INCREASED HYDROGEN ESCAPE FROM MARS ATMOSPHERE DURING PERIODS OF HIGH OBLIQUITY.

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Higher loss rates in the "recent" Mars history

Mars was not always as dry as it is today, as several geologic and mineralogical observations indicate the evidence for past liquid water [Bibring et al., 2004]. Atmospheric loss to space appears to explain why the Mars atmosphere evolved from an early, warmer climate to the cold, dry climate that we see today. Substantial amounts of water could have escaped into the interplanetary medium in the form of atomic hydrogen [Jakosky et al., 2018]. Furthermore, observations indicate that the amount of exosphere hydrogen at Mars has important seasonal variations, with significant increases of both the water abundance in the mesosphere and the H escape rate during dust storms [Chaffin et al., 2014, Clarke et al., 2014, Mayyasi et al., 2023]. By analysing observations by SPICAM on board Mars Express and simulations with the Mars Planetary Climate Model (MPCM), Chaufray et al. [2021] suggested that episodic dust storms and associated enhancement at high altitude near the perihelion, averaged over one Martian year or longer period, are a major factor in the H escape estimates.
Although present-day H-loss rates ($\sim$ 3 x 10^{26} $s{-1}$ on average) are in very good agreement with observed seasonal and inter-annual trend (see Figure 1), they cannot explain the geological evidence of the presence of large volumes of liquid water on ancient Mars. Both the dust and the water content of the atmosphere are expected to vary with the obliquity of the planet. Thus, the loss rate is not expected to have been constant with time and may vary significantly during Martian history.

In this study we have used an updated and improved version of the MPCM to show that H-loss rates could have increased up to more than one order of magnitude (6 x 10^{27} $s{-1}$) during higher spin axis obliquity periods [Gilli et al., 2025] (see Figure 2), notably in the last millions of years when Mars's obliquity was about 35° on average [Laskar et al., 2004]. The resulting accumulated H escape over Mars history translates into $\sim$ 80 m Global Equivalent Layer, which is close to the lower limit of geological estimates and confirm the important role of atmospheric H loss to remove a large fraction of Mars' initial water.

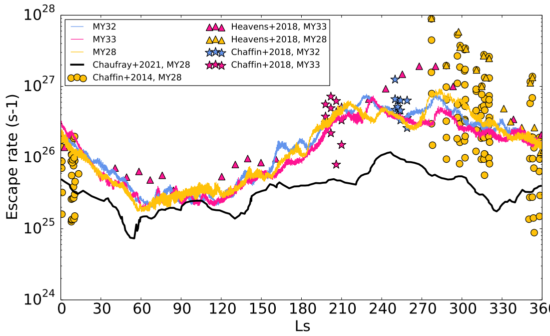

Figure 1: Globally integrated escape rate (atoms/s) simulated with the Mars-PCM. A simulation using a version similar to the one in Chaufray et al. [2021] is in black. Simulations with the improved version for different Mars Years are shown by color lines as indicated in the legend. Different observational datasets are represented with symbols: Mars Express observations during MY28 (yellow circles) Chaffin et al. [2014], Hubble Space Telescope observations also taken during MY28 (yellow triangles) Heavens et al. [2018], IUVS observations obtained during MY32 (blue stars) and MY33 (purple stars) Chaffin et al. [2018] and MAVEN SWIA observations during MY33 (purple triangles) Heavens et al. [2018].

Processes leading to larger H-escape

In current obliquity conditions (25.2°) the water ice in the polar caps sublimes in Summer, and then it is recycled back in Winter. Large dust load in the lower atmosphere facilitates the transport of water to the upper atmosphere, where it is chemically converted into atomic H that can easily escape to space (panel A, Figure 3). In the last 20 million year, when the obliquity of Mars was higher than today (panel B, Figure 3), larger north pole insolation induced a more intense water cycle: the amount of sublimated water vapour in the atmosphere of Mars was much larger than today, and localised surface water ice reservoirs were created after precipitation in tropics and mid-latitudes [Madeleine et al., 2009] In addition, the formation of thick clouds warmed the middle atmosphere (up to 50 K at 45 km) by absorbing both solar radiation and IR radiation emitted by the surface, inducing positive feedback. All this favoured

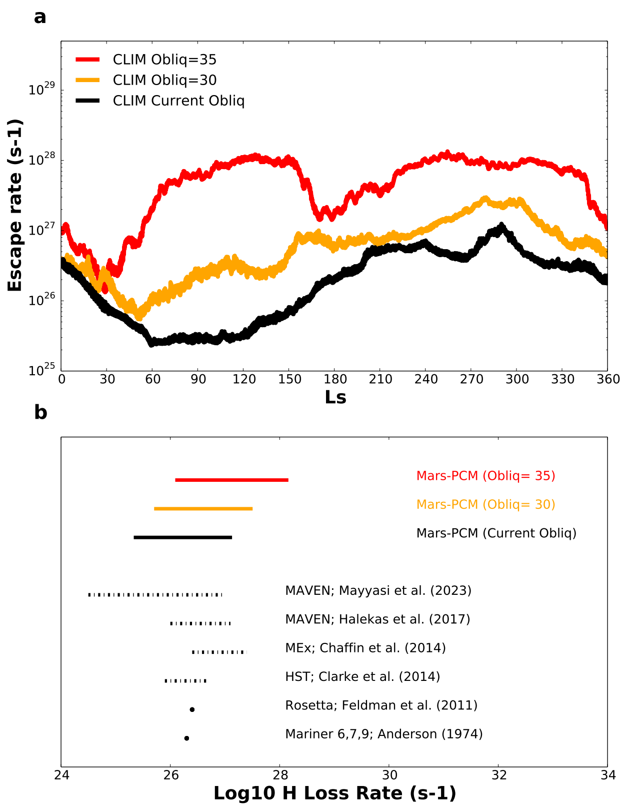

Figure 2: Panel a: Globally integrated escape rate (atoms/s) simulated with the Mars-PCM. A climatological dust scenario called "CLIM" is used with current obliquity (black), obliquity of 30º(orange), obliquity of 35º (red). Panel b: Comparison of Mars-PCM H escape rates with H-loss rates estimated for current obliquity from different spacecrafts [Chaffin et al., 2014, Clarke et al., 2014, Clarke, 2018, Mayyasi et al., 2023, Heavens et al., 2018, Halekas, 2017, Anderson Jr., 1974, Feldman et al., 2011]. Figure after Gilli et al. [2025]

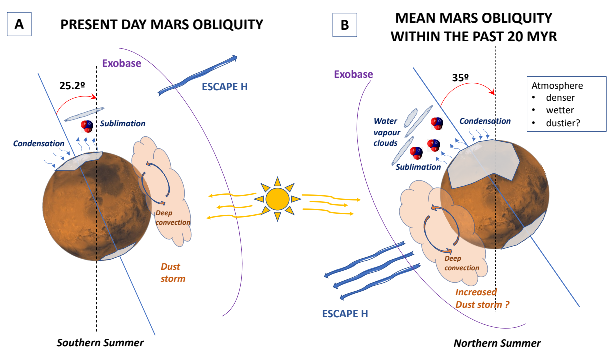

Figure 3: The H loss rate is not expected to have been constant with time and may vary significantly during Martian history. The processes that may have led higher H-escape are described in the text. Figure after Gilli et al. [2025].

water penetration into the mesosphere (e.g. with up to 5 order of magnitude increased water abundances at about 45 km, near the aphelion), resulting in larger H escape rate. Other processes not accounted for in our study could also contribute to further changes in the H escape rate. Buried deposits of CO_2 ice within the south polar layer could have been released in the atmosphere at the time of high obliquity, producing an atmosphere with double its current pressure [Kurokawa et al., 2014]. With higher pressure and warmer temperature conditions, is uncertain if the seasonal dust activity was more (or less) intense than today, due to higher water content and changes in the circulation patterns.

It should be noted that our simulations are relevant only for the Amazonian period, because early Mars was in a very different environment than the present one (e.g. with a fainter Sun at visible wavelengths and stronger UV radiation). The limitations of our approach of assuming the same bulk atmosphere than today at different obliquity must also be taken into account, so the results should be interpreted as a first approximation to the full problem. In spite of that, this study highlights that H escape has probably had a stronger role than that based on current estimates, leaving a lesser fraction to water sequestration in the crust.

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