

EVOLUTIONARY IMPLICATIONS OF A STEADY-STATE WATER ABUNDANCE ON VENUS;  
David H. Grinspoon, Laboratory for Atmospheric and Space Physics, University of  
Colorado, Box 392, Boulder, CO 80309

In 1987 Grinspoon proposed that the data on hydrogen abundance, isotopic composition and escape rate were consistent with the hypothesis that water on Venus might be in steady-state rather than monotonic decline since the dawn of time [1-3]. This conclusion was partially based on a derived water lifetime against nonthermal escape of approximately  $10^8$  years. Others have questioned this conclusion. De Bergh *et al.* [4] found  $H_2O$  lifetimes of  $> 10^9$  years. Donahue and Hodges[5], derived  $H_2O$  lifetimes of  $0.4 - 5 \times 10^9$  years. The most sophisticated analysis to date of near-IR radiation from Venus' nightside reveals a water mixing ratio of approximately 30 ppm [6]. Recent re-analysis of Pioneer Venus Mass Spectrometer Data are consistent with a water abundance of 30 ppm [7].

Hodges and Tinsley [8] found an escape flux due to charge exchange with hot  $H^+$  of  $2.8 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$ . Gurwell and Yung [9] estimated an escape flux of  $3.5 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$  from collisions with hot O produced by dissociative recombination of  $O_2^+$ . Brace *et al.* [10] estimated an escape flux of  $5 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$  from ion escape from the ionotail of Venus. The combined estimated escape flux from all of these processes is  $3.7 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$ , suggesting a lifetime against escape for water of less than  $10^8$  years. A recent estimate of H escape flux employing a different ionospheric model and using Pioneer Venus reentry data to estimate the response of the escape flux to the solar cycle finds a somewhat lower escape flux of  $1.4 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$  [11], suggesting a water lifetime closer to  $2 \times 10^8$  years, significantly less than the age of the planet. Large uncertainties remain in these quantities, yet the data suggest that a source of water more recent than primordial sources is required and that a steady-state is likely. Two obvious candidates for this source water are cometary impact and volcanic outgassing.

If water on Venus is in steady-state, then the escape flux of hydrogen provides an upper limit on the outgassing flux of hydrogen containing compounds averaged over the last  $10^8$  years. If the source hydrogen is dominated by outgassed water and the recent cometary contribution is unimportant, then the escape flux is a direct measure of the time-averaged outgassing flux.

Gurwell and Yung [9] have reanalyzed the collisional ejection escape process, yielding improved values for the efficiency of H and D escape. This process was previously thought to be extremely inefficient at causing D to escape, but is now found to be the dominant escape mechanism for deuterium. This leads to an estimated fractionation factor (a measure of the efficiency of D escape relative to H) of  $f = 0.13$ , an order of magnitude higher than previous estimates. This change has a paradoxical effect on the interpretation of the observed high D/H ratio on Venus: The timescale to reach a "mature" steady-state - where the D/H ratio has relaxed to the limiting steady-state value and the signature of the "primordial" D/H is erased - is reduced by an order of magnitude, making it quite likely that such a state has been reached. Yet, the change in  $f$  also means that a mature steady state is only consistent with the observed high D/H ratio if the source hydrogen is enhanced over terrestrial by a factor of 10 or 15. This may rule out comets as a source if the observations of D/H on Comet Halley [12] are representative of average cometary hydrogen.

The escape fluxes given above could be supported by an outgassing flux of approximately  $6 \times 10^{10}$  grams of water per year. Magellan mapping of volcanic features, combined with

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simulations of the crater population [13,14] have allowed preliminary estimates of volcanic resurfacing rates of around  $0.5 \text{ km}^3/\text{yr}$ , yielding a rate of magma production (RMP) of approximately  $1.5 \times 10^{15}$  grams/yr. This rate may be combined with the outgassing flux derived above to estimate the average water content by weight of Venusian magmas:

$$\text{magma water content} = \frac{\phi_{\text{OG}}}{\text{RMP}} + \beta \quad (1)$$

where  $\beta$  is a parameter representing the efficiency of outgassing which equals 1 for complete outgassing. There are many complex factors which have not been fully modeled which determine the efficiency of volcanic degassing under the thick, hot atmosphere of Venus [15]. These include considerations of solubility and diffusion. If  $\beta$  is close to 1, perhaps reasonable for thin, voluminous flows, then Eq. 1 yields a magma water content of 40 ppm by weight. This is more than 1000 times drier than typical basaltic magmas on Earth [16]. Thus even if  $\beta$  is much lower than this, Venusian magmas are apparently extremely desiccated, perhaps implying a desiccated mantle as well. Such a desiccated mantle could be the result of continuous outgassing over the planet's history, with no recycling of water in the absence of a surface reservoir and possible absence of subduction. Could this mantle reservoir be the source of the fractionated hydrogen necessary to reconcile the observed D/H ratio with the expected value for a mature steady state? Such processes as differential diffusion and bond-breaking could lead to preferential outgassing of H over D, yet the expected fractionation factor for mantle degassing has not been modeled, and is probably near unity. However large fractionation effects are found in severely depleted reservoirs. If water in the mantle has been depleted by a factor of  $10^5$  (the approximate difference in the known water reservoirs of Venus and Earth), then an outgassing fractionation factor of  $f = 0.8$  could have produced an enhancement of D/H in the mantle by a factor of 10. Alternatively, an enhanced mantle D/H ratio could reflect massive hydrogen escape which occurred very early in the planet's history and was then frozen into the mantle when an early magma ocean solidified. In this scenario, the observed D/H may indeed be the result of primordial water loss, but this signature would have been preserved in the mantle reservoir, not in the atmosphere.

Another resolution of the paradox described above is that the observed high D/H ratio could be the isotopic signature of massive outgassing associated with catastrophic resurfacing of the planet in the last one-billion years.

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