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Non-thermal escape rates of light species from Mars using MAVEN in-situ measurements

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Abstract

We present a theoretical analysis of non-thermal escape rates of molecular hydrogen and other light species from Mars induced by collisions with superthermal oxygen atoms produced either photochemically or by precipitating energetic neutral particles (ENAs). The hot oxygen production rates were derived from MAVEN density and temperature in-situ measurements taken over last 36 months and used to calculate collisional escape rates of light atmospheric species. The energy transfer in collisions is described using either extensive quantum-mechanical calculations of state-to-state elastic, inelastic, and reactive cross sections[1] or model momentum transport cross sections[2]. We find that D/H escape ratio may be modified by up to 15% by this non-thermal process. The described collisional ejection mechanism is theoretically estimated to be able to eject atmospheric species up to mass 30 *u*, including H_2O and OH[3], possibly affecting primordial water loss from Mars. Based on in-situ data, seasonal variation of non-thermal escape is discussed.

1. Introduction

Dissociative recombination (DR) of photoionized O_2^+ with electrons in the upper atmosphere of Mars produces translationally superthermal O atoms capable of overcoming martian gravitational potential and escaping into space. This process is known as photochemical escape and found to be one of the major escape mechanisms presently active on Mars. In addition to escaping, superthermal O atoms can collide with thermal atmospheric atoms and molecules and transfer sufficient kinetic energy to eject them to space. This non-thermal escape mechanism is significant for the species heavier than atomic hydrogen, and more efficient than Jeans escape for light atmospheric species heavier than deuterium. For example, the non-thermal escape rate of HD molecules from Mars was estimated to be about 25 times greater than their Jeans escape rate[4]. The collisionally ejected molecules will be preferentially excited to higher rotational and/or vibrational states.

The Mars Atmosphere and Volatile EvolutioN Mission (MAVEN), launched in 2014 as a part of NASA's Mars Scout program, is the first mission that can perform in-situ measurements of physical quantities necessary to derive photochemical escape fluxes on orbit-to-orbit basis [5]. Specifically, MAVEN measurements constrain photochemical oxygen escape from Mars in three separate ways: Hot oxygen production rates are calculated from measured electron temperatures and densities (from the Langmuir Probe and Waves (LPW) experiment) and ion temperatures and densities from the SupraThermal And Thermal Ion Composition (STATIC) and Neutral Gas and Ion Mass Spectrometer (NGIMS), while escape probability are calculated with neutral densities measured by NGIMS instrument. We have constructed average and seasonal escape fluxes of hot O from the Martian atmosphere based on more than 36 months of data from the listed instruments. The altitude profiles of hot O escape rates were to determine the altitude profiles of non-thermal escape rates of light neutrals (with focus on H_2, HD, He, OH and H_2O) driven by collisions with superthermal O atoms and their impact on the total escape fluxes. The determined average and seasonal dayside escape fluxes of hot O were found to be broadly consistent with pre-MAVEN predictions. The non-thermal escape rates of H_2 and HD induced by collisions with hot O were found to exceed the pre-MAVEN predictions and to exhibit potentially observable seasonal variations (Fig. 1), while preliminary results for other light species show similar trends.

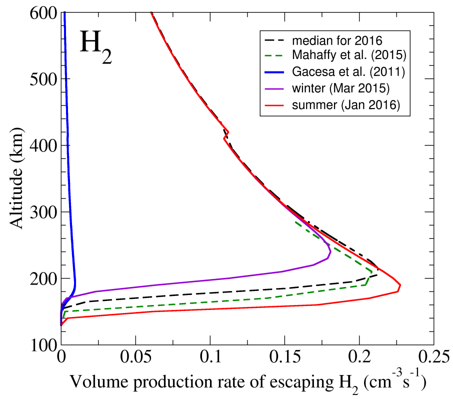

Figure 1: Sample altitude profiles of volume production rate of escaping H_2 molecules ejected by collisions with photochemically produced superthermal O atoms. Our preliminary results, based on MAVEN in-situ seasonal temperature and density measurements, are shown for selected orbits during a martian summer (red curve), martian winter (purple curve), and a single deep-dip (orbit #1064) [6] (dashed green). A pre-MAVEN estimate of non-thermal escape rate of H_2 for assumed low solar activity [4] is also shown (blue). Note the seasonal differences in altitudes for the maximal rates.

2. Results and discussion

Our preliminary estimates of collisionally induced non-thermal escape rates of H_2, HD, He, and OH, based on MAVEN in-situ measurements, are nearly an order of magnitude larger than pre-MAVEN theoretical estimates based on theoretical atmospheric density and temperature profiles [2, 3, 4]. Major factors influencing the results are differences in assumed vs measured atmospheric density and temperature profiles on Mars, as well as improved cross sections used in the study. We found that differences in momentum transfer cross sections (previous works used mass-scaling of O+Ar cross sections to model unknown cross sections) account for 30-50% difference in results, indicating their importance. The results also show significant variations between seasons. The work to fully understand the seasonal and diurnal variations is in progress and likely requires 3D models of escape. Our results indicate that non-thermal escape of D, as HD and possibly OD and HDO, may contribute up to 15% of the total D loss from Mars. Similarly, non-thermal escape likely plays a more significant role in helium isotope (^{3}He vs ^{4}He) fractionation.

The work to compare the measured contributions of ENAs to simulated superthermal oxygen altitude profiles is in progress. Here, as for the photochemically produced superthermal oxygen, we expect the measured atmospheric densities and temperatures to affect the non-thermal escape rates, possibly resulting in similar enhancements in escape rates of ejected light species.

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