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KEY UNKNOWNNS FOR VENUS ATMOSPHERIC EVOLUTION 1: PRESENT-DAY D/H ESCAPE RATE UNCERTAINTIES AND IMPLICATIONS FOR UPCOMING HDO/H₂O MEASUREMENTS.

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Introduction: The highly enriched D/H ratio on Venus relative to the Earth indicates that the overwhelming majority of the planet's water has escaped to space [1]. Even if such loss occurred primarily during a period of hydrodynamic escape, a substantial fraction of Venus' initial water would likely remain in the atmosphere after hydrodynamic escape ceased [2, 3]. Such water would need to be removed either by surface processes or escape to space in order to account for the present low abundance of atmospheric water [4]. Venus H and D escape in the post-runaway epoch must occur via nonthermal channels, a necessity imposed by the Earth-like mass of the planet combined with its cool, Mars-like thermosphere temperature [5, 6]. However, a lack of knowledge regarding key loss mechanisms leads to significant uncertainties in the possible current and geologically recent escape rates of H and D [7], posing challenges to the interpretation of planned DAVINCI and EnVision HDO/H₂O measurements. In this presentation we will provide a summary of these uncertainties and suggest new analysis and observations that could improve knowledge of Venus H and D loss to space and fractionation.

Importance of Contemporary D/H Escape Rates for Venus Evolution: Hydrodynamic loss has likely played a major role in removing water from Venus, either early in the planet's history before condensation of the primordial steam atmosphere, or later in its history following a period of relatively mild, potentially habitable surface conditions. In either case, hydrodynamic escape is the result of gas outflow from a hydrogen-dominated atmosphere unable to balance the incident solar energy in any other way. Hydrodynamic escape ceases once enough H has escaped that two and three atom molecules can effectively cool the upper atmosphere via radiative and conductive processes. This transition is likely to occur before all atmospheric H has escaped, so that a substantial amount of H can remain in the atmosphere as water, perhaps ~10 bars or ~100 m GEL [4]. Because the present atmosphere contains only 2×10^{-3} bars of H₂O, the dregs remaining after the conclusion of hydrodynamic escape must be removed by nonthermal loss processes, of which photochemical

escape and ion outflow (via ambipolar electric fields) are thought to be dominant [7].

If the amount of water left behind after hydrodynamic escape and the nonthermal escape rates are both known, limits can be placed on the time at which hydrodynamic escape ended, with important implications for Venus evolution [8, 9]. Unfortunately, significant uncertainties in both photochemical escape and ion loss at the present epoch limit the conclusions that can be drawn. For ion loss, early upper limits on loss rates suggested that the process might be strongly dominant [7, 10], but later investigations found much lower rates, below what is expected via photochemical processes [11]. For photochemical loss, existing model calculations of H and D escape are limited by uncertainties in available cross sections and input ion densities/temperatures, and by the recent discovery of several potentially important photochemical processes. Taken together, these uncertainties mean that it is unknown whether H or D escapes predominantly as a neutral or ion, as both ion and neutral loss rates are similar and uncertain by a factor of several. The fractionation factor of D/H loss, equal to the ratio of relative escape fluxes to relative atmospheric abundances, is similarly uncertain (see Table).

Need for Improved Knowledge to Interpret Planned HDO/H₂O Measurements: DAVINCI will measure HDO/H₂O in the lower atmosphere of Venus at very high precision, providing a vital and long-needed constraint for understanding the evolution of

Table: Photochemical and ion loss rates of D and H via computed by Hodges+1999 based on Pioneer Venus Orbiter measurements [6], and the fractionation factor of escape, $f = \frac{\phi_D/\phi_H}{[\text{HDO}]/2[\text{H}_2\text{O}]}$. Whether ion or neutral loss dominates depends on the assumed ion escape boundary condition, and the total H loss rate and the fractionation factor vary by a factor of several.

	H Escape Flux $10^7 \text{ cm}^{-2} \text{ s}^{-1}$			D Escape Flux $10^5 \text{ cm}^{-2} \text{ s}^{-1}$			f
	ϕ_H	ϕ_{H^+}	Total	ϕ_D	ϕ_{D^+}	Total	
No Ion Loss	1.90	–	1.90	0.91	–	0.91	0.20
Jeans Ion Loss	2.03	2.63	4.66	1.15	0.27	1.42	0.13
Radial (Max) Ion Loss	1.86	4.47	6.33	1.05	1.28	2.33	0.15
Donahue&Hartle'92	0.90	1.50	2.40	1.59	0.56	2.15	0.44

water on the planet. Together with constraints on volcanism provided by VERITAS and EnVision, and in tandem with middle atmosphere HDO/H₂O measurements made with the high-resolution infrared spectrometer suite on EnVision, the stage will be set for a re-evaluation of water evolution since the last climate transition on Venus. This comprehensive set of lower and middle atmosphere D/H measurements must be paired with renewed study of upper atmosphere D and H loss to space to fully understand the history of water on Venus.

For example, 1D evolution models proposed by Grinspoon (1993) [8] and others to study the long-term evolution of the Venus atmosphere as a function of the bulk HDO/H₂O ratio and the escape rate of H to space are critically dependent on the fractionation factor of escape to space (see Figure). In the primordial hydrodynamic escape scenario, the effect of existing uncertainties in the fractionation factor of escape frustrates any attempt to infer the long-term H loss rate. Conversely, in a late runaway greenhouse / hydrodynamic escape scenario, existing uncertainties in H loss rates produce a >1 Gyr uncertainty in the timing of the transition. For both scenarios, renewed study of existing H and D escape datasets is essential, as is planning for future Venus orbiter measurements capable of constraining the loss rates of H and D as ions and neutrals. Beyond Venus, such measurements are important for understanding planetary evolution in general: because thermal H loss at present day Venus is negligible, the planet is a unique laboratory for the study of nonthermal H loss processes likely to control the water inventory of planets throughout the cosmos with CO₂-dominated atmospheres and Earth-like (or greater) gravity.

In this presentation we will outline a program of analysis that would tighten uncertainty bounds on D/H escape derived from existing datasets, and discuss the possibility of new spacecraft measurements capable of constraining H and D escape from Venus.

References: [1] [Donahue+1982](#), [2] [Gillmann+2020](#), [3] [Krissansen-Totton+2021](#), [4] [Gillmann+2022](#), [5] [Anderson1976](#), [6] [Hodges1999](#), [7] [Lammer+2006](#), [8] [Grinspoon1993](#), [9] [Donahue1999](#), [10] [Hartle&Grebowksy1993](#), [11] [Persson+2018](#)

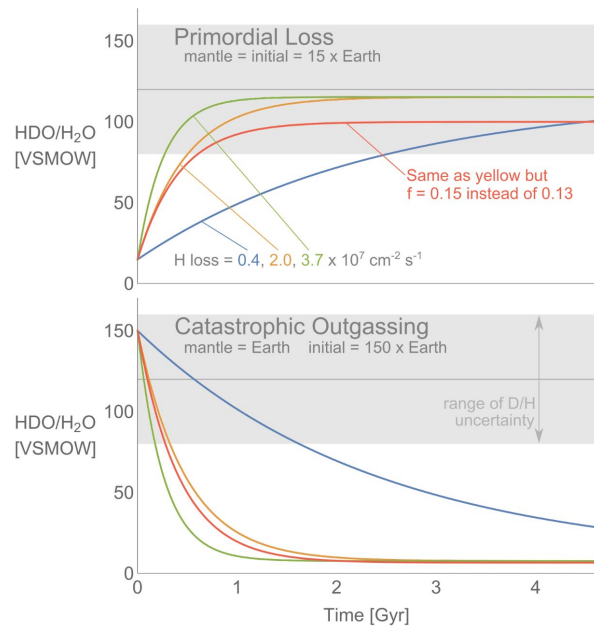


Figure: Evolution of Venusian HDO/H₂O as a function of time, adapted from Grinspoon+1993. Curves in each panel show the evolution of D/H in water in the well-mixed atmosphere as a function of initial enrichment, enrichment of outgassed water vapor resupplying the atmosphere, the loss rate of H to space, and the fractionation factor of that loss. Gray line and shading in each panel shows the PVO descent probe D/H measurement and measurement uncertainty (i.e., the composition of the present-day atmosphere). (*upper panel*) A primordial loss scenario in which early enrichment due to hydrodynamic escape is supplemented by later loss at one of three rates consistent with existing measurements. In this scenario, the long-term average H loss rate over Venus history can be inferred from the present-day HDO/H₂O ratio, but only if the fractionation factor of D/H escape is known quite precisely, as indicated by the red curve. (*lower panel*) A catastrophic outgassing scenario in which late hydrodynamic escape enriches the atmosphere to a very high value, which falls over time as the atmosphere is resupplied by outgassing of unfractionated water. In this scenario, a combination of precise bulk HDO/H₂O measurements and knowledge of the escape rate can be used to determine the time since the event, but existing H escape rate uncertainties lead to a >1 Gyr uncertainty in timing.