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Ionization Efficiency in the Dayside Martian Upper Atmosphere

Xiaoshu Wu (1), Jun Cui (1,2,3) and Shaosui Xu (4)

(1) National Astronomical Observatories, Chinese Academy of Sciences, Beijing, China

(2) School of Atmospheric Sciences, Sun Yat-sen University, Zhuhai, Guangdong, China

(3) Lunar and Planetary Science Laboratory, Macau University of Science and Technology, Macau, China

(4) Space Science Laboratory, University of California at Berkeley, Berkeley, CA, USA

Abstract

Combining the Mars Atmosphere and Volatile Evolution (MAVEN) measurements of neutral atmospheric density, solar EUV/X-ray flux, and differential photoelectron intensity made during 240 nominal orbits, we calculate the ionization efficiency, defined as the ratio of the secondary (photoelectron impact) ionization rate to the primary (photon impact) ionization rate, in the dayside Martian upper atmosphere under a range of solar illumination conditions. Both the CO_2 and O ionization efficiencies tend to be constant from 160 km up to 250 km, with respective median values of 0.19±0.03 and 0.27±0.04. These values are useful for fast calculation of the ionization rate in the dayside Martian upper atmosphere, without the need to construct photoelectron transport models. No substantial diurnal and solar cycle variations can be identified, except for a marginal trend of reduced ionization efficiency as approaching the terminator. Our analysis further reveals a connection between regions with strong crustal magnetic fields and regions with high ionization efficiencies, likely indicative of more efficient vertical transport of photoelectrons near magnetic anomalies.

1. Introduction

The Martian ionosphere contains at the dayside a well-defined primary layer and a low altitude secondary layer which are produced by solar EUV/X-ray ionization along with impact ionization by photoelectrons (Withers 2009 and references therein). These processes are parameterized by the primary and secondary ionization rates, respectively, with the ratio of the latter to the former being frequently termed as ionization efficiency (Richards & Torr 1988). The calculation of the primary ionization rate is straightforward with the aid of the classical Beer-Lambert law, whereas the calculation of the secondary ionization rate, which requires either the implementation of the Monte Carlo algorithm (Bhardwaj & Jain 2009) or the multi-stream solution to the Boltzmann equation (Wedlund et al. 2011), is far more involved.

The ionization efficiency in the dayside upper atmosphere was calculated for the Earth (Lilensten et al. 1989), Titan (Lilensten et al. 2005), Mars (Nicholson et al. 2009), Saturn (Galand et al. 2009), as well as giant exoplanets such as HD 209458b (Ionov et al. 2014). In each of the aforementioned works, a photoelectron transport model was coupled with a neutral background atmosphere model to compare the primary and secondary ionization rates under a range of solar illumination conditions. Empirical formulae for these model-based ionization efficiencies were provided in some of the existing works, allowing fast calculation of the total ionization rates in the dayside ionospheres of selected planetary bodies.

Since information on ionization efficiency is crucial for aeronomical studies, it is instructive to validate the model results of this key parameter with real data. This was not feasible for Mars until the arrival of the Mars Atmosphere and Volatile Evolution (MAVEN) mission (Jakosky et al. 2015), which provides a unique opportunity to explore a wide parameter space of controlling factors required for calculating both primary and secondary ionization rates in the dayside Martian upper atmosphere. These controlling factors include solar EUV/X-ray flux, measured by the Extreme Ultraviolet Monitor (EUVM) (Eparvier et al. 2015), the neutral atmospheric density, measured by the Neutral Gas and Ion Mass Spectrometer (NGIMS) (Mahaffy et al. 2015), as well as the differential electron intensity, measured by the Solar Wind Electron Analyzer (SWEA) (Mitchell et al. 2016). The above sources of data are utilized in this study to determine the ionization efficiency, which is then compared with existing model results (Fox & Yeager 2006, Haider et al. 2006, Nicholson et al. 2009).

2. Summary and Conclusions

Combining the NGIMS, EUVM, and SWEA measurements of neutral atmospheric density, solar EUV/X-ray flux, and differential photoelectron intensity made during 240 nominal MAVEN orbits, we calculate the ionization efficiency, defined as the ratio of the secondary ionization rate to the primary ionization rate, in the dayside Martian upper atmosphere under a range of solar illumination conditions. The photoelectron energy spectra are corrected for spacecraft charging using the MAVEN Langmuir Probe and Waves (LPW) potentials (Andersson et al. 2015), and a portion of the spectra showing strong fluctuations at the top of the atmosphere, likely indicative of significant energy input via Solar Wind (SW) electron precipitation, are excluded. This ensures a clean selection of orbits where secondary ionization is predominantly caused by photoelectrons. The data from the dayside DD campaign on 17-22 Apr 2015, as well as the outbound data from all nominal orbits, are excluded to reduce the effect of NGIMS wall chemistry.

Our analysis reveals that both the CO_2 and O ionization efficiencies remain constant over the altitude range of 160 km to 250 km. No substantial diurnal and solar cycle variations are suggested by the data, except for an insignificant trend of reduced ionization efficiency as approaching the terminator. At the top of the atmosphere, the median ionization efficiencies are 0.19 ± 0.03 for CO_2 and 0.27 ± 0.04 for O, respectively, in fair agreement with various model results covering a range of solar irradiance levels from low to high solar activities and a range of solar illumination angles from subsolar to near-terminator (e.g., Fox & Yeager 2006, Haider et al. 2006, Nicholson et al. 2009). These values are useful for fast calculations of the total ionization rate in the dayside Martian upper atmosphere, without the need to construct photoelectron transport models. A tentative trend of enhanced ionization efficiency is observed near the periapsis of nominal MAVEN orbits. The inclusion of extra data gathered during dayside DD campaigns, along with a rigorous treatment of NGIMS wall chemistry, is required to pin down the vertical trend at low altitudes unambiguously.

Our analysis also reveals a connection between regions with strong crustal magnetic fields and regions with relatively high ionization efficiencies. One possible interpretation is the trapping of in-situ produced photoelectrons by closed magnetic field lines typically found over strong crustal magnetic anomalies (Brain et al. 2007). Since photoelectrons also play a crucial role in the local energy balance of both neutrals and thermal electrons, we expect enhanced neutral and electron temperatures encountered near magnetic anomalies as well. The observation of enhanced neutral temperature was reported by Cui et al. (2018) with the aid of the NGIMS data acquired during several DD campaigns, but these authors argued that photoelectron trapping was unlikely to be a viable mechanism since the difference in photoelectron impact heating between regions with and without strong crustal magnetic fields was far insufficient to account for the difference in neutral temperature. Meanwhile, Flynn et al. (2017) showed that regions over magnetic anomalies featured low electron temperatures, in contrast to our ideal expectation. According to Xu et al. (2017), the magnetic field configuration throughout the entire atmospheric regions of interest here is dominated by closed field lines, indicating that photoelectrons are always trapped at these altitudes irrespective of the magnetic field strength. However, the same authors concluded that the field lines in regions with strong magnetic fields were more vertical as compared to regions with weak fields. Therefore, it is more likely a higher tendency for vertical photoelectron transport that is responsible for the observed enhancement in ionization efficiency near strong crustal anomalies. For comparison, a higher tendency for vertical diffusion is thought to contribute to the enhanced thermal electron content in the Martian upper atmosphere also observed near crustal anomalies (Ness et al. 2000, Nielsen et al. 2007, Safaeinili et al. 2007), as supported by the model calculations of Matta et al. (2015). Clearly, the construction of realistic photoelectron transport models with properly imposed ambient magnetic field topology is required to interpret unambiguously the observed impact of crustal fields on ionization efficiency.

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