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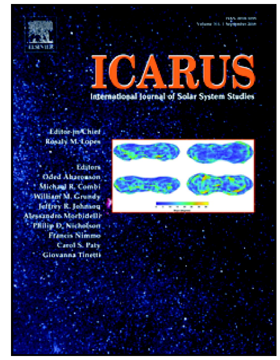

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The Martian oxygen green line dayglow: response to solar activity

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Highlights

- The Martian oxygen green line dayglow is monitored for the first time during an increasing phase of solar activity.
- The lower peak brightness varies over time in response to seasonal effects and increases with solar activity.
- The emission peak altitude varies with season but is not sensitive to solar activity.
- The emission occurs at the 0.39-µbar pressure level, whose altitude is overestimated by the MCD v6 model.
- A decrease of up to 90% of the modeled CO_2 density is required to match the peak altitude of the observations.

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Abstract

The Ultraviolet and Visible Spectrometer (UVIS) instrument of the Nadir and Occultation for MArs Discovery (NOMAD) aboard the ExoMars Trace Gas Orbiter (TGO) observes the Martian dayglow at 557.7 nm, which corresponds to the oxygen green line emission. Soret et al. (2022) analyzed a full Martian year of dayside limb observations and implied that some variability could be observed in both the altitude and intensity of the green dayglow. In this work, we take advantage of three Martian years of observations to analyze the evolution of the peak brightness and peak altitude of the oxygen green line emission during a period of increasing solar activity. We show that the limb brightness can change by ~70 % from one Martian year to the other. The green line brightness is highly correlated with both seasonal and solar activity effects. The brightest observations of the oxygen green line occur near perihelion and when solar insolation is highest. However, we observe that the peak altitude is highly correlated with season (maximum at perihelion) but it does not show a dependence on solar activity. Finally, we compare the evolution of the green line peak altitude with that of the 0.39-µbar pressure level provided by the Mars Climate Database (MCD) v6.1 and show that the calculated CO_2 density can be overestimated by a factor of 2, especially in the northern hemisphere. We conclude that dayside observations of the green line emission are a powerful tool to constrain global circulation models and remotely monitor the dynamics of the Mars atmosphere over time and season in the 70-100 km region.

Keywords

Planetary atmospheres (1244), Mars (1007), Solar activity (1475), Atomic spectroscopy (2099), Line intensities (2084)

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1. Introduction

The presence of the O(^{1}S – ^{1}D) oxygen emission at 557.7 nm was discovered (Gérard et al., 2020) in Mars dayglow limb spectra collected with the Ultraviolet-Visible Spectrometer (UVIS, Vandaele et al., 2018; Patel et al., 2017) on board the ExoMars Trace Gas Orbiter (TGO) during a period of low solar activity. It was characterized by a main emission peak located near 80 km and a second one, less intense, close to 120 km. The study was based on limb observations performed during 24 TGO orbits between April and December 2019, covering a period between spring equinox and late summer in the northern hemisphere. It showed that the green line was present at all latitudes during daytime. The oxygen red doublet at 630-636.4 nm was later observed (Gérard et al., 2021; Soret et al., 2022) but at much reduced brightness, as a consequence of collisional deactivation by the neutral constituents. Model simulations with the PAM model (Gkouvelis et al., 2018; Soret et al., 2022) showed that the excitation of the O(^{1}S) atoms in the dayglow is predominantly caused by photodissociation of CO_2 by solar radiation:

$$CO_2 + h\nu\ (\lambda < 128.6\ \text{nm}) \rightarrow CO + O(^1S) \quad (1)$$

The interaction of solar EUV photons create a wide upper layer while the main lower peak is formed by absorption of solar Lyman-α (Ly-α) radiation. A second oxygen emission at 297.2 nm, corresponding to the ^{1}S – ^{3}P, transition originates from the same upper state. It was observed in dayglow limb spectra both with the Imaging Ultraviolet Spectrometer (IUVS, McClintock et al., 2015) on board the Mars Atmosphere and Volatile EvolutioN (MAVEN) orbiter and the NOMAD-UVIS instrument on board TGO (Gérard et al., 2020). The quantum yield of O(^{1}S) from CO_2 photodissociation from Ly-α wavelength was retrieved from Mars dayglow observations with a production efficiency 9 ± 2% (Gkouvelis et al., 2018, 2024). Comparisons of simultaneous measurements of the two emissions with UVIS showed that the ratio of these emissions was equal to 16.5±0.4, in close agreement with the value of 15.5 derived from *ab initio* calculations (Chantler et al., 2013).

Gkouvelis et al. (2018) compared simulations of the OI 297.2 nm dayglow, calculated with the Photochemical Airglow Mars (PAM) model, and IUVS observations. They showed that the model correctly predicts the brightness and altitude of the peak at the expense of a

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correction of the CO_2 density provided by the Mars Climate Database (MCD, version 5.3, Forget et al., 1999; González-Galindo et al., 2005; Millour et al., 2015). A decrease up to 40% of the CO_2 column from the MCD was needed to match the observed peak altitude of the main dayglow layer. Their study also demonstrated that the altitude of the main emission peak at 297.2 nm (and consequently at 557.7 nm as well) varies quasi-linearly with the logarithm of the overlying CO_2 column density. Gkouvelis et al. (2020a) calculated that the altitude of the lower emission peak corrected for overhead Sun conditions is located at a pressure level of 0.39 ± 0.03 µbar. This is a consequence of the simplicity of the dominant excitation process (1), closely meeting the conditions of a Chapman layer. Therefore, observations of the emission peak altitude make it possible to remotely monitor the altitude variations of the 0.39-µbar level. An application of the 297.2-nm emission tracer was shown in Gkouvelis et al. (2020b) where they probe changes of the altitude of the isobar in response to lower atmospheric dust storms.

Further analyses of the OI 557.7-nm dayglow emission with UVIS observations have been described by Aoki et al. (2022) and Soret et al. (2022, 2023). Aoki et al. (2022) focused on the retrievals of atmospheric density and temperature from inertial limb observations of the green dayglow, where a whole range of altitudes of the tangent point is scanned. Soret et al. (2022, 2023) analyzed over 25,000 UVIS dayglow spectra collected during the April 2019-December 2021 time span, a period of low solar activity. These spectra have been acquired both in the inertial limb and limb tracking (the altitude of the tangent point is constrained to remain constant during the acquisition of a latitudinal scan) observation modes. They derived a 557.7-nm/297.2-nm intensity ratio equal to 16.8 ± 0.4. They also showed that the peak brightness of the 557.7-nm emission responds to changes in the solar Ly-α flux reaching the planet, that is simultaneously measured with the Extreme Ultraviolet Monitor (EUVM) (Eparvier et al., 2015) on board MAVEN. They also noted that the 557.7-nm brightness shows asymmetry between the northern and southern hemispheres. It was statistically 34% brighter in the southern hemisphere than in the north, a consequence of the stronger Ly-α solar flux near perihelion. During this quiet solar activity period previously analyzed, the variations of the incident Ly-α flux were essentially controlled by the seasonal changes of the Sun-Mars distance. After removing the influence of the solar zenith angle, Soret et al. (2022) observed seasonal variations of the altitude of the main peak which statistically dropped by 15–20 km from perihelion to aphelion at mid and low latitudes. These variations were explained by the

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thermal expansion of the Martian atmosphere in response to the increasing amount of solar radiation in the vicinity of perihelion.

In this study, we analyze the response of the green oxygen dayglow to solar activity. We use a larger dayglow UVIS database (Section 2) encompassing Martian years 35 to 37, during a period of increasing solar activity when the sunspot number varied between 0 and 240 (Sunspot data from the World Data Center SILSO, Royal Observatory of Belgium, Brussels, https://www.sidc.be/SILSO/home). We first present in section 3.1 the interannual variability of the green line emission. In Section 3.2, we analyze the correlation between the brightness of the OI 557.7-nm emission and the incoming Ly-α solar flux reaching the planet. We separate the seasonal variation associated with the varying Sun-Mars distance from the intensity changes caused by the intrinsic increase of the Ly-α emission. In section 3.3, we quantify the variations of the dayglow peak altitude and distinguish the seasonal effects from those potentially caused by the solar variation increase. Comparisons between the seasonal variations of altitude of the green line emission from UVIS and that of the 0.39-µbar level from the MCD are presented in section 3.4.

2. TGO observations of the oxygen green line dayglow

TGO started orbiting Mars in October 2016. Since March 2018, its orbit is quasi-circular at ~400 km and inclined by 74° relative to the equator. The UVIS spectrometer aboard NOMAD observes between 200 and 650 nm, with a spectral resolution that varies from 1.2 nm at 200 nm to 1.6 nm at 650 nm. In a special pointing mode, UVIS is able to take limb measurements of the Mars atmosphere. About two orbits per month are dedicated to dayside limb measurements.

The data processing pipeline consists in removing the instrumental background and dark current (DC) on the CCD frame, and correcting the noise from cosmic rays, anomalous and hot pixels. An average spectrum is generated by binning the 81 fully illuminated CCD lines and the count rate is converted into brightness units (Rayleigh, R) based on laboratory measurements obtained during the ground-based and in-flight calibration campaigns. During the dayglow limb measurements, stray light is removed from dayglow limb observations using the nonilluminated regions at the top and bottom parts of the CCD. In addition to the statistical error on the measured brightness, a possible systematic error is associated with the uncertainties of the relative instrumental calibration estimated to be less than 5% above 220 nm. More details about calibration can be found in Willame et al. (2022).

Between April 23, 2019 (Martian Year MY 35, solar longitude L_S = 15°) and May 11, 2024 (MY 37, L_S = 253°), 172 dayside limb observations have been performed, corresponding to a total of 41,468 UVIS spectra. Only spectra acquired with a solar zenith angle (SZA) less than 70° at the tangent point and an altitude ranging between 60 and 200 km have been retained for this dayglow study (9,881 spectra). The green line oxygen brightness is retrieved from each individual spectrum. It is derived by subtracting the background signal defined as the averaged signal from the adjacent [537.7–556.6] and [558.8–577.70]-nm wavelength intervals (Soret et al., 2022). The peak of the emission, corresponding to the maximum of the measured datapoints in each individual UVIS limb profile, can be extracted. The peak brightness has been corrected from any solar zenith angle dependence, using a 1/cos(SZA) law, with SZA<70°. This correction tends to increase the brightness measured at high SZA values. Peak altitudes have been corrected from the SZA dependence to SZA=0° for the entire database, following the ln(1/cos(SZA)) semi-empirical normalization equation from Gkouvelis et al. (2020a). All measurements can therefore be considered as if acquired at the subsolar point. As a consequence, any variation presented afterwards cannot be attributed to spatial variations.

3. The oxygen variability

3.1. Interannual variability

We first illustrate the variability of the 557.7-nm emission brightness over two Martian years with average limb profiles (Figure 1). These plots include individual limb scans obtained both in the UVIS inertial limb and limb tracking modes. All observations have been grouped into 5-km altitude bins between 80 and 180 km. Both limb profiles include observations acquired between 296° and 26° of solar longitude, during the northern winter season, for three different Martian years: MY35 (black), MY36 (green) and MY37 (magenta). All limb profiles present similar shapes, but with drastically different intensities. The peak intensity is 231 ± 7 kR at 78 km for MY35, while it reaches 280 ± 5 kR at 81 km during MY36 and 348 ± 16 kR at 78 km during MY36. Therefore, the green line dayglow is much brighter during MY37 than during MY35 at the same season. We will see in the following sections that this brightness increase is due to the solar activity increase during these Martian years. All limb profiles show an upper peak at ~115 km. The ratios between the lower and the upper peaks are 2.3, 1.9 and 1.7 in MY35, MY36 and MY37, respectively. These ratios between the upper and the lower peaks tend to suggest that the ratio is slightly anticorrelated with solar activity.

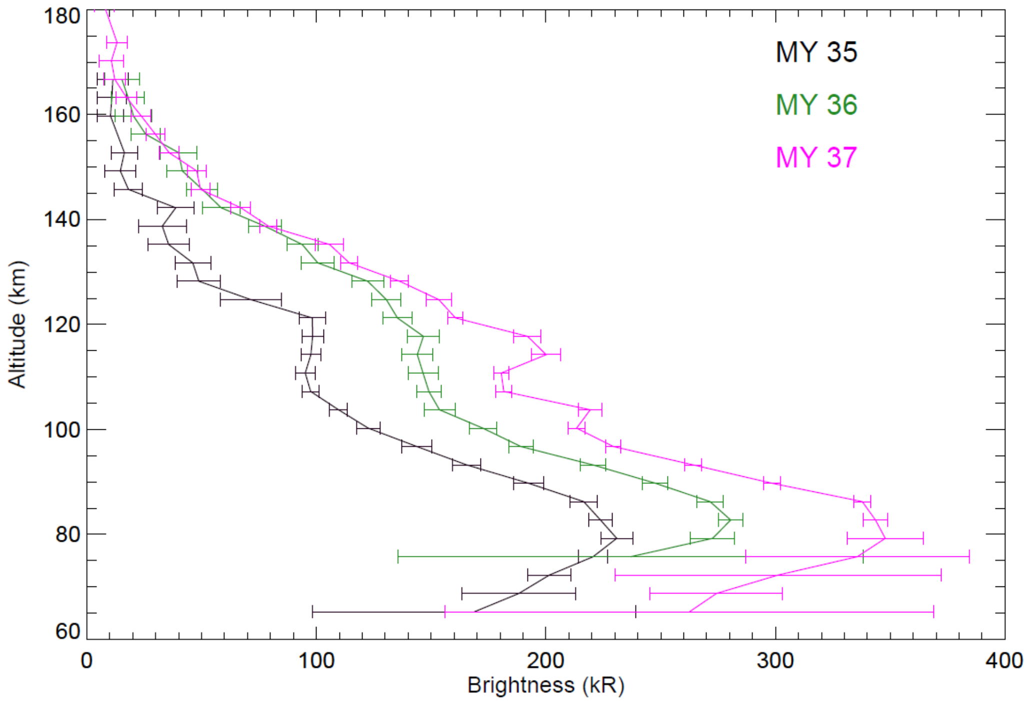

Figure 1: Average limb profiles of the oxygen green line emission between L_S=296° and 26° for MY35 (black), MY36 (green) and MY37 (magenta). The peak brightness has increased by a factor 1.5 between MY35 and MY37. Brightness uncertainties are based on the 1-σ deviation of the background noise in the neighborhood of the emission, similarly to Soret et al. (2022, 2023).

3.2. Brightness variations

In this section, the oxygen peak brightness (I_{peak}) is studied over time, from April 23, 2019 (MY35, L_S = 15°) to January 11, 2025 (MY38, L_S = 28°). Figure 2a shows that the 557.7-nm emission varies over time (black): a general increase is observed from MY35 to MY38, together with oscillations generated by the changing Sun-Mars distance. A seasonal variation was previously observed at 557.7 nm by Soret et al. (2022), with an increase near perihelion. No global rising trend was observed though, because of the limited time span (less than a full Martian year) of the dataset used for that study. Gkouvelis et al. (2018) showed with model simulations that the brightness of the lower peak of the oxygen emission at 297.2 nm (and consequently at 557.7 nm as well) depends on the Ly-α solar flux reaching the top of the Martian atmosphere. We therefore compare the NOMAD-UVIS lower peak brightness to the solar flux concurrently measured by MAVEN-EUVM. Solar spectra with a resolution of 1 nm are calibrated according to the solar irradiance measured in the 0–7, 17–22 and 117–125 nm channels. The absolute calibration uncertainty at Ly-α is estimated to be on the order of 5%. Calibrated solar spectra are available from NASA's Planetary Data System website on a daily average basis. At the time of writing, EUVM data are available up to November 14, 2024. The Ly-α solar irradiances ($F_{Ly\text{-}\alpha}$) deduced from the EUVM observations over time are overplotted in blue in Figure 2a. The oxygen dayglow brightness and the incident Ly-α irradiance are strongly correlated, with a Pearson-R correlation coefficient of 0.94 (Figure 2b). We deduce the following statistical analytical relation between the two variables: $I_{peak} = 80.2 \times F_{Ly\text{-}\alpha} + 5.8$.

In order to isolate the seasonal effects of the orbital period of Mars, both the 557.7-nm peak brightness and solar Ly-α irradiance have been corrected from the Sun-Mars distance using the $1/r^2$ relation, where r is the Mars orbital radius. The quasi-continuous increase observed in Figure 2c is therefore solely caused by the increase of solar activity over time, as demonstrated by the blue curve showing the solar Ly-α irradiance. The de-seasonalized Ly-α incident flux increases by a factor of ~1.7, from ~2.7 mW m^{-2} in 2019 to ~4.5 mW m^{-2} in 2025. The peak brightness of the oxygen green line increases by a similar factor of ~1.8 (from ~200 to ~350 kR). Both variables are highly correlated, with a Pearson-R coefficient of 0.88 (Figure 2d). In that case, the statistical analytical relation between the two variables corrected from the Sun-Mars distance is $I_{peak\ corr} = 88.2 \times F_{Ly\text{-}\alpha\ corr} - 18.9$.

These observations confirm that the incident solar Ly-α flux directly influences the brightness of the main OI 557.7 dayglow emission which responds linearly to its increase during the rise of the solar cycle.

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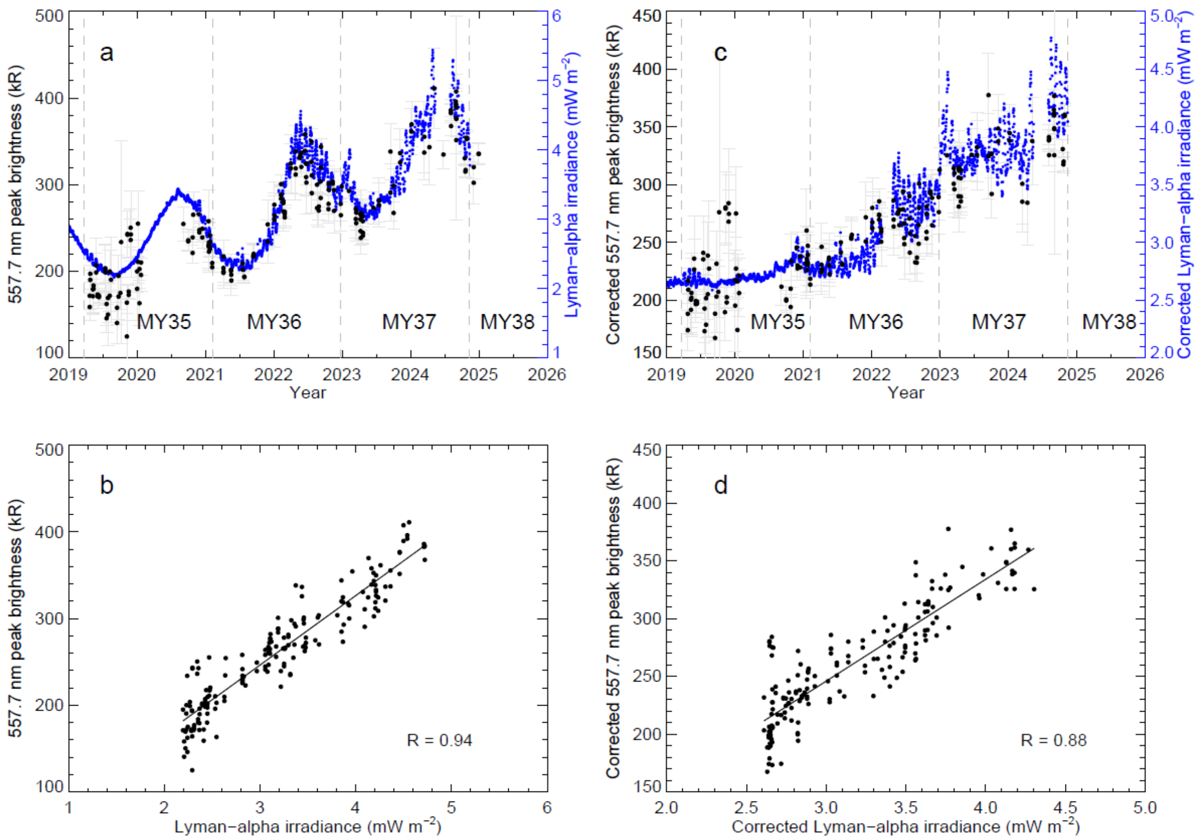

Figure 2: a) The green line peak brightness (black) and the Ly-α irradiance (blue) are represented over time. Martian years are indicated with vertical dashed lines. b) Correlation between the green line peak brightness and the Ly-α irradiance. c and d) Both the 557.7-nm peak brightness and solar Ly-α irradiance have been corrected from the Sun-Mars distance ($1/r^2$). Brightness uncertainties are based on the 1-σ deviation of the background noise in the neighborhood of the emission, similarly to Soret et al. (2022, 2023). Altitude uncertainties are estimated with the vertical sampling resolution.

3.3. Altitude variations

This section focusses on the peak altitude of the 557.7-nm emission. Figure 3a represents the peak altitude of the emission over the three considered Martian years. Peak altitudes are corrected from the dependence on SZA (see end of Section 2). Oscillations are observed, with maxima near the perihelion periods and minima at aphelion. The solar Ly-α irradiance measured onboard EUVM in orbit around Mars is plotted in blue. Both curves are well correlated during MY 35 and 36, but the minimum observed in the peak altitude at aphelion during MY 37 remains as low as the minima observed in MY 35 and 36: no increase is observed, contrary to the rise observed in the solar Ly-α irradiance at the same period. Similarly, no increase of the oxygen altitude layer is observed at the end of MY 37. Therefore, the solar activity increase that occurs during MY37 does not influence the altitude of the green line peak (R=0.82). In contrast, the 557.7-nm peak altitude (in black) is very well correlated (R=0.97) with the Sun-Mars distance (blue) as shown in Figure 3b. Indeed, the peak altitude is controlled by the vertical motion of the pressure levels (Gkouvelis et al., 2020a; Soret et al., 2022), which depends on other complex factors (ground pressure, infrared cooling, vertical thermal

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structure, gravity waves, etc.). In Figure 3c, the peak altitudes retrieved from the four Martian years are color-codded in black, green, magenta and cyan as a function of solar longitude. The peak altitude varies between 70 and 84 km during the first part of the Martian year and between 84 and 94 km near perihelion. This variability is not dependent on the Martian year, and therefore to the solar activity increase, since no particular pattern can be observed. MAVEN-IUVS observations of the 297.2-nm emission peak altitude are overplotted in blue on top of the NOMAD-UVIS data of the 557.7-nm emission. These data are taken from Gkouvelis et al. (2020a) and gather observations acquired between MY 32 (L_S = 216°) and 34 (L_S = 224°), a period of high to low solar activity. The MAVEN-IUVS data follow the same trend as the NOMAD-UVIS observations, with somewhat less variability. Once again, this plot demonstrates that the peak altitude of the green line emission is not related to the Ly-α brightness, but to seasonal effects.

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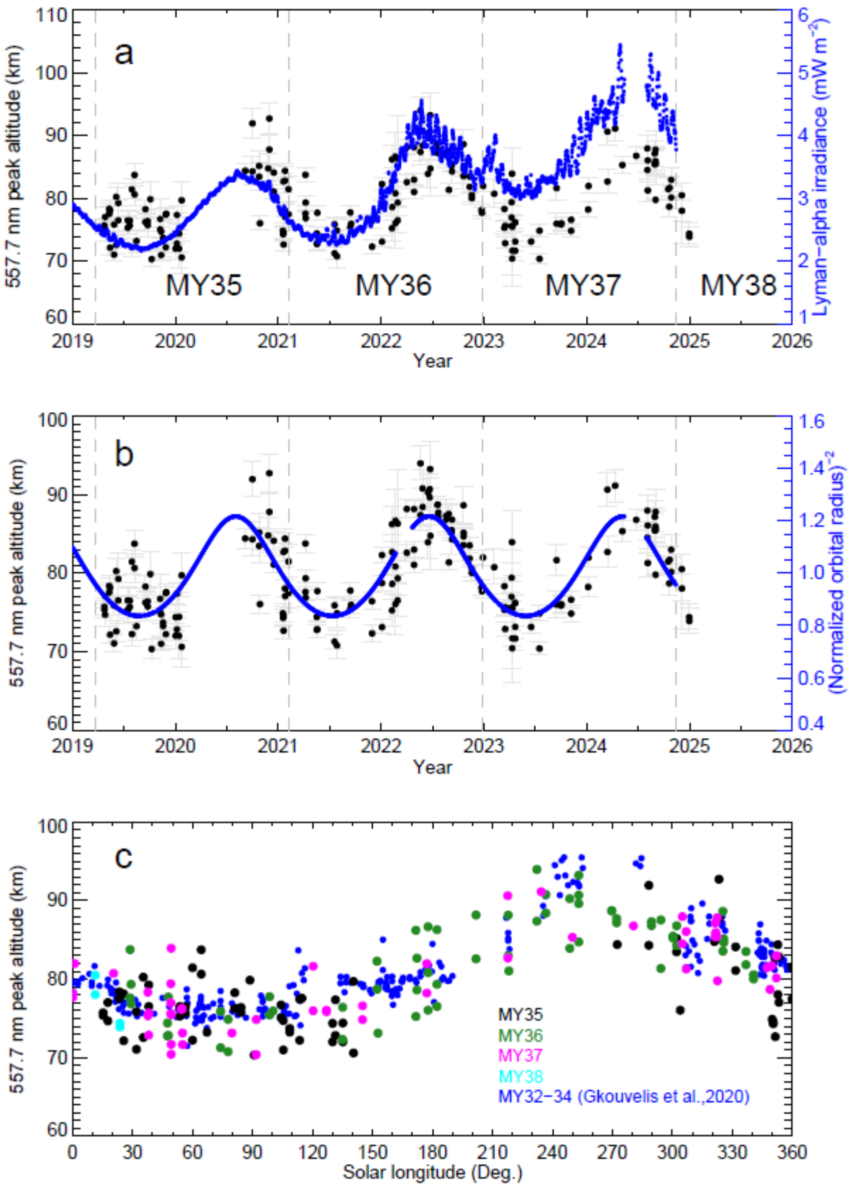

Figure 3: The oxygen green line peak altitude (black) is represented over time together with the Ly-α irradiance (blue, top panel), and with the Sun-Mars distance ($1/r^2$) (blue, middle panel). Martian years are indicated with vertical dashed lines. In the bottom panel, NOMAD-UVIS observations (black, green, magenta and cyan for MY 35, 36, 37 and 38, respectively) of the 557.7-nm emission peak altitude are plotted versus solar longitude together with the MAVEN-IUVS observations (blue) monitoring the 297.2-nm emission peak altitude (Gkouvelis et al., 2020a).

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3.4. Pressure level

Gkouvelis et al. (2020a) showed that the altitude of the lower peak of the 297.2-nm limb emission is located at a pressure level of 0.39 ± 0.03 µbar. This conclusion also applies to the 557.7-nm emission since both emissions share the same oxygen upper state. In Figure 4, the altitudes corresponding to the 0.39-µbar pressure levels have been retrieved from the MCD (Figure 4b) at the exact times and locations of the NOMAD-UVIS peak limb observations (Figure 4a). The MCD v6.1 contains data up to the MY35. To model more recent observations, climatological conditions appropriate to each observation date were used (e.g. EUV solar activity and dust load in the lower atmosphere). The dots in Figure 4a are identical to those presented in black, green, magenta and cyan in Figure 3c, except that they are now color-coded according to the latitude of the measurements. The altitudes of the 0.39-µbar isobar level calculated by the MCD model are in general good agreement with the dayglow measurements, with a correlation coefficient of 0.59 (Figure 4c). The present study therefore confirms that the simulated 0.39-µbar isobar level is in general agreement with the peak altitude of the green line emission, similarly to the 297.2-nm emission.

However, a slight difference between the two datasets can be noticed during the first part of the Martian year (L_S < 180°): while the altitude retrieved of the 0.39-µbar level from the NOMAD measurements does not depend on the latitude of the observations, the retrieved altitudes of the isobar levels show two distinct branches (red and blue dots) caused by a latitudinal effect. Figure 4c shows that the 0.39-µbar simulated altitude is globally correctly calculated in the southern hemisphere (blue dots, second part of the Martian year) but that they can be overestimated by up to 20 km poleward of 20°N. Consequently, the seasonal range of the simulated peak altitude (~20 km from 75 to 95 km) is lower than that of the observations

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(~25 km from 70 to 95 km). The same difference was already observed by Gkouvelis et al. (2020a) with the 5.3 version of the MCD model. Therefore, none of the updates applied between versions 5.3 and 6.1 of the MCD have solved this discrepancy. We also note that any quenching does not affects the oxygen green line emission above 80 km.

The CO_2 density can actually be scaled to modify the peak altitude of the simulated green line emission (see Equation 1). The CO_2 density has therefore been linearly scaled so that every single model simulation matches the observed NOMAD-UVIS altitude. This scaling factor is a qualitative indicator of the discrepancy between the NOMAD observations and the MCD simulations. The scaling factors applied to the MCD CO_2 density can be seen in Figure 4d. While the right order of magnitude is calculated by the MCD, density values from the southern hemisphere (blue dots) generally would need to be decreased by 20 to 60%, while density values in the northern hemisphere (red dots) should be corrected by 60 to 95% between ~70 and ~90 km. These corrections are constant over the Martian year and do not depend on season. It therefore appears that the MCD CO_2 density is slightly overestimated, especially in the northern hemisphere. A similar study based on the atomic oxygen UV emission at 297.2 nm by Gkouvelis et al. (2018) showed that CO_2 densities had to be scaled by a factor between 0.38 and 0.66. They explain that Forget et al. (2009) already noticed that modeled densities were higher by a factor of 2 between 70 and 100 km compared to the SPICAM stellar occultation measurements. They concluded that this was due to the temperature profiles predicted by the model between 85 and 100 km. Even if the MCD model has been improved Forget et al. (2000), Montmessin et al. (2017) showed that some discrepancies remain, especially between L_S=120 and 200°. Gkouvelis et al. (2020a) confirmed that the MCD CO_2 vertical distribution in the upper atmosphere, that depends on solar and dynamical heating, radiative cooling, heat conduction and atmospheric coupling with the lower atmosphere

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(González-Galindo et al., 2005), needs to be improved. According to the present study, it seems that a north/south temperature asymmetry, that is not correctly reproduced by the MCD, exists.

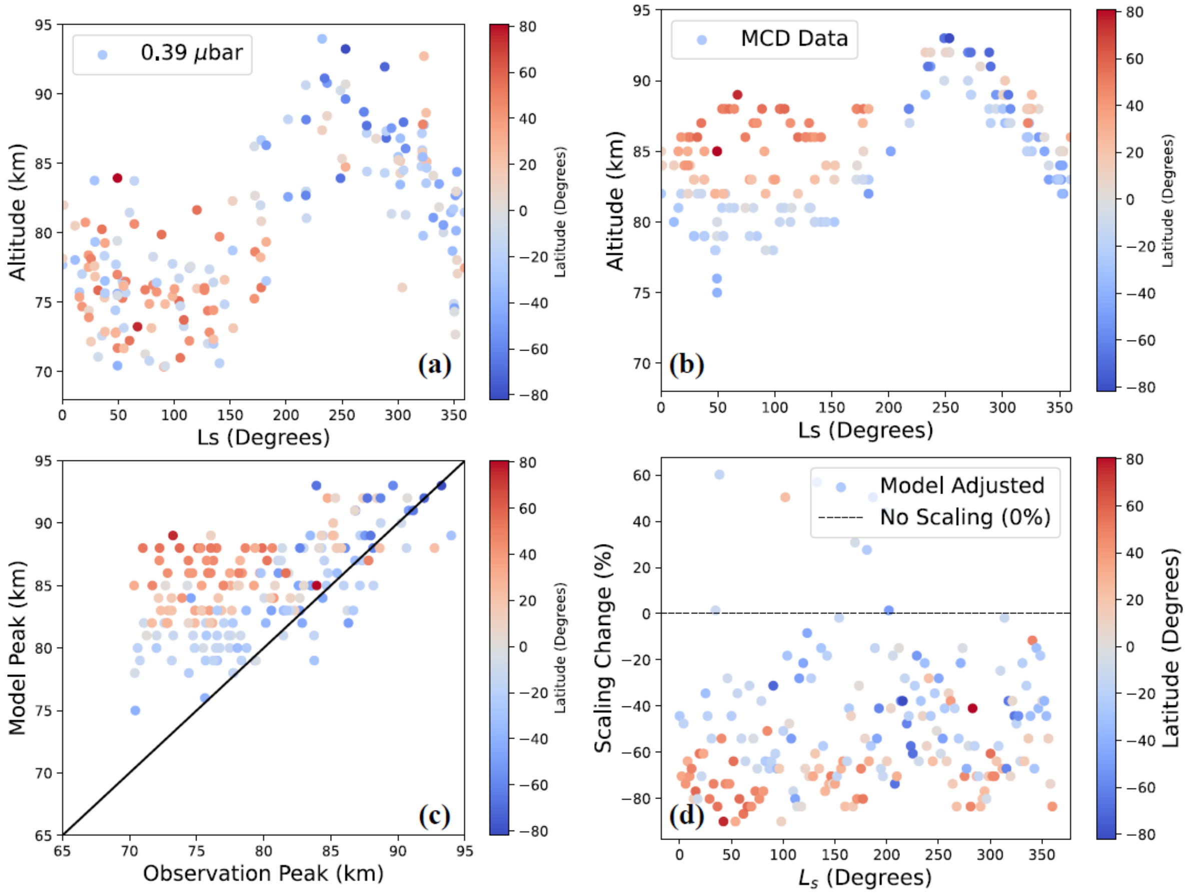

Figure 4: The altitude of the lower green emission peak extracted from the NOMAD-UVIS data, which corresponds to the 0.39-μbar pressure level, is plotted as a function of solar longitude (a). The altitude of the 0.39-μbar pressure level extracted from the corresponding MCD data is plotted as a function of solar longitude (b). The linear correlation coefficient of both quantities is 0.58 (c). The MCD CO_2 density can be linearly scaled so that the simulated altitudes match the observation altitudes (d). Values are color-codded according to the latitude of the observations.

4. Discussion and summary

NOMAD/UVIS dayglow measurements acquired during three Martian years of increasing solar activity have been analyzed in this study. The oxygen green line emission shows significant variability on different scales:

1 – The brightness of the 557-7nm limb profile increases by a factor of 1.7 from one Martian year to the other, owing to its sensitivity to the incident EUV flux;

2 – The lower oxygen peak brightness ranges between 150 and 370 kR. It is strongly correlated both to the Mars orbital distance (with maxima at perihelion) and to solar activity;

3 – The altitude of the lower peak is highly correlated with the Sun-Mars distance. It ranges between 65 km at aphelion and 90 km at perihelion.

4 – We show that it follows the altitude of the atmospheric 0.39-µbar pressure level that is located at higher altitudes when the atmosphere is inflated, near perihelion.

5 – Between ~70 and ~90 km, the MCD CO_2 density is overestimated by up to 90%, especially in the northern hemisphere.

This study shows that monitoring the changing altitude of the green line emission peak is a powerful tool to remotely track variations in the vertical structure of the mesosphere to lower thermosphere. These Martian atmospheric layers cannot be monitored from the surface or space-borne in-situ measurements. In addition, only a very few airglow emissions can be observed below 100 km, since the optical depth in EUV for most wavelengths become much higher than unity below this altitude. The green line is therefore a unique tracer to study the effects coming from the interaction of the lower atmosphere and the space environment on these atmospheric layers. Furthermore, our results can be used to constrain global circulation models connecting the lower and upper atmospheres (e.g. LMD GCM, González-Galindo et al., 2005).

It would be interesting to know whether the peak brightness and/or peak altitude of the green line emission is correlated with local time as well and examine if an asymmetry between dawn and dusk exists. However, the statistics is currently not good enough to perform this kind of analysis and additional data are required. Another future study would be to monitor the green line emission during global dust storms that modify the vertical temperature and the CO_2 density distributions in the atmosphere. Altitude is expected to increase with global dust storms, as demonstrated by Gkouvelis et al. (2020b) with MAVEN data during MY 32 to 34, but no such event has been observed between MY 35 and 37 with NOMAD. Continued monitoring of this emission will allow investigating the correlation of the peak emission brightness and altitude with rising solar activity and with more sporadic events such as global dust storm events and solar flares. Finally, with additional data, impact of strong solar events, which are more frequent during high solar activity periods, on green line variability can be studied.

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Data availability

The Mars Climate Database is available online at http://www-mars.lmd.jussieu.fr/mcd_python/ and the EUVM solar flux is available online at https://doi.org/10.17189/1517691. The ExoMars orbiter NOMAD-UVIS observations since the beginning of the nominal science mission (21 April 2018) are available on the ESA Planetary Science Archive at https://archives.esac.esa.int/psa/.

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References

Aoki, S., Gkouvelis, L., Gérard, J.-C., Soret, L., Hubert, B., Lopez-Valverde, M. A., et al. (2022). Density and temperature of the upper mesosphere and lower thermosphere of Mars retrieved from the OI 557.7 nm dayglow measured by TGO/NOMAD. Journal of Geophysical Research: Planets, 127, e2022JE007206. https://doi.org/10.1029/2022JE007206

Chantler, C. T., Nguyen, T. V. B., Lowe, J. A., & Grant, I. P. (2013). Relativistic calculation of transition probabilities for 557.7 nm and 297.2 nm emission lines in oxygen. The Astrophysical Journal, 769, 1, 84. https://doi.org/10.1088/0004-637X/769/1/84.

Eparvier, F.G., Chamberlin, P.C., Woods, T.N. et al. (2015). The Solar Extreme Ultraviolet Monitor for MAVEN. Space Sci Rev 195, 293–301. https://doi.org/10.1007/s11214-015-0195-2

Forget, F., Hourdin, F., Fournier, R., Hourdin, C., Talagrand, O., Collins, M., & Huot, J. P. (1999). Improved general circulation models of the Martian atmosphere from the surface to above 80 km. Journal of Geophysical Research, 104(E10), 24155–24175.

Gérard, J.C, S. Aoki, Y. Willame, L. Gkouvelis, C. Depiesse, I. R. Thomas, B. Ristic, A. C. Vandaele, F. Daerden, B. Hubert, J. Mason, M. R. Patel, J.-J. López-Moreno, G. Bellucci, M. A. López-Valverde, & B. Beeckman (2020). Detection of green line emission in the dayside atmosphere of Mars from NOMAD-TGO observations, Nature Astronomy, 4, 11, 1049-1052.

Gérard, J. C., Aoki, S., Gkouvelis, L., Soret, L., Willame, Y., Thomas, I. R., et al. (2021). First observation of the oxygen 630 nm emission in the Martian dayglow. Geophysical Research Letters, 48(8), e2020GL092334. https://doi.org/10.1029/2020GL092334

Gkouvelis, L., Gérard, J.C., Ritter, B., Hubert, B., Schneider, N. M., & Jain, S. K. (2018). The O(^{1}S) 297.2-nm dayglow emission: A tracer of CO_2 density variations in the martian lower

Journal Pre-proof

thermosphere. Journal of Geophysical Research: Planets, 123,3119–3132. https://doi.org/10.1029/2018je005709.

Gkouvelis, L., Gérard, J.C., Ritter, B., Hubert, B., Schneider, N. M., & Jain, S. K. (2020a). Airglow remote sensing of the seasonal variation of the Martian upper atmosphere: MAVEN limb observations and model comparison. Icarus, 341, 113666. https://doi.org/10.1016/j. icarus.2020.113666

Gkouvelis, L., Gérard, J.-C., González-Galindo, F., Hubert, B., & Schneider, N. M. (2020b). Isobar altitude variations in the upper mesosphere observed with IUVS-MAVEN in response to Martian dust storms. Geophysical Research Letters, 46, e2020GL087468. https://doi.org/10.1029/2020GL087468

Gkouvelis, L., C. Akm & K. Heng (2024). The quantum yield of $O(^1S)$ in CO_2 photolysis retrieved from the Martian atmosphere. Astronomy and Astrophysics, 690, A319, https://doi.org/10.1051/0004-6361/202450588

González-Galindo, F., M. A. López-Valverde, M. Angelats i Coll, and F. Forget (2005), Extension of a Martian general circulation model to thermospheric altitudes: UV heating and photochemical models, J. Geophys. Res., 110, E09008, doi:10.1029/2004JE002312

McClintock, W. E., Schneider, N. M., Holsclaw, G. M., Clarke, J. T., Hoskins, A. C., Stewart, I., ... & Deighan, J. (2015). The imaging ultraviolet spectrograph (IUVS) for the MAVEN mission. Space Science Reviews, 195, 75-124.

Journal Pre-proof

Millour, E., Forget, F., Spiga, A., Navarro, T., Madeleine, J. B., Montabone, L., et al. (2015). The Mars Climate Database (MCD Version 5.2), (Vol. 10). EPSC abstract 2015-438.

F. Montmessin, O. Korablev, F. Lefèvre, J.-L. Bertaux, A. Fedorova, A. Trokhimovskiy, J.Y. Chaufray, G. Lacombe, A. Reberac, L. Maltagliati, Y. Willame, S. Guslyakova, J.-C. Gérard, A. Stiepen, D. Fussen, N. Mateshvili, A. Määttänen, F. Forget, O. Witasse, F. Leblanc, A.C. Vandaele, E. Marcq, B. Sandel, B. Gondet, N. Schneider, M. Chaffin, N. Chapron, (2017), SPICAM on Mars Express: A 10 year in-depth survey of the Martian atmosphere, Icarus, Volume 297, Pages 195-216, ISSN 0019-1035, https://doi.org/10.1016/j.icarus.2017.06.022.

Patel, M. R., Antoine, P., Mason, J., Leese, M., Hathi, B., Stevens, A. H., et al. (2017). NOMAD spectrometer on the ExoMars trace gas orbiter mission: Part 2—Design, manufacturing, and testing of the ultraviolet and visible channel. Applied Optics, 56, 2771–2782. https://doi.org/10.1364/AO.56.002771.

SILSO, World Data Center - Sunspot Number and Long-term Solar Observations, Royal Observatory of Belgium, on-line Sunspot Number catalogue: http://www.sidc.be/SILSO.

Soret, L., J.C. Gérard, S. Aoki, L. Gkouvelis, I. R. Thomas, B. Ristic, B. Hubert, Y. Willame, C. Depiesse, A. C. Vandaele, M. R. Patel, J. P. Mason, F. Daerden, J.-J. López-Moreno, & G. Bellucci (2022). The Mars Oxygen Visible Dayglow: A Martian Year of NOMAD/UVIS Observations, Journal of Geophysical Research: Planets, 10.1029/2022JE007220, 127, 6.

Journal Pre-proof

Journal Pre-proof

Soret, L., J.C. Gérard, B. Hubert, A. C. Vandaele, I. R. Thomas, B. Ristic, Y. Willame, N. Schneider, S. Jain, S. Gupta, J. P. Mason, & M. R. Patel (2023). The Ultraviolet Martian Dayglow Observed With NOMAD/UVIS on ExoMars Trace Gas Orbiter, Journal of Geophysical Research: Planets, 10.1029/2023JE007762, 128, 5.

Vandaele, A. C., López-Moreno, J.-J., Patel, M. R., Bellucci, G., Daerden, F., Ristic, B., et al. (2018). NOMAD, an integrated suite of spectrometers for the ExoMars Trace Gas Mission: Technical description, science objectives, and expected performance. Space Science Reviews, 214(5), 80. https://doi.org/10.1007/s11214-018-0517-2

Willame, Y., Depiesse, C., Mason, J. P., Thomas, I. R., Patel, M. R., Hathi, B., et al. (2022). Calibration of the NOMAD-UVIS data. Planetary and Space Science, 218, 105504. https://doi.org/10.1016/j.pss.2022.105504

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Declaration of Interest Statement

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Highlights

- The Martian oxygen green line dayglow is monitored for the first time during an increasing phase of solar activity.
- The lower peak brightness varies over time in response to seasonal effects and increases with solar activity.
- The emission peak altitude varies with season but is not sensitive to solar activity.
- The emission occurs at the 0.39-μbar pressure level, whose altitude is overestimated by the MCD v6 model.
- A decrease of up to 90% of the modeled CO_2 density is required to match the peak altitude of the observations.

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