SIMULATION OF THE H ESCAPE VARIABILITY WITH A GLOBAL CLIMATE MODEL.

F. González-Galindo, *Instituto de Astrofísica de Andalucía-CSIC, Granada, Spain (ggalindo@iaa.es)*, **J.-Y. Chaufray,** *LATMOS, Paris, France*, **G. Gilli, A. Brines, M.A. López-Valverde,** *Instituto de Astrofísica de Andalucía-CSIC, Granada, Spain*, **F. Lefèvre, M. Vals, F. Montmessin, L. Rossi,** *LATMOS, Paris, France*, **F. Forget, E. Millour,** *LMD, Paris, France*.

Introduction

The geological evidences show that liquid water was present in Mars surface about 4 billions year ago, implying that the Martian atmosphere at that time was denser, wetter, and probably warmer than it is today (Haberle et al., 2017). Atmospheric escape to space is thought to have been the main loss process of the ancient Martian atmosphere and water, driving the atmospheric evolution resulting in the current thin atmosphere with a dry and cold climate (Brain et al., 2017). The large abundance of deuterium (D/H ratio) in Mars when compared to the terrestrial values suggests that the thermal (Jeans) escape of Hydrogen from Mars has been a major loss mechanism of the ancient Martian water. Understanding current escape to space, in particular H thermal escape, and its links with the different processes operating in the Martian atmosphere, is thus mandatory in order to have a better and more precise view of the long-term evolution of the Martian climate.

During the last decade, observations made by different spacecrafts have completely changed our understanding of how Hydrogen escapes from the Martian atmosphere. While the old paradigm established that water vapor remained confined in the lower atmosphere, and the source of H atoms to the upper atmosphere was the slow diffusion of H2 molecules to the upper atmosphere, the recent observations (e.g. Chaffin et al., 2014, Heavens et al., 2017) show strong and fast variations in the rate of H atmospheric escape, incompatible with the old paradigm. These observations suggest that the penetration of water into the upper atmosphere significantly enhances the rate of H escape, indicating a strong link between the water cycle in the lower atmosphere and the H escape to space.

However, many unknowns remain, including the role of the different processes responsible of transporting water from the lower to the upper atmosphere and converting it to Hydrogen atoms, or the effects of global dust storms (GDS hereafter) compared to the regular seasonal variability.

While different 1D models have been used to reproduce and understand some of the observations (e.g. Chaffin et al., 2017), until now global models have failed to reproduce the observed variability of the H escape. In particular, a recent study with the Laboratoire de Météorologie Dynamique Mars Global Climate Model (LMD-MGCM hereafter) evidences that the model significantly underestimates the H escape rate when comparing with Mars Express SPICAM observations, in particular during the perihelion season (Chaufray et al., 2021).

In this work we will summarize the recent improvements that we have included in the LMD-MGCM in order to better reproduce the observed Hydrogen escape rate, and will discuss some of the preliminary results obtained with the improved model.

Model description

We have included three improvements with respect to the version of the LMD-MGCM used in Chaufray et al., 2021.

First, we have incorporated in the simulations a sophisticated model of the microphysics of water ice clouds allowing for the formation of supersaturated layers (Navarro et al., 2014). It has to be noted that the microphysical model was already included in the LMD-MGCM, but was not activated in the version used for the calculations in Chaufray et al., 2021.

Second, we have extended the photochemical model in the LMD-MGCM (González-Galindo et al., 2013) to include additional ionospheric reactions. In particular, we have incorporated the chemistry of H_2O^+ and derived ions, which has been proposed (e.g. Stone et al., 2020) to play an important role in the conversion of water to H atoms in the Martian thermosphere, and thus in the escape of Hydrogen.

Third, we have also included in the calculations an improved model of deuterium fractionation (Vals et al., 2022), as well as included deuterated species and their chemical reactions (including HDO photodissociation) in the photochemical model, which will allow us to study in the future the D/H ratio in the thermosphere and at escape, an important parameter to reconstruct the history of Martian climate. However, we will focus here in the H escape.

Preliminary results

The incorporation in the calculations of the microphysical model allowing for the formation of supersaturated

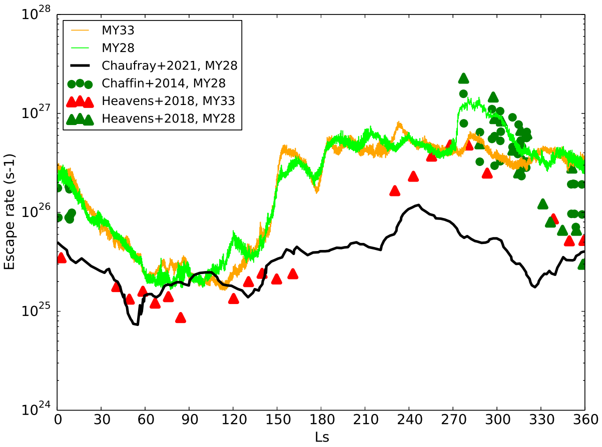

Figure 1: H escape rate simulated for MY28 (light green line) and MY33 (orange line). The black thin line shows the escape rate for MY28 simulated with the previous model version, taken from Chaufray et al. (2021). The green and red symbols represent measured values of the H escape rate during MY28 and MY33, respectively, taken from Chaffin et al. (2014) and Heavens et al. (2018)

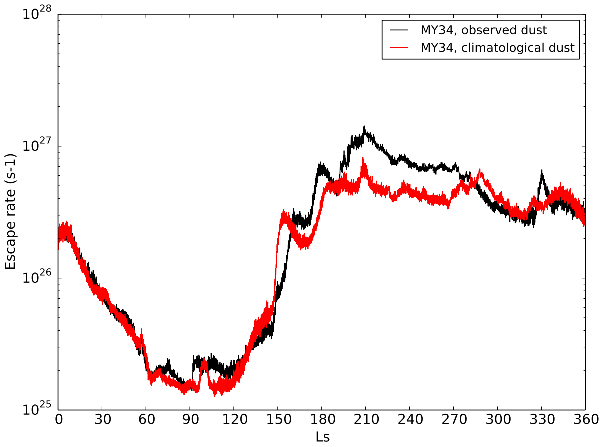

Figure 2: H escape rate simulated by the LMD-MGCM for MY34. The black line shows the simulated escape rate when using the observed dust abundance in the lower atmosphere, while the red line shows the result of a simulation using the climatological dust scenario, without global dust storms.

water layers significantly increases the amount of water in the upper atmosphere of the planet with respect to the previous calculations. This increase of the mesospheric and thermospheric water abundance produces a strong enhancement of the H escape rate when compared to previous calculations (Figure 1), in particular during the perihelion season, the period where comparisons with Mars Express observations had shown a significant underestimation of the escape rate by the model (Chaufray et al. 2021).

This results in a significantly better agreement with observations of H escape (Figure 1). However, significant differences still remain. In particular, the decrease in the rate of H escape at the end of the year is not well captured by the model, suggesting that, in the model, water remains in the upper atmosphere longer than observed. This is in agreement with previous comparisons of the mesospheric water content predicted by the model with ACS and NOMAD observations (Vals et al., 2022; Brines et al., 2022), which show that the model tends to overestimate the abundance of mesospheric water during the second half of MY34. It also seems that the increase in the H escape rate starts earlier in the model than in the observations, although the absence of data in the Ls=180-240 period prevents prevents a firm conclusion on this point.

The results shown here correspond to simulations covering a period of 11 Mars Years, using the observed variation of the dust abundance in the lower atmosphere as in Montabone et al., (2020), and the variation of the UV solar flux using the same method as in González-Galindo et al., (2015). These simulations allow us to study the interannual variability of the simulated escape rate. While the solar activity seems to play a minor role, the effects of dust storms in the lower atmosphere can be clearly felt in the H escape rate. For example, the dust storm around Ls=270 in MY28 produces a significant and sudden increase in the H escape rate (see Fig. 1).

We have also studied in detail the effect of the GDS in MY34. By performing a simulation for the same solar activity, but using a climatological dust scenario without GDSs, we have been able to separate the effects of this GDS from the regular seasonal increase observed during the perihelion season (Fig. 2). In the simulation with the GDS, the H escape rate during the period Ls=180-270 is up to 2 times larger than in the simulation without the global dust storm. The yearly accumulated H escape rate is 30% larger in the simulation including the GDS, which confirms the importance of taking into account the effects of GDSs when calculating the accumulated escape rate over Martian history.

By switching on and off different processes in the model, we have been able to quantify their relative contribution to the transport of water to the upper atmosphere and its conversion to H atoms. So, we find that the incorporation of the chemistry of water-derived ions increases the H escape rate in between 20 and 40%, depending on the season. This qualitatively agree with previous studies (Stone et al., 2020) showing the importance of ionospheric H2O reactions in the production of thermospheric H. We will discuss the relative importance of the different neutral and ionospheric chemical reactions in the production of thermospheric H.

This work opens the doors to studying the H escape rate at past Mars conditions characterized by different orbital parameters (e.g. obliquity, time of perihelion, etc.). See Gilli et al., this issue, for a first study in this direction.

Acknowledgments

F.G-G. and G.G. are funded by the Spanish Ministerio de Ciencia, Innovación y Universidades, the Agencia Estatal de Investigación and EC FEDER funds under project RTI2018-100920-J-I00. AB and MALV were supported by grant PGC2018-101836-B-100 (MCIU / AEI / FEDER, EU). The IAA team acknowledges financial support from the State Agency for Research of the Spanish MCIU through the \Center of Excellence Severo Ochoa" award to the Instituto de Astrofísica de Andalucía (SEV-2017-0709)

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