The variations of the Martian exobase altitude

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Abstract: The exobase is defined as the interface between the strongly collisional and the collisionless parts of an atmosphere. Although in reality the exobase is a transition region of finite depth, it is conventionally defined as the boundary above which an upwardly ejected neutral particle makes one collision at higher altitudes. Such an idealized definition is of practical use and serves as a good tracer of the overall size of an atmosphere as it expands and contracts under the influences of both external and internal sources. Knowledge of the atmospheric properties near the exobase is crucial to first-order estimates of atmospheric escape rates on terrestrial planets. Since its arrival at Mars on 21 September 2014, the Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft has provided comprehensive maps of the Martian upper atmosphere under a variety of conditions. This allows, for the first time, a thorough investigation of the variations of the exobase altitude on this red planet. In this study, we use the N2 density measurements accumulated by MAVEN’s Neutral Gas and Ion Mass Spectrometer from October 2014 to November 2018 to determine the exobase altitudes for a large number of MAVEN orbits. Our analysis reveals clearly the variations of exobase altitude with local time and solar extreme ultraviolet (EUV) flux, as well as tentative evidence for the impact of global dust storms. These observations are indicative of thermal expansion of the Martian upper atmosphere, driven either externally by solar EUV energy deposition or internally by global dust storms.

Keywords: Mars; Exobase; MAVEN

1. Introduction
Mars is a terrestrial planet with a thin atmosphere consisting primarily of CO2, with much smaller amounts of O, O2, N2, CO, and Ar, among others (Nier and McElroy, 1976, 1977; Bougher et al., 2015; Mahaffy et al., 2015a). The structure and dynamics of the Martian upper atmosphere has been widely explored during several missions over the past four decades. The first density profiles of various neutral species in the Martian atmosphere at 120–200 km were measured by the Upper Atmospheric Mass Spectrometers onboard the Viking 1 and Viking 2 spacecrafts (Nier and McElroy, 1976, 1977). Subsequent information was acquired by the Mars Global Surveyor and Mars Odyssey accelerometer experiments (Withers, 2006). More recent measurements were made by the Spectroscopy for Investigation of Characteristics of the Atmosphere, driven either externally by solar EUV energy deposition or internally by global dust storms. These observations are indicative of thermal expansion of the Martian upper atmosphere, driven either externally by solar EUV energy deposition or internally by global dust storms.

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1. Introduction
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background species under the assumption of thin atmosphere (Johnson et al., 2008). Information on the exobase altitude is of great importance not only for studying the response of the Martian upper atmosphere to both internal and external conditions but also for understanding the atmospheric escape processes. Here with the aid of NGIMS level 2 data, we determine the exobase altitudes for four relatively abundant neutral species, CO₂, CO, N₂, and O, from which we are able to investigate systematically the variations of the Martian exobase altitude with local time and solar extreme ultraviolet (EUV) flux, as well as its response to global dust storms.

2. Determination of the Exobase Altitude

The analysis presented in this study relies primarily on neutral density data accumulated by the MAVEN NGIMS instrument. The NGIMS is a quadrupole mass analyzer with a dual ion source, including an open source to measure reactive neutral species and a closed source to measure non-reactive neutral species (Mahaffy et al., 2015b). It is capable of measuring the densities of various species in the ambient atmosphere over the mass range from 2 to 150 atomic mass units (amu) at unit mass resolution (Mahaffy et al., 2015b). In the present work, we use the NGIMS data collected in the closed source mode only, which involves a gas inlet system made up by a spherical antechamber and a transfer tube. In this mode, the ambient gas at the spacecraft velocity flows into the closed source through a small aperture and thermally accommodates to the antechamber wall. Then a portion of the captured gas flows through the transfer tube to the ionization zone where it is ionized by the electron beam generated by a hot filament. Compared with the open source mode, the density enhancement in the closed source mode allows the abundance of the ambient species to be measured with a higher precision. The electron impact ionization efficiencies are obtained from laboratory measurements. The raw count rates need to be corrected for several instrumental effects, such as subtraction of residual gas, correction for ram enhancement, and correction for saturation, before the count rates can be converted robustly to number densities. The procedures of NGIMS data reduction have been described in detail in previous studies (e.g., Mahaffy et al., 2015a; Stone et al., 2018) and are not repeated here.

All MAVEN orbits from October 2014 up to November 2018 are included in our analysis. The sample included here covers a large solar zenith angle (SZA) range, from near subsolar to deep nightside, as well as a large range of 10.7 cm solar radio index at Earth from 70 to 200 in solar flux unit (10⁻²⁸W⁻¹m⁻²), allowing both the variations of the exobase altitude with local time and with solar EUV flux to be explored.

It has been proposed that NGIMS density data are likely subject to strong contamination by physical adsorption or heterogeneous chemistry on the antechamber walls, a feature that is also known to occur on the Cassini Ion Neutral Mass Spectrometer with a similar design (Cui J et al., 2009). Therefore as the first step, it is necessary to evaluate the reliability of NGIMS density data for various species before their respective exobase altitudes could be determined. For such a purpose, we approximate the measured number density profile by the traditional barometric relation characterized by a constant density scale height; we have implicitly assumed the atmosphere to be isothermal at 150–200 km.

Several examples of isothermal fitting to the NGIMS densities are displayed in Figure 1 for all four species considered here during the dayside MAVEN orbit #1050 with the inbound and outbound profiles indicated separately. The figure reveals clear asymmetry between inbound and outbound densities of CO₂ and O, in that the latter tend to be systematically higher than the former at any given altitude except near the periapsis; the same asymmetry is observed, but is substantially less prominent, for N₂ and CO. This is indicative of strong NGIMS wall contamination of CO₂ and O. The wall contamination appears to be especially strong for O as a fairly reactive species, and Stone et al. (2018) proposed the possibility of O interacting with the NGIMS walls to form O₂. For a further demonstration of the wall effect, we compare in Figure 2 the density scale heights from the inbound and outbound NGIMS measurements for all available MAVEN orbits. The figure reveals that the median outbound scale heights for CO₂ and O are 10% and 40% larger than their respective inbound median values, whereas for N₂ and CO, the difference between the inbound and outbound median density scale heights is less than 2%.

For the reason addressed above, we use in the present investigation the NGIMS density measurements of N₂ and CO over both the inbound and outbound portions of each MAVEN orbit, but the measurements of CO₂ and O over the inbound portion only. To determine the exobase altitude, z_exo, we require that the total number of collisions of an upwardly ejected particle of species i is exactly one, expressed as

\[ 1 = \int_{z_{\text{exo}}}^{z_{\text{max}}} \sum_{j=1}^{4} n_i \sigma_{ij} \, \text{d}z, \]

where \( z \) is the altitude, \( n_i \) is the number density of species \( j \), \( \sigma_{ij} \) is the cross section for binary collisions between species \( i \) and \( j \) obtained from their rigid body radii (adapted from Table 2 of Lillis et al., 2017), and the summation is over CO₂, CO, N₂, and O. In using Equation (1), the directly measured NGIMS densities are numerically fed into the integration. For the portion of the integration above the highest altitude, \( z_{\text{max}} \), where the NGIMS data are available, an isothermal and thin atmosphere is assumed with a constant density scale height obtained from a barometric fitting to the data gathered at \( z_{\text{max}} \approx 50 \) km to \( z_{\text{max}} \). The detailed treatment near \( z_{\text{max}} \) should have little impact on the derived exobase altitudes since the atmosphere above \( z_{\text{max}} \) typically makes a negligible contribution to the vertical column density.

The mean exobase altitudes for the four species derived from Equation (1) are shown schematically in Figure 3, along with their standard deviations. These exobase altitudes are 221±25 km for CO₂, 217±24 km for CO, 202±21 km for O, and 217±24 km for N₂. The slight difference in the mean exobase altitude is linked to the difference in rigid body radius, in the sense that the exobase for large neutral particles such as CO₂ tends to lie above the exobase for small particles such as O, as predicted by Equation (1). We also caution that the strong wall contamination for O revealed in Figures 1 and 2 likely indicates that even the inbound NGIMS densities for this species, and thus the O exobase height based upon these data, should be taken with caution. Without showing...
the details, we mention that Ar is another species in the Martian upper atmosphere likely free from NGIMS wall contamination, as implied by its equality in scale height between inbound and outbound, but this species is not considered here because the relatively low abundance of this species does not allow its scale height to be determined rigorously in many cases.

3. Variations of the Exobase Altitude

This section is devoted to an analysis of the possible variations of the exobase altitude in the Martian upper atmosphere, taking $N_2$ as an example. The exobase altitudes for the other species present similar variations.

We start with an examination of the diurnal variation of the exobase altitude, as motivated by the SZA variation of atmospheric density scale height revealed by MAVEN Accelerometer measurements (Zurek et al., 2015). To distinguish between the dawn and dusk sides and also to account for the retarded thermospheric response to solar inputs (Bougher et al., 1999), we show in Figure 4 the variation of the exobase altitude as a function of local time on Mars, with each solid circle reflecting measurements from an individual MAVEN orbit. Despite the large scattering among different orbits, the median trend, given by the dashed red line, demonstrates clearly the response of the exobase altitude with the varying condition of solar illumination; a maximum altitude of 230 km is observed near the local time of 14 hour. Such a trend is analogous to the local time variation of neutral temperature in the Martian upper atmosphere, as predicted by three-dimensional thermospheric global circulation models (e.g., Bougher et al., 1999). Our analysis indicates that the local time variation of the exobase altitude could be reasonably described by a sinusoidal function, given by the solid blue line in Figure 4, with an amplitude of around 20 km reflecting half of the maximum difference in exobase altitude along a full diurnal cycle. Such an empirical function predicts a dawn-dusk asymmetry of about 5 km in exobase altitude.

We further present our analysis of the variation of the exobase altitude with solar EUV flux, as shown in Figure 5. The solar EUV irradiance is obtained by integrating the level 3 solar spectral model at Mars from 0.5 nm to 190 nm, constructed from the Flare Irradiance Spectral Model–Mars and calibrated with MAVEN Extreme...
Ultraviolet Monitor band irradiance data (Eparvier et al., 2015; Thiemann et al., 2017). To decouple the variations with local time and with solar EUV flux, we normalize the NGIMS-derived exobase altitude to a common local time of 14 h on Mars with the aid of the best-fit sinusoidal relation shown in Figure 4. More specifically, we assume that the difference in exobase altitude between two different local times is independent of the solar EUV flux. Therefore any derived exobase altitude is divided by the ratio in exobase altitude between the time of measurement and a constant local time of 14 h according to the sinusoidal relation in Figure 4. The variation of the exobase altitude derived following the above procedure is displayed in Figure 5 as a function of the solar EUV flux. According to Figure 5, the Martian exobase shows a systematic elevation with increasing solar EUV flux. For an increase in solar EUV flux from 0.02 W·m\(^{-2}\) to 0.03 W·m\(^{-2}\), the median exobase altitude at 14 h is observed to rise by more than 25 km in an approximate linear manner as represented by the solid blue line in Figure 5.

Another important mechanism controlling the exobase altitude on Mars is global dust storms, which occur every few Mars years and persist for weeks to months (e.g., Pollack et al., 1979; Straussberg et al., 2005). Global dust storms are able to strongly modify the global circulation and radiative energy transport in the Martian atmosphere, causing thermal expansion and lifting the exobase altitude (e.g., Haberle et al., 1982; Bouger et al., 1997; Gurnell et al., 2005; Kass et al., 2016). The impact of global dust storms could extend even to the Martian ionosphere and thus enhance ion escape (e.g. Hantsch and Bauer, 1990; Wang JS and Nielsen, 2003; Liemohn et al., 2012; Xu SS et al., 2014; Fang XH et al., 2013). The impact of global dust storms is investigated here.
based on the variation of the exobase altitude observed in 2018, during which the onset and growth of a global dust storm have been well documented (e.g., Guzewich et al., 2019; Sánchez-Lavega et al., 2019). Such a variation is depicted in Figure 7; the dust storm season is shadowed by yellow. The figure reveals tentatively the expected trend that global dust storms will elevate the exobase on Mars, here by nearly 10 km, during global dust storms.

The exobase altitudes shown in the figure are normalized, as previously described, to a common local time of 14 h and a common solar EUV flux of 0.025 W·m\(^{-2}\) with the aid of the solid blue lines in Figures 4 and 5.

4. Discussions and Concluding Remarks
The exobase is the idealized interface between the strongly collisional and collisionless parts of an atmosphere; it is of great interest to the aeronomical community because it is a diagnostic of the expansion or contraction of the entire atmosphere under the influences both of internal and of external driving forces (e.g., Johnson et al., 2008). In this study, we determine the exobase altitude of Mars with the aid of NGIMS neutral density measurements accumulated over a large number of MAVEN orbits (Jakosky et al., 2015). Based on a comparison of wall contamination between several important neutral species in the Martian up-
per atmosphere, we suggest $N_2$ to be an ideal species for the purpose of the present study, with both inbound and outbound measurements suitable for locating the exobase.

Our analysis indicates a median $N_2$ exobase altitude of 215 km with a scattering of about 10 km from orbit to orbit; we arrive at this value by considering variations of the exobase altitude both with local time and with solar EUV flux, as well as variation attributable to global dust storms on Mars. The diurnal variation of the exobase altitude is clearly revealed by the data, with the maximum altitude observed at 14 h, higher than the nightside minimum altitude by about 20 km. The NGIMS data also suggest the presence of clear variation with solar EUV flux, for which the exobase altitude rises by more than 25 km over the range of solar EUV flux encountered here. Combining the variations with local time and with solar EUV flux, the $N_2$ exobase altitude, $z_{exo}$, in the Martian upper atmosphere could reasonably be described by

$$z_{exo} = \left[215.7 + 20.5 \cos\left(\frac{2\pi}{24}(t-14)\right)\right] \left[0.29 \times \frac{F}{0.025} + 0.73\right] \text{km},$$

where $t$ is the local time on Mars, $F$ is the integrated solar EUV flux at 0.5–190 nm, and the numerical values in the equation are constrained by data-model comparison. Our analysis also suggests tentative evidence for the expected elevation of the exobase by nearly 10 km during the global dust storm season in 2018 (e.g., Guzewich et al., 2019; Sánchez-Lavega et al., 2019). The NGIMS observations presented here are indicative of thermal expansion of the Martian atmosphere driven either externally by solar EUV energy deposition (e.g., Fox et al., 2008) or internally by global dust storms (e.g., Kass et al., 2016). Possible influences of other driving forces such as energetic electron precipitation, known to have an influence on Titan’s exobase altitude (Cui J et al., 2011), are not examined here but will be scrutinized in follow-up studies combining the suprathermal plasma data accumulated by the MAVEN Solar Wind Electron Analyzer (Mitchell et al., 2016).

**Figure 7.** Variation of the exobase altitude on Mars in 2018 from January to November, where the global dust storm season is shadowed by yellow. A vertical bar gives the standard deviation within each month.

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