The History Of Water On Mars During The Hesperian and Amazonian

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Introduction. We explore the processes affecting the history of water at the Martian surface from the Hesperian up through the present. Major processes that affect the overall surface inventory of water include:

- Loss of water to space through time.
- The increased EUV earlier in time that affects (and controls) loss to space.
- Supply of juvenile water via volcanism that continues up to the present.
- The changing axial obliquity of Mars, with values greater than the present value being more typical and resulting in increased atmospheric water vapor.
- The changing stability of near-surface ground ice and of surface ice with changing atmospheric water abundance.

These processes combine to result in a greater loss of water to space during the last three billion years than would be predicted just from the present-day loss rate. A consequence of this is that there would have been more water at the surface (and near-surface regions) than there is today.

Three lines of evidence point toward there having been more polar, atmospheric, and surface water and ice during the Hesperian and Amazonian epochs, both as a steady amount and with intermittent increases. First, interpretation of the D/H isotopic ratio suggests that the total amount of H_2O lost to space during the Amazonian was significant relative to the amount currently locked up in the polar and non-polar ice deposits. Thus, there would have to have been more water at the surface during the earlier epochs.

Second, the Dorsa Argentea Formation (DAF), surrounding the SPLD and having an area larger than the SPLD, is thought to represent a Hesperian-era polar-cap-like deposit that contained ~20 m Global Equivalent Layer (GEL) or more of water. The water is not thought to be present in the DAF today.

Third, periods of higher axial obliquity that are likely to have occurred throughout this time would have been accompanied by greater atmospheric water than is seen at present, due to enhanced summertime sublimation from the polar ice.

The bulk of any earlier increased water would have equilibrated rapidly with the polar ice caps. A greater water vapor abundance, and any enhancement in CO_2 abundance during this time, would not be expected to have produced significant additional greenhouse warming. Therefore, climate during the late Hesperian and the Amazonian likely would have been similar to the present obliquity-driven climate (albeit with decreased solar constant and increased UV radiation), but with more surface and atmospheric water.

We expect that the combination of polar and atmospheric processes would have resulted in larger H_2O polar caps, an enlargement of regions having stable ground ice at a given obliquity, somewhat enhanced atmospheric water content, and possible enhanced loss of H and O to space. We will explore these processes and their ramifications. Keep in mind that the Martian volatile system is highly coupled between the deep interior, the crust, the surface, the polar caps, the atmosphere and upper atmosphere, and loss to space (Fig. 1).

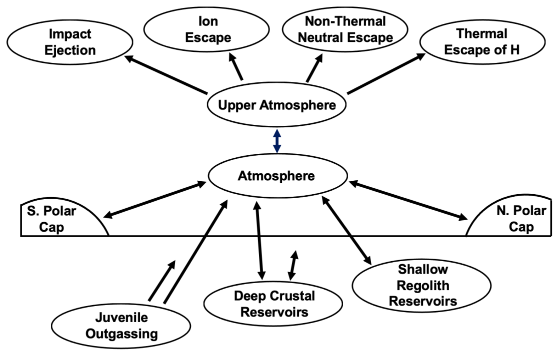

Fig. 1. Schematic diagram of coupled Mars volatile system in which all components must be considered when evaluating volatile/atmosphere/climate evolution. From Jakosky and Byrne (2025).

Loss of H_2O to space through the Amazonian. There would have been an overall dynamical equilibrium between how much water was present at the start of the Amazonian, subsequent volcanic (or other) outgassing, and loss to space, in determining the present-day surface water abundance and D/H. Solutions are not unique, however, and multiple scenarios are viable. For 30 m GEL current surface H_2O, the initial water at 3.3 b.y.a. would have been ~40-90 m GEL. Thus, the early Amazonian surface water would have been ~1.3-3.0x the current polar-cap/ground-ice volume. This requires that the average loss rate of water to space would have to have been up to 40x the current loss rate, and that, accounting for outgassed water, the total amount of water lost to space would have been ~15-120 m GEL.

Larger polar caps in early Amazonian. This additional surface water in the early Amazonian would have resided predominantly in the polar caps – the timescale for atmospheric water to reach a dynamical equilibrium with annual sublimation and desublimation is only ~1-2 Mars years. This would have resulted in there having been ~1.3-3x the volume of polar ice. It is difficult to estimate the resulting spatial extent of the polar caps, but we note that the current polar layered terrain is ~2x the area of polar ice (both poles combined), and the sum of polar ice + layered terrain is ~3x the area of polar ice. Perhaps more importantly, the Dorsa Argentea Formation (DAF, described in detail by Head and Pratt), which may be an ancient polar deposit, is larger than the area of the current SPLD, and may have contained 20 m GEL H_2O or more.

Greater seasonal polar sublimation, more atmospheric water. The larger polar caps would have resulted in greater net summertime sublimation of water (e.g., 3x area → 3x the total integrated summertime H_2O sublimation). In addition, there would have been greater sublimation at higher obliquity – possibly more than 100x the present summertime sublimation at 35-40° obliquity. The resulting dynamical-steady-state atmospheric water content would reflect the balance between summer sublimation, transport, and winter accumulation. The enhanced summertime sublimation would result in a greater steady-state atmospheric water content; the increase would be by at least a factor of several based on the increased cap surface area, and up to several hundred during periods of high obliquity.

Widespread near-surface ice. The larger atmospheric water content would have resulted in higher condensation temperatures, and larger areas of regolith would be below this temperature (i.e., there would be expansion of the "Leighton and Murray" near-surface ice-condensation region). For example, a ~20-30x increase in water, appropriate for an obliquity near 30° (still well below the statistical modal value of 42°), would produce nearly global ground ice. Global near-surface ice (top few meters) may have been the norm as Mars cycles through obliquity values, especially given the decreased solar constant 3 b.y.a. Whether surface ice would form depends on atmospheric temperatures, surface temperatures, and atmospheric water abundance, and on how these play off against each other; the resulting consequences for stability of surface ice are unclear.

Greater EUV in the past, atmosphere/upper atmosphere chemistry, structure, and composition. The solar EUV flux has been declining with time, even as the solar constant increases. The average solar EUV flux at 3.3 b.y.a. was ~5x the present values (depending on wavelength). The greater EUV in earlier epochs would increase photodissociation and photoionization of H_2O and CO_2, increasing steady-state O and O_2 abundances. The greater H and O abundances would increase abundances of both species in the extended coronae above the exobase; there is a large uncertainty, however, due to uncertainties in the vertical distribution of atmospheric species based on the dust behavior that has been seen to increase coronal abundances.

Greater H and O escape? Greater H and O thermospheric and coronal abundances should result in greater rate of loss to space, due to enhanced dissociative recombination (DR), sputtering, and pickup, and due to enhanced impact of coronal mass ejections (CMEs). Using Chassefiere et al.'s models based on the EUV flux at 3.3 b.y.a., there would be an ~5x increase in DR, 30x in pickup, 8x in outflow, and 15x in sputtering; the net increase in total loss would be ~10x (the 5x increase in loss from today's dominant DR loss mechanism plus an equal loss from pickup). Enhanced loss due to CMEs, as observed by MAVEN, increase the loss rate further, especially considering the increased CME rate earlier in history.

This increase does not include any effects from increased atmospheric or upper-atmospheric H_2O resulting from intermittent greater obliquity. However, an increase in atmospheric water alone should not increase the O abundance via photodissociation, as the EUV photons that photodissociate are already all being absorbed at present. Importantly, the H escape rate is likely to be governed over timescales longer than $\sim 10^5$ years by the O escape rate, as described by McElroy; models calculating the H loss rate through time without also including variability of O loss will be in error.

Preliminary conclusions. The net consequence of these processes, based on the increased surface, near-surface, polar, and atmospheric water in the early Amazonian and the Hesperian, would be:

- The total amount of water present at the surface (polar caps, atmosphere, near-surface ground ice) during the Hesperian and early Amazonian would have been significantly greater than it is today. Most of the additional water would have been locked up in the polar caps or ground ice, with the atmospheric water content reflecting balance between seasonal sublimation and desublimation.
- Larger polar caps in the Hesperian and early Amazonian would be consistent with geological evidence for significant quantities of water being contained within the Dorsa Argentea Formation and subsequently released.
- Increased atmospheric water vapor resulting from larger polar caps and intermittent higher obliquity would have resulted in much-more-

widespread near-surface ground ice and possibly widespread surface ice.

- Larger loss rates of H and O to space predicted for the earlier epochs appear to be able to explain the greater average loss rate of water to space compared to that seen at the present, as required in order to be consistent with the D/H. In particular, the enhanced loss rate can explain where much of the water from the DAF went.

The quantitative results are not unique due to uncertainties in what the actual water abundance and boundary conditions would have been. However, the present discussion provides a framework through which we can understand the nature of relevant processes and the coupling between them. Especially, understanding the behavior and history of water requires considering the behavior and evolution of the system as a whole, including exchange between the mantle, crust, polar caps, regolith, atmosphere, upper atmosphere, and loss to space, as shown in Fig. 1.