Effect of Incoming Solar Particle Radiations on The Exosphere of Mars

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Abstract

Mars Exospheric Neutral Composition Analyzer (MENCA) of Mars Orbiter Mission (MOM) measures the \textit{in-situ} neutral upper atmospheric constituents of Mars. Martian lower atmosphere predominated by the presence of CO\textsubscript{2} which photo-dissociates into atomic oxygen (O) in higher altitudes much near the exobase. Atomic O plays a significant role in invoking stronger presence of O\textsubscript{2}+ in the Martian ionosphere. Primary photo-dissociative species CO\textsubscript{2}, crossover its neutral abundance with atomic O in the collisionless heterogenous atmosphere with varying local solar conditions. Initial measurements from Neutral Gas and Ion Mass Spectrometer (NGIMS) instrument on Mars Atmosphere and Volatile Evolution (MAVEN) estimated these crossover/transition altitude wavering between \(\approx 225\) km to \(240\) km during solar maximum conditions with peak solar illuminations. MENCA sampled the neutral atmospheric species, below the exobase upto periareion of \(\approx 160\) km, under low solar active conditions during June 2018. Observations of partial pressures of CO\textsubscript{2} and O in subsequent orbits reveals that solar inputs are crucial in quantifying these crossing points, where \([O]/[CO_2]\) remain unity, alongside the influences from temperature. The multi-spacecraft measurements of the direct influences of solar wind charged particle fluxes and velocity on the daily variation of neutral thermospheric/exospheric compositions were observed on the local evening hours of Mars and presented. It marks the first-ever direct \textit{in-situ} observation of interaction between the energetic solar particle radiations on Martian exospheric compositions, potentially contributing for the steady escape and differing population of atomic O in the exosphere.

Keywords: Mars, MOM, MAVEN, Solar Activity

1 Introduction

The seasonal cycles of summer, autumn, winter and spring on Mars are similar to that of Earth due to their near similar axial tilts (25° for Mars and 23.5° for Earth), but each season lasts for almost double the time on Mars as compared to Earth because of the difference in their periods of revolution around the Sun. Along with seasons, parameters such as solar extreme ultraviolet fluxes, radiative and collisional cooling, gravity waves, heliocentric distance, latitude, etc., would have influenced the upper atmospheric processes on Mars \cite{Bougher2015a}. For several decades, the results on upper atmospheric composition and density of Mars were limited to the entry, descent and landing (EDL) observations carried out by the Viking Lander 1/2 that reached Martian surface.
on 20 July 1976 at 22.5°N, 48°W and 03 September 1976 at 48°N, 22°W respectively. These in-situ measurement of atmospheric profile below 200 km confirmed the presence of abundant CO$_2$ supporting earlier Ultra-Violet Spectroscopic (UVS) observation using Mariner 6, 7 and 9 missions (Barth et al., 1971, 1972; Stewart et al., 1972). Alongside CO$_2$, the presence of N$_2$, Ar, and trace measurements of atomic and molecular oxygen (O and O$_2$), CO, NO, Kr, Ne and Xe were reported (Nier and McElroy, 1976; Owen and Biemann, 1976; Owen et al., 1977). The complete set of near surface meteorological data obtained from Viking Landers (1976) to the Curiosity Rover (2012) has been analysed and results have been consolidated in terms of diurnal, seasonal and inter-annual variations of meteorological parameters including dust storms over a span of more than 20 Martian years (Martínez et al., 2017). Though, the Viking missions successfully identified the major and minor species of Martian atmosphere to surface, it is to be noted that this observational data provides paucity on the study pertaining to seasonal and solar activity related variations of the Martian thermosphere and exosphere. A similar analysis to characterise the thermosphere/exosphere system has not been possible due to the lack of observational data on the atmospheric neutral/ionised gas constituents covering the exospheric region (Bougher et al., 2015a).

Indian Space Research Organisation (ISRO) has launched its first interplanetary mission to Mars viz. Mars Orbiter Mission (MOM) on 05 November 2013, reached Mars on 24 September 2014 during Martian nighttime. MOM arrived at Mars with its initial primary objective concerning studies on planet’s morphological features, detection of Methane (CH$_4$), estimating the ratio between Deuterium and atomic Hydrogen (D/H), coverage of spatio-temporal profiles of various neutral atmospheric constituents and cartographic events including dust storms, atmospheric clouds and so-on (Kumar and Chauhan, 2014). As of August 2020, the MOM spacecraft remains healthy in performing the extended mission objectives.

Utilizing the opportunity that Mars approaches Earth closely, for every ≈2 Gregorian years, in collateral to the Mars Orbiter Mission, National Aeronautics and Space Administration (NASA) launched the Mars Atmosphere and Volatile Evolution (MAVEN) mission on 18 November 2013 reaching Mars on 22 September 2014. MAVEN mission dedicated to study the structure, composition and dynamics of the upper atmosphere of Mars (above ≈150 km), also investigated the role of solar wind plasma and habitability aspects of Mars (Jakosky et al., 2015). The ExoMars Trace Gas Orbiter (ExoMars TGO) mission launched on 14 March 2016, as an joint venture between the European Space Agency (ESA) and Roscosmos (Russian Space Agency), inserted intially into a periareion of ≈400 km exospheric orbit at an inclination of 74°, much similar to MAVEN’s orbit inclination, for observing biologically relevant trace constituents such as Methane (CH$_4$) and potential organic gases (Olsen et al., 2017).

Based on the observations using MENCA payload between December 2014 and May 2015, analysis to extract spatial and temporal distribution of the atmospheric composition of the thermosphere-exosphere region of Mars have been carried out by Nagaraja et al. (2020). The results obtained from NGIMS-MAVEN data have provided valuable information about the spatial variation of the thermospheric neutral/ion constituents delineating their vertical and latitudinal distribution, and the effect of solar zenith angle (Maahaffy et al., 2015a). MAVEN Deep Dip campaign to sample the sub-solar collisional homosphere and magnetic field structure in April 2015 demonstrated the orbit-to-orbit variation of thermosphere and ionosphere of Mars (Bougher et al., 2015b). Direct measurements of atmospheric neutrals from MENCA-MOM and NGIMS-MAVEN has been used in our study to examine the influence of solar activity driven changes on Martian upper atmosphere. The results from both the spacecrafts agrees that the energetic particle fluxes deposited over the exosphere plays a major role in steering the daily variations on the exospheric compositions of Mars.
2 Data Analysis and Methodology

2.1 Mars Orbiter Mission

Mars Orbiter Mission spacecraft inserted into Martian orbit on 24 September 2014, initially with a periareion of \( \approx 400 \text{ km} \). MOM had a orbital period of \( \approx 72 \text{ hours} \) due to its highly eccentric orbit inclined at 150° focusing observations over the Martian equator. Comet Siding Spring (C/2013 A1) had a closest approach by Mars on 19 October 2014, within a month of arrival of MOM and MAVEN spacecrafts at Mars. Operations of all spacecrafts were ceased to protective mode to prevent from the meteor shower caused during the passage of the comet \cite{Schneider2015}. MOM occulted behind Mars through orbital manoeuvres, later brought down its periareion altitudes to around 262 km during December 2014, more feasible region to study the Martian exosphere.

![MOM Orbital Maneuvers](image)

Figure 1: Mars Orbiter Mission’s periareion altitudes between October 2014 and October 2020, as projected by the MOM team at Jet Propulsion Laboratory. The figure forecasts the periareion altitudes reached by MOM immediate after orbital maneuvers due to the closest encounter of Comet Siding Spring (C/2013 A1) by Mars on 19 October 2014 \cite{Helfrich2015}.

Mars Exospheric Neutral Composition Analyser (MENCA), a dedicated atmospheric suite of MOM, sampled exospheric neutrals near the exobase from December 2014 through May 2015 comprising of 88 orbits. MENCA measures the total atmospheric pressure and partial pressures of various atmospheric constituents covering the mass range from 1-300 \textit{amu}, which is further programmable to limit its operation under mass-sweep and trend modes. MENCA consists of a built-in electron impact ionizer operated at \( \approx 70 \text{ eV} \) to ionize the atmospheric neutrals, a set of four quadrupole rods and a detector assembly. The detector comprises of Faraday Cup and Channel Electron Multiplier measures the partial pressures of gas constituents with a mass resolution of 1 \textit{amu}. Part of positively ionized atmospheric neutrals inside the ionization chamber known as the source grid region drags the ions inside the quadrupole mass filter system. Another part of neutrals ionized outside the source grid were collected by the Bayard-Alpert gauge, which is calibrated to measure the total pressure. The detailed description of the instrumentation, calibration factors, complete working mechanism, sensitivity and measurement limitations were given by \cite{Bhardwaj2016}.
Indian Space Science Data Centre (ISSDC) at Bengaluru, India archives the MOM observational data and disseminate to scientific users. This archived data consists of total pressure and partial pressure values in the units of Torr with variable time resolution of ≈12 to 30 s. The data is used for scientific studies after incorporating calibration, correction and normalization factors, and time tagging the processed data with ancillary information such as latitude, longitude, altitude and solar zenith angle (SZA) corresponding to the orbital phase of MENCA-MOM using relevant SPICE/Ephemeris kernels [Nagaraja et al. 2020]. The data sets are identified and arranged with respect to different orbit numbers of MOM. However due to the oscillatory nature of periareion height of MOM, good coverage of lower and crucial exospheric altitudes has been obtained only for a small number of orbits (in spite of some orbit lowering exercises) during 5-13, June 2018.

Figure 1 shows the periareion altitude forecast of MOM spacecraft from October 2014 through October 2020. It is clear that after 2014-2015 there has been only a very short period during 2018-2019 when useful data could be collected closer to the exobase and above. The predicted minimum periareion altitude reached by MOM will be 112.9 km on 08 July 2029 and can traverse above 100 km [Helfrich et al., 2015]. The analysis was carried out for the additional MENCA data available during June 2018 and results obtained are discussed in detail.

2.2 Mars Atmosphere and Volatile Evolution

The Mars Atmosphere and Volatile EvolutioN (MAVEN) mission inserted into a highly elliptical orbit, focuses on the search for past history of Martian atmosphere and to understand its present climate. The Neutral Gas and Ion Mass Spectrometer (NGIMS) instrument of the MAVEN spacecraft studies the structure and composition of the upper neutral atmosphere of planet Mars, measures isotope ratios, and measures thermal and supra-thermal ions [Mahaffy et al., 2015b]. NGIMS measures in a mass range of 2-150 amu. NGIMS science operation starts below 500 km to periapsis (inbound) and periapsis to 500 km (outbound) during each orbit lasting for ≈600 s for each leg, with spatial resolution of 1 km. These observation covers both exosphere as well as thermosphere of Martian atmosphere that peers through the exobase at ≈200 km, falls within NGIMS limits. The level-2 (version 08 and revision 01) data-sets of NGIMS-MAVEN has been retrieved from MAVEN Science Data Center at Laboratory for Atmosphere and Space Physics (LASP), during the period June 2018 were used for this study. NGIMS-MAVEN observation has been chosen from 03 June 2018 through 15 June 2018 in parallel to MENCA-MOM observations.

3 Results and Discussion

Figure shows the analysis of atomic $H$ ion current data on 5 June 2018 covering the time period 10 to 13 h UTC having both temporal and spatial variations. The time period of closest approach i.e. near periareion, of MOM towards Mars has been shown along with altitude coverage. The top panel shows altitude profile derived from SPICE kernels provided along with the observational data and ion current of raw data. The middle panel shows the ion current of atomic $H$ with background corrected at ≈500 km. The bottom panel shows the calibrated partial pressure of atomic $H$ for the actual time sampled values with background correction. The pressure values have been converted to Torr units by using the calibration procedure prescribed in [Bhardwaj et al., 2016]. The terminal panel plot clearly shows that the maximum pressure values occur much near to the periareion altitudes though it can vary from orbit-to-orbit. The figure also shows a small height interval near periareion with increasing pressure much above the noise levels of the instrument. This is the region of useful data to be used for further analysis.

From the ion currents differentiated with amu values, the partial pressures of atmospheric constituents can be estimated for obtaining the time/altitude profiles. Since the traverse of spacecraft through the periareion is relatively of shorter time to collect useful data within same orbit, the effect
Figure 2: Spatio-temporal variation of raw ion current and calibrated partial pressure of atomic Hydrogen (H) observed from MENCA-MOM on 05 June 2018.

of change in solar zenith angle may be insignificant. However, for long-term variability, the seasonal changes in solar zenith angles need to be corrected for studying any effect of solar activity related variations in exospheric partial pressures.

Figure 3: Variation of atmospheric CO₂ and O abundances observed on 05, 08 and 13 June 2018 by MENCA-MOM. Corresponding variation in local solar time (LST) in hours and solar zenith angle (SZA) in degrees has been shown.
Figure 3 shows details of the variation of atmospheric CO$_2$ and O partial pressures near the periareion region between $\approx$160 km to 500 km, subtracting the background noise at 500 km. This covers the Martian upper thermosphere, its exobase and lower exosphere regions for ascertaining relative effects of gaseous transition and escape. While the pattern of variation of partial pressure is similar on 05 June 2018 and 08 June 2018, there is a shift of about few minutes in the peak density observed on 13 June 2018, where maximum of pressure has not occurred at the lowest height of observation in both CO$_2$ and atomic O. This anomaly needs to be examined by studying the condition of atmospheric dynamics. It is also observed that the rate of change of pressure values for inbound and outbound trajectories are generally symmetric. It can be seen that the SZA variation is from the nighttime and moving towards the evening hours of Mars. This transition does not affect the density profiles appreciably for short duration of observations.

Figure 4: Relative abundance of major atmospheric species measured from MENCA-MOM on 05 June 2018. Increased N$_2$ + CO/amu28 has contributions from CO$_2$/amu44. Variation of water vapour ($H_2O$) is mainly due to the outgassing of MOM spacecraft and eliminated during background correction.

Figure 4 shows the relative partial pressure of major atmospheric constituents. It is noted that the CO$_2$ shows the maximum density values. According to the known pattern of variations, the other constituents have relatively lower pressures compared to CO$_2$. In addition, the water vapor density, product of outgassing, in MOM has reduced considerably compared to the values observed during December 2014. However, the temporal profile of $H_2O$ follows similar pattern of other species due to reduction in further degassing. The escaping remanent water vapour may be maintained through the hydrostatic equilibrium.

To understand the day-to-day variations of the partial pressures of the exospheric constituents, the profiles of CO$_2$, Ar, O and N$_2$ + CO are plotted for the three orbits of observations in Figure 5. It is seen that during a short period of nine days, there is considerable reduction in pressure on 13 June 2018 compared to 05 June 2018 and 08 June 2018. Such short period changes of gas concentrations in the thermosphere/exosphere need to be first confirmed before extending any possible explanation. To strengthen MENCA observations and analysis, the simultaneous observations from MAVEN on Martian thermosphere/exosphere were used. NGIMS-MAVEN atmospheric payload measures the neutral/ions of upper atmosphere has been utilised to validate the observed variations. A detailed analysis was carried out using NGIMS-MAVEN data during 03-14, June 2018 to match period of MENCA-MOM. There are about five orbits of MAVEN per Earth day with NGIMS data covering the Martian atmospheric altitude between $\approx$150 km and 500 km taking about 11-min for
Figure 5: Inbound (top) and Outbound (bottom) altitude profiles of CO$_2$, O, CO + N$_2$ and Ar on 05, 08 and 13 June 2018 from MENCA of Mars Orbiter Mission.

Figure 6: Vertical profiles of upper atmospheric neutral gas constituents for four days viz., 03, 04, 08 and 13 June 2018. The corresponding variations of SZA during the period of each profiles are also shown.

On 13 June 2018, differences in the density profiles can be seen compared to the profiles on 03, 04 and 08 June 2018 that are similar. Particularly, the [CO$_2$] and [O] crossover point has shifted to a higher altitude of $\approx$240 km on 13 June 2018 compared to $\approx$190 km on other days. This indicates a reduction in photodissociation driven concentration of atomic oxygen (O) on 13 June 2018. Such
Figure 7: Vertical profiles of daily mean concentrations of $CO_2$ and $O$ densities on 03, 04, 08 and 13 June 2018. $[CO_2]$ steadily increase with decline in $[O]$ during this period as observed from NGIMS-MAVEN.

Figure 8: Ion and electron fluxes signifying the solar-wind variations as measured from the SEP instrument (forward and rear-view) of MAVEN during 03-13, June 2018. Steady reduction in the incoming solar flux, immediate after 05 June 2018, shows significant contribution to the decrease of the photodissociative product, atomic oxygen ($O$).

The reduction of atomic oxygen concentrations has been observed by MENCA also (see Figure 5). The independent results from two separate spacecrafts confirms the anomalies which could have resulted...
from the solar wind particle velocity and flux variations. Figure 7 shows the mean daily profiles of CO$_2$ and O. There exists a striking relationship between the decrease in O and increase in CO$_2$ densities during the period from 03 June 2018 to 13 June 2018.

The Solar Energetic Particle (SEP) instrument onboard MAVEN measured the solar-wind electron and ion fluxes over various energy levels during the same period. The SEP sensors are positioned on two corners to ensure that the field of view (FOV) adequately cover the canonical Parker spiral direction around which solar energetic particle distributions are normally centered. SEP provides measurements with $\approx$1 h time resolution. The data of the electron and ion fluxes have been analysed from 03-13, June 2018 and are shown in Figure 8. The energy fluxes of both ion and electron were reduced from 09 June 2018. This reduction in solar heating of the upper atmosphere resulted in the fall of photoionization of CO$_2$. Further, the dissociation of CO$_2$ under this condition has limited the production of O, and the same is reflected.

4 Summary

The upper atmosphere of Mars has been observed from MENCA-MOM and NGIMS-MAVEN instruments during June 2018. Interesting, the solar wind particle fluxes show a steady decrease between 09 June 2018 and 13 June 2018, providing the possible clues of charged particle interactions with Martian atmospheric constituents playing a major role in the day-to-day variation of O and CO$_2$ concentrations. This study shows the increase in concentration of O and decrease in CO$_2$ during 03-08, June 2018 indicates an enhanced production of O from the dissociation of CO$_2$ corresponding to higher energy and fluxes of solar wind particles. Hence, it marks the first-ever observation that in absence of a global magnetic field of Mars, the direct interaction of solar wind charged particles affect the daily variation of thermosphere/exosphere gaseous concentrations, contributing to the steady escape of O with enhanced solar activity.

Acknowledgement

This work was funded by the Indian Space Research Organisation (ISRO) under Mars Orbiter Mission’s Announcement of Opportunity Program through the research project, Observation and Modeling Studies of the Atmospheric Composition of Mars (OMAC), vide reference number ISRO:SPL:01.01.33/16. We greatly acknowledge the use of MENCA data from MOM, archived at Payload Operation Center, Space Physics Laboratory, Vikram Sarabhai Space Centre, Thiruvananthapuram, India. The NGIMS and SEP datasets of MAVEN used for this study were publicly available on MAVEN Science Data Center at LASP (https://lasp.colorado.edu/maven/sdc/public/) as well as the Planetary Data System (http://pds.nasa.gov). The MAVEN mission is supported by NASA through the Mars Exploration Program. We thank AMDA Science Analysis System (http://amda.irap.omp.eu/) provided by the Centre de Données de la Physique des Plasmas (CDPP) supported by CNRS, CNES, Observatoire de Paris and Université Paul Sabatier, Toulouse for performing initial MAVEN data analysis on NGIMS and SEP instruments. This research work was carried at Atmospheric and Space Science Research Lab, Department of Physics, Bangalore University, Bengaluru, India.

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