The sea level response to this warming should be carefully determined to aid our understanding of the processes and to allow early detection of any nonlinear response.

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Escape of Hydrogen from Venus

Abstract. *Recombination of O_2^+ represents a source of fast oxygen atoms in Venus' exosphere, and subsequent collisions of oxygen atoms with hydrogen atoms lead to escape of about 10^7 hydrogen atoms per square centimeter per second. Escape of deuterium atoms is negligible, and the ratio of deuterium to hydrogen should increase with time. It is suggested that the mass-2 ion observed by Pioneer Venus is D^+, which implies a ratio of deuterium to hydrogen in the contemporary atmosphere of about 10^{-2}, an initial ratio of 5×10^{-5}, and an original H_2O abundance not less than 800 grams per square centimeter.*

Venus contains quantities of carbon and nitrogen similar to Earth, but hydrogen is deficient (*1*). The abundance of water on Venus is about 4.2 g cm^{-2}, which may be compared to the terrestrial value of 2.7×10^5 g cm^{-2}. Walker *et al.* (*2*) argued that the amount of H_2O on Venus should have been initially similar to that on Earth; they proposed that escape of H from a hot steamy atmosphere played a major role in Venus' early evolution. Lewis (*3*) thought that the H_2O content was low from the outset, because Venus formed in a warmer region of the solar nebula.

Analysis of processes influencing the current budget of Venus' hydrogen should shed some light on this issue. The upper atmosphere contains significant quantities of H, measured first by Mariner 5 (*4*). The density of H in outer regions of a planetary atmosphere provides direct information on the exchange of hydrogen with the interplanetary medium, and analysis of data for Earth (*5*) indicates an escape flux for H of 2.7×10^8 cm^{-2} sec^{-1}. The distribution of H is more complex for Venus, with at least two components (*6*), and interpretation is correspondingly ambiguous (*7*).

One component of Venus' exospheric H has a scale height of about 300 km, consistent with temperatures observed by Pioneer Venus (*8*). The second is more extensive, with a scale height of about 1000 km. Escape of atoms in the cold component is trivial, about 10 cm^{-2} sec^{-1}. Escape from the extended distribution may proceed more readily. The escape rate would be 1.5×10^6 cm^{-2} sec^{-1} if the velocity distribution were characterized by an effective temperature of 1000 K as suggested by the observed scale height.

Fast atoms comprising the extended component must be produced in the exosphere, either by acceleration of ambient H or by exothermic reactions involving hydrogen-bearing gases such as H_2. Proposed chemical sources (*9, 10*) include charge transfer of H with solar wind and a variety of reactions involving ionospheric ions, for example, reactions 1 through 6 in Table 1. We propose here an additional source, collisions of fast O with thermal H, reaction 7. Energetic O atoms, O*, are formed by the recombination of exospheric O_2^+ and CO_2^+, reactions 8 and 9. Recombination of O_2^+ proceeds mainly (*11*) by reaction 10, which represents a source for O* with an initial speed of 5.6 km sec^{-1}. Oxygen atoms formed in reaction 10 can escape directly from Mars (*12*). They are gravitationally bound to Venus but can induce significant escape of H by momentum transfer in reaction 7.

Consider an elastic collision of O* with stationary H and assume that the scattering is isotropic. The fraction of collisions leading to production of H atoms with speeds in excess of the escape velocity, 10.2 km sec^{-1}, is 6 percent for a O* velocity of 5.6 km sec^{-1} (*13*). The fraction is increased to approximately 15 percent if we account for the thermal velocity of H in an exosphere of temperature 300 K as implied by the cold H component observed by Mariner 5 (*6*).

The rate for escape of H due to reaction 7 on the dayside may be estimated as follows. Photoionization above the exobase leads to the production of O_2^+ and subsequently O*. The rate for production of O* is given by $2JN$, where J denotes the ionization rate (per second) and N is the column density of gas above the exobase (per square centimeter). Typical values for J range from 5×10^{-7} to about 1.2×10^{-6}, with higher values appropriate for solar conditions during the Venus flyby of Mariner 5 (*14*). The value of N is about 3×10^{14} (*15*), and the resulting source for O* is 8×10^8 cm^{-2} sec^{-1}. The fraction of exospheric O* that collides with H depends on the relative abundance of H and is approximately 2 percent for conditions during the Mariner 5 flight (*16*). The corresponding rate for escape of H from the dayside is about 10^6 cm^{-2} sec^{-1}.

The source of exospheric O* and H* may be even larger at night. The nightside ionosphere is variable (*17*), with densities as high as 10^5 electrons per cubic centimeter at altitudes between 140 and 150 km (*18*). The dominant positive ion at these altitudes is O_2^+, produced by reaction 11. The Pioneer data imply a recombination rate for the ions of about 3×10^8 cm^{-2} sec^{-1} (*18, 19*), which may be supplied either by transport from the dayside thermosphere or by in situ production (*17–20*). The corresponding rate for production of nightside O* is 6×10^8 cm^{-2} sec^{-1}. In contrast to the dayside, most of this source is located in the exosphere. The density of H in the lower nightside exosphere is 100 times larger than that on the dayside (21). Approximately half of the nightside O* collides with H, providing a source for H* of 3×10^8 cm^{-2} sec^{-1} (22). Half of the hot H atoms move up, and 10 percent of them, 1.5×10^7 cm^{-2} sec^{-1}, have speeds sufficient to escape (13).

We estimate a planetary average rate for escape of H due to reaction 7 of 8×10^6 cm^{-2} sec^{-1}. Charge transfer between planetary H and solar wind contributes an additional 2×10^6 cm^{-2} sec^{-1} (23). Rates for escape of H due to reactions 1 and 2 are negligible on the dayside but could be as large as 10^6 cm^{-2} sec^{-1} for reaction 2 on the nightside (24). Escape of H due to reactions 3 and 4 would be very large (10^8 cm^{-2} sec^{-1}) if H_2 densities were as high as suggested by Kumar *et al.* (25) but would be approximately 100 times less if the densities were as given by Sze and McElroy (10).

The ion mass spectrometer on Pioneer Venus detected a signal at mass 2 that was approximately 10^{-2} of that at mass 1. Taylor *et al.* (17) attributed it to H_2^+ formed by the photoionization of H_2, removed primarily by reaction with O. Their interpretation would require a mixing ratio for H_2 of approximately 10^{-5} at the turbopause (25). The corresponding source for H would be large and difficult to reconcile with the relatively low densities of H observed by Mariner 5. Kumar *et al.* (25) invoked an upward flux of H atoms of 3.3×10^8 cm^{-2} sec^{-1} and suggested that this flux could be balanced by transfer of H through the exosphere to the nightside. Other work (26) suggests that the transfer of H through the exosphere may proceed in the opposite sense, driven by higher densities of H on the nightside (21). The H_2^+ model encounters further problems in that H_2 is photochemically unstable below the turbopause, and it is difficult to transport adequate quantities of H_2 to the exobase (10). Further work is needed to resolve this issue. In the meantime, we suggest that the signal at mass 2 is due to D^+ rather than H_2^+. Interpretation of the data in this case requires a D/H ratio in the bulk atmosphere of approximately 10^{-2}, consistent with the available upper limits (27).

The escape rate for H estimated above for reactions 1, 2, and 7, 10^7 cm^{-2} sec^{-1}, implies a lifetime of 9×10^8 years for Venus' H, if atmospheric H_2O is the dominant reservoir for hydrogen. Escape of D is negligible, and the D/H ratio may be expected to increase with time. The initial value of this ratio 4.6×10^9 years ago is calculated as 5×10^{-5} if escape of H is proportional to the abundance of H_2O and if we adopt a value of 10^{-2} for the present ratio as discussed above (28). The value derived here for the primordial D/H ratio on Venus is similar to ratios observed for Jupiter and Earth (29). The analysis implies an initial abundance for H_2O on Venus of 8×10^2 g cm^{-2}, approximately 300 times less than the terrestrial value.

Table 1. Reactions involved in the production of hot O and H; *denotes a translationally hot atom; E^* is its kinetic energy (expressed in electron volts), based on the assumption that reactants and products are in ground states. The ion temperature (H^+ in reactions 1 and 2) is taken to be 1200 K.

$H^+ + O$	$\rightarrow H^* + O^+$,	$E^* = 0.1$	(1)
$H^+ + H$	$\rightarrow H^* + H^+$,	$E^* = 0.1$	(2)
$O^+ + H_2$	$\rightarrow OH^+ + H^*$,	$E^* = 0.6$	(3)
$OH^+ + e$	$\rightarrow O + H^*$,	$E^* = 8$	(4)
$CO_2^+ + H_2$	$\rightarrow CO_2H^+ + H^*$,	$E^* = 1$	(5)
$CO_2H^+ + e$	$\rightarrow CO_2 + H^*$,	$E^* = 8$	(6)
$O^* + H$	$\rightarrow O^* + H^*$		(7)
$O_2^+ + e$	$\rightarrow O^* + O^*$		(8)
$CO_2^+ + e$	$\rightarrow CO + O^*$		(9)
$O_2^+ + e$	$\rightarrow O(^1D) + O(^3P)$		(10)
$O^+ + CO_2$	$\rightarrow O_2^+ + CO$		(11)

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23. Hydrogen atoms ionized above the Venus ionopause are rapidly removed by solar wind. We place an upper limit on the rate for charge transfer with solar wind of 8×10^{-7} sec^{-1} by assuming an unattenuated solar wind above the ionopause. The rate for photoionization is 1.7×10^{-7} sec^{-1}, and the net loss of H from these processes on the dayside is less than 4×10^6 cm^{-2} sec^{-1}. Similar loss of O may occur above the ionopause.
24. The rate for nightside production of H* by reaction 2 is about 0.5×10^8 cm^{-2} sec^{-1} on the basis of H^+ profiles of Taylor *et al.* (17), H profiles by Brinton *et al.* (21), the ion temperatures (2000 K) by K. L. Miller, W. C. Knudsen, K. Spenner, R. C. Whitten, V. T. Novak [*J. Geophys. Res.* **85**, 7759 (1980)]. The fraction of H* produced with upward speeds in excess of 10.2 km sec^{-1} (1 percent) yields an escape rate of 0.5×10^6 cm^{-2} sec^{-1}.
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