultation technique is one of the very few available tools that can provide constraints on the molecular oxygen in the martian middle/upper atmosphere. We have not only been able to establish for the first time how O_2 varies on a diurnal scale and what are the day/night differences in its mole fraction under diffusive separation, but also found that the model predictions are inconsistent with the observations. The MCD profiles correspond to an overestimation of atmospheric mixing by a factor of ~ 2 that has important implications on how species diffuse through the martian atmosphere and escape to space. This suggests that our current understanding of how O_2 undergoes molecular diffusion and day/night transport is inadequate.

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