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Cometary Water on Venus: Implications of Stochastic Impacts[1]

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The short lifetime of water on Venus suggests that the water abundance is in a near steady-state balance between loss by escape and replenishment by infall. In addition, the observed deuterium-to-hydrogen ratio on Venus is consistent with a steady state and does not necessarily imply a past water excess. We present results of a model incorporating a stochastic cometary source and nonthermal escape of hydrogen that produces the observed water abundance and D/H ratio. The stochastic variability of each of these quantities is shown to be large. We conclude that water on Venus is in a quasi-steady state mediated by large comet impacts and that the early history of water on the planet has been obscured by a history of random impacts. © 1988 Academic Press, Inc.

INTRODUCTION

Venus is an exceedingly dry place by terrestrial standards, having a global water inventory five orders of magnitude lower than that on Earth. The aridity of Venus has often been explained as due to the loss of a much greater primordial endowment of water, perhaps up to a full terrestrial ocean, which has been lost due to a runaway greenhouse, UV photolysis, and thermal and nonthermal escape of hydrogen. This model is supported by a deuterium-to-hydrogen ratio 100 times the terrestrial ratio, which is interpreted as a residue left by mass-selective escape of at least 100 times the current water abundance, perhaps a much greater amount depending on the efficiency of deuterium escape (Donahue *et al.* 1982). This scenario has been widely accepted and has diffused into the popular science literature, where it is often presented as a parable of a sister Earth gone astray.

A consideration of the current lifetime of water on Venus casts doubt on this monotonic secular decline in abundance. Dividing the current hydrogen column abundance by the nonthermal escape flux yields a characteristic lifetime on the order of 10^8 years. Either we have arrived just in time to witness the final departure of water from Venus or, much more likely, there is a source of water, and the abundance is in or near steady state. Possible sources include volcanic outgassing (Kumar *et al.* 1983) and cometary impact (Lewis 1974, Grinspoon and Lewis 1986).

Models of planetary formation differ on how much water and bound water should have been incorporated in the original material which accreted to form Venus. It is not known whether there was enough heliocentric mixing of planetesimals in the formation region of the terrestrial planets to give them similar original volatile inventories (Wetherill 1985). The observed variation of density with heliocentric radius among the terrestrial planets would not be produced in an extremely "well-mixed" accretion process. Planet formation may have been a more quiescent process with low eccentricities preventing a large degree of exchange (Greenberg 1987). In this case, the temperature gradient in the nebula would have resulted in a compositional trend

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among the planets which would provide Venus with a much smaller water endowment than Earth (Lewis 1972).

We have pursued an extreme model in which endogenous water sources are neglected, in order to explore and illustrate the possible importance of exogenous water on Venus. The apparent steepness of the size–frequency distribution of comets indicates that the bulk of the mass in the impacting flux may be contained in a relatively small number of massive nuclei. This suggests the possibility of large stochastic variations in water abundance. (The K-T impactor on Earth may have been a 10^{19}-g comet (Lewis *et al.* 1982). This would provide about 50% of the current water abundance on Venus! The mean interval between such impact events appears to be similar to the characteristic lifetime for water on Venus.) Accordingly, we have constructed a model incorporating stochastic impact injection and nonthermal escape of hydrogen, in order to explore the behavior of this interesting system.

WATER ON VENUS

There is a discrepancy between Venera and Pioneer Venus measurements of water abundance, but the favored interpretation is of a surface mixing ratio of 20 ppm rising to a value of 200 ppm at the cloud tops (Young *et al.* 1984). The cause of this gradient is not understood.

The current hydrogen escape flux is dominated by hot O impact (McElroy *et al.* 1982) and charge exchange with hot H^+ (Kumar *et al.* 1983), yielding a total escape flux of 2×10^7 H atoms cm^{-2} sec^{-1}. Assuming that water is the major H-containing species, which appears to be the case, then the column abundance of 0.1 g of H per square centimeter has a lifetime of 10^8 years, quite short compared to the age of Venus.

It is unsatisfactory simply to assume (although it is conceivable) that the present epoch is a unique point in the evolution of the atmosphere of Venus. A much more likely possibility is that Venus is being supplied with water at a rate which balances the nonthermal escape flux. Two potentially large water sources suggest themselves: long-term continuous volcanic outgassing, and impact of volatile rich bodies, among which icy comet nuclei should carry the bulk of the incoming hydrogen.

Although there is good evidence for volcanic activity at some point in the history of Venus (Barsukov *et al.* 1986), the amount of accompanying outgassing is totally unknown. It is not known whether this activity continues at present, although there have been intriguing observations of secular changes in the SO_2 abundance above the clouds (Esposito 1984). Estimates of the time dependence and total extent of outgassing on Venus must be highly dependent on one's preference of models for the origin and geologic evolution of the planet.

Lewis (1974) found that the flux of comets and volatile-rich asteroids could be sufficient to maintain a steady-state abundance of hydrogen on Venus. Estimates of the cometary flux through the inner Solar System have been made based on cratering records, astronomical observations, and dynamical calculations (Weissman 1985, Wetherill and Shoemaker 1982, Ip and Fernandez 1987). Although there is also a large uncertainty in these estimates, this is a known hydrogen source for Venus which may be considered independently of geologic models.

DEUTERIUM ON VENUS

The large deuterium-to-hydrogen ratio in the atmosphere of Venus was established by McElroy *et al.* (1982), who derived a D/H ratio of 1×10^{-2} from the mass 2 ion detection by the Pioneer Venus ion mass spectrometer. Donahue *et al.* (1982) analyzed the PV large probe neutral mass spectrometer measurement of HDO, finding a D/H ratio of $(1.6 \pm 0.2) \times 10^{-2}$. This measurement was regarded as a critical test between theories in which Venus formed in its present dry state and those in which large amounts of water were lost over the history of the planet.

For computational simplicity it is assumed that the escape flux of hydrogen is close to the diffusion limit, and therefore proportional to the hydrogen abundance, and that the escape of deuterium is likewise proportional to the deuterium abundance multiplied by a factor f, the fractionation factor, which represents the relative inefficiency of deuterium escape due to its larger mass. The differential equations representing the escape of these isotopes have the solution (Hunten 1982, Kasting and Pollack 1983)

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_1 = \left(\frac{\mathrm{D}}{\mathrm{H}}\right)_0 \left[\frac{(f_{\mathrm{H_2O}})_0}{(f_{\mathrm{H_2O}})_1}\right]^{1-f}, \quad (1)$$

where the subscripts 1 and 0 can be taken to mean "present" and "primordial," respectively, and $f_{\mathrm{H_2O}}$ is the mixing ratio of water in the atmosphere which we have assumed represents the total hydrogen inventory. It can easily be seen that, using this formalism, the interpretation of a 100-fold deuterium enrichment is that the water abundance has declined by at least a factor of 100, perhaps much greater if f, the deuterium escape efficiency, was significantly larger than zero.

This interpretation depends upon the assumption that there was no concurrent source of hydrogen during the fractionating escape and that the original D/H ratio on Venus was equal to the modern terrestrial ratio. The latter assumption is questionable since the origin of this "standard" is not understood and thus its applicability beyond the Earth is not known (Grinspoon and Lewis 1987). In this model the fractionating nonthermal escape was preceded by a period of hydrodynamic escape of much larger quantities of water, perhaps up to a full terrestrial ocean (Kasting and Pollack 1983). There is little evidence for this hydrodynamic escape phase, beyond the argument that some models of planet formation would have provided Venus with Earthlike quantities of water which then would have escaped in this fashion. An early period of massive hydrodynamic escape has also been invoked by Pepin (1987) to generate the observed mass fractionation of noble gas elements and isotopes.

If, as suggested in the previous section, water on Venus may be in a near steady state, rather than in monotonic decline, then the D/H ratio must be explained in a consistent fashion.

When a time-averaged source term for hydrogen, ϕ, which is equal to the escape flux, is introduced we obtain the solution

$$\frac{\mathrm{D}}{\mathrm{H}}(t) = \frac{\alpha}{f} - \left[\frac{\alpha}{f} - \left(\frac{\mathrm{D}}{\mathrm{H}}\right)_0\right] e^{-(\phi f/H)t}, \quad (2)$$

where α is the D/H ratio of the hydrogen source, H is the steady-state hydrogen abundance, and t is the time elapsed.

If we assume that D/H in the hydrogen source is equal to the primordial D/H, an assumption which is perhaps more safe for outgassing than for an external source, then this reduces to Eq. (10) in Krasnopolsky (1985).

Hunten (1982) and Hunten *et al.* (1987) give the solution

$$\mathrm{D/H} = \alpha/f \quad (3)$$

for the steady-state case. This is indeed the limiting solution, with the exponential term (representing the decaying signature of the original D/H ratio) disappearing as t goes to infinity. However, it is not obvious that this term can be ignored. The time constant for decay of this exponential term is

$$\tau = \mathrm{H}/\phi f. \quad (4)$$

For a hydrogen inventory corresponding to 20 ppm water, an escape flux of 2×10^7 $\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$, and $f = 0.022$ for charge exchange (Krasnopolsky 1985), we find $\tau = 3.97 \times 10^9$ years. Hunten *et al.* (1987) suggest a weighted fractionation factor, allowing for the relative magnitude and differing fractionation factors of the various escape mechanisms, of $f = 0.013$. Employing this value in (4) gives us $\tau = 6.71 \times 10^9$ years. Thus the decay time for this term seems to be on the order of the age of the Solar System.

The solar EUV flux was more intense in the past (Zahnle and Walker 1982) and thus it seems likely that the escape flux of H may have been at the diffusion limit, or closer to the limit than at present, for much of the planet's history (Krasnopolsky 1985). This increased flux for a given water abundance would have the effect of lowering τ by an amount proportional to the increase in flux. Uncertainties in estimating the present and past values of ϕ, H, and f make it difficult to determine whether or not the limiting solution of (2), represented by (3), should be reached in 4.5×10^9 years of steady-state evolution of the D/H ratio.

If the source of hydrogen has a terrestrial D/H ratio and the fractionation factor is as modeled by Hunten *et al.* (1987) ($\alpha = 1.6 \times 10^{-4}, f = 0.013$), then (3) gives D/H = 1.23×10^{-2}. The average cometary D/H ratio is unknown. Some models of comet formation lead to predictions of enhanced D/H in cometary ices (Vanysek and Vanysek 1985, Ip 1984). Eberhardt *et al.* (1987) used Giotto Neutral Mass Spectrometer measurements to find $0.6 \times 10^{-4} <$ D/H $< 4.8 \times 10^{-4}$ for Comet Halley. Whether or not this measurement represents the bulk D/H in Comet Halley and whether Halley should contain average cometary D/H are both unknown. Using this range for α in (3) gives a steady-state D/H of 4.6×10^{-3} to 3.7×10^{-2} for Venus, nicely bracketing the observed value. Including the exponential term in (2) with a decay constant on the order of the age of the Solar System lowers these values somewhat, depending on the chosen value for "original" D/H. Yet it is still possible with reasonable assumptions for the unknown parameters α, f, $(\mathrm{D/H})_0$, and H to derive D/H values, employing the steady-state solution, which are consistent with the observations. It is not necessary to postulate any past or "primordial" excess of water on Venus to explain the observed D/H ratio.

THE STOCHASTIC IMPACT INJECTION MODEL

For a power law mass–frequency distribution with a cumulative slope index of less than 2, most of the mass is contained in the largest objects in the distribution. The size distribution of comets appears to be of this nature (Hughes and Daniels 1980, Shoemaker and Wolfe 1982). Thus it seems likely that an exogenous source of hydrogen would be injected in a relatively small number of sudden events rather than as a smooth stream. This should produce large stochastic fluctuations in the water abundance and D/H ratio on Venus. In order to understand better the nature of these fluctuations we constructed a model including a stochastic impacting flux of comet nuclei and nonthermal escape of hydrogen.

There is a large uncertainty in our knowledge of the flux of large bodies through the inner Solar System and the resulting frequencies of impact with the terrestrial planets. Thus any conclusion based on a model including such an impact flux must be robust against large variations in the magnitude of this flux. To treat this uncertainty we defined a baseline flux, which we consider to be the most likely frequency distribution based on the available evidence, and then ran the model with a wide range of modifications to this.

Our baseline flux is an adaptation of the work of Watkins (1983), who, using the results of Dohnanyi (1972), defined the flux of impactors on the Earth in terms of the average time between impact of objects of a given mass or greater as a function of the mass, which for a power law distribution gives a straight line on a plot of log (mass) versus log (time). This flux distribution agrees quite closely with those given by Wetherill and Shoemaker (1982) and Kyte and Wasson (1986). We have modified this flux to include only the cometary impactors and considered the relative probabilities of impact on Venus and Earth for objects in cometary orbits.

Within the limits of observational uncertainty, it appears that the size distributions of asteroids and comets are similar (Hughes and Daniels 1980, Watkins, 1983). Thus, we represent the flux of comets as a fraction of the total impacting mass, having the same size distribution as the overall flux. In light of the spacecraft observations of the 1986 apparition of Comet Halley, which revealed a lower albedo and larger object than expected, Weissman (1986) now estimates that 50% of the recent terrestrial large impacts are by active cometary nuclei of which approximately one-third are long period and two-thirds are short period. For long-period comets the impact probability on Venus is 77% greater than that on Earth (Weissman 1985). For short-period comets the impact probability is 75% greater on Earth (Basaltic Volcanism Study Project 1981). Thus the cometary flux on the two planets can be considered to be equal within the limits of the other uncertainties involved in the flux estimate.

Based on these considerations we have employed a baseline comet flux which is 50% of the total flux used by Watkins (1983). This distribution is shown in Fig. 1. A pseudo-random-number generator was used to simulate a stochastic flux with this size–frequency distribution. The largest comet in our baseline distribution has a mass of 4.2×10^{19} g, having a characteristic time between impacts of 4.5×10^{9} years. The integrated mass of this flux of comets over the age of the Solar System is 5×10^{20} g. By comparison the mass which Ip and Fernandez (1987) estimated to have been received by Venus from mass loss from the Oort cloud is 6×10^{20} g over this same time period. This is independent of a much larger component of 10^{24} to 10^{25} g which would have been received by Venus in the first few hundred million years of Solar System history due to planetesimals scattered during the formation of Uranus and Neptune (Ip and Fernandez 1987). For a cometary composition of 50% H_2O by mass, an influx of 5×10^{20} g over the age of Venus would be balanced by an average escape flux of 2.5×10^{7} H atoms cm^{-2} sec^{-1}, within 25% of the present escape flux.

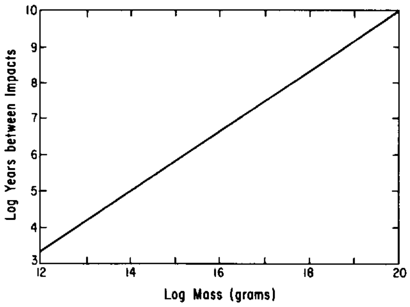

FIG. 1. Estimated comet flux on Venus. The formula for this distribution is $\log_{10}(t) = 0.8333 \ldots \times \log_{10}(M) - 6.699$, for t in years and M in grams.

Kyte and Wasson (1986) have estimated the uncertainty in the terrestrial impact flux as a factor of 4 at the low mass end of the spectrum. For larger masses the uncertainty is at least an order of magnitude, perhaps several. Our baseline flux is conservative in that we have assumed a time-independent flux, remaining at currently estimated impact rates throughout the entire history of Venus. Yet impact rates were surely greater in the past. It is not clear what fraction of the massive early bombardment suffered by the terrestrial planets was due to comets, but dynamical considerations suggest that the rate of comet impact in the early Solar System should have been greater than that at present by many orders of magnitude (Ip and Fernandez 1987). An additional potentially significant source of hydrogen which we have not included is volatile-rich asteroids, particularly that subset of Apollo asteroids that may be extinct cometary nuclei. These objects may have substantial volatile reservoirs in their interiors.

We assume a cometary composition which is 5% hydrogen by mass (Whipple 1984). We further assume that the impacting nuclei are vaporized and that the hydro-

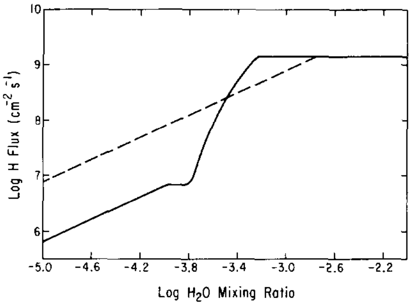

FIG. 2. Hydrogen escape flux adapted from Krasnopolsky (1985). At high f_{H_2O} the cold trap results in an escape flux which is independent of hydrogen abundance. We have extended this function to low f_{H_2O} by assuming a linear relationship. The dashed line is the diffusion-limited flux described in the text.

gen enters the atmosphere and chemically equilibrates, mostly ending up in water molecules. Both Watkins (1983) and Walker (1986) studied impact blowoff of atmospheres and concluded that it is not a significant process for Venus.

The second essential component of this model is the escape flux of hydrogen and deuterium. The function $\phi(f_{H_2O}^s)$, which describes the dependence of the hydrogen escape flux on the water mixing ratio at the surface, is quite complex, involving many different escape processes which dominate in different regimes of homopause hydrogen abundance, f_H, and several regimes of differing functional dependence of f_H on $f_{H_2O}^s$. The latter is controlled at present by the sulfuric acid trap and in larger f_{H_2O} regimes by the cold trap. This has been modeled in detail by Kumar *et al.* (1983), Kasting and Pollack (1983), and Krasnopolsky (1985). The results of this modeling are displayed graphically in Fig. 13 of Kumar *et al.* (1983) and Fig. 1b of Krasnopolsky (1985). These results differ somewhat due to different assumptions about the behavior of the sulfuric acid trap and the nature of the cold trap. We have found that these differences are not great enough to affect our results significantly. Our model employs the escape function shown in Krasnopolsky's Fig. 1b. It was necessary to extend this function to regimes of water abundance below the current abundance, where it has not been modeled in detail (since all previous models have assumed a declining water abundance). It was sufficient for our purposes to assume that in this regime the escape flux simply declines in proportion to the water abundance, as the results are not very sensitive to the detailed shape of the escape function in this region. The escape function employed is shown in Fig. 2.

We also performed some runs with escape occurring at the diffusion limit for all water abundances. For this function, also shown in Fig. 2, we used the diffusion-limited flux as a function of homopause hydrogen abundance $\phi = 4 \times 10^{13}$ (f_H) cm^{-2} sec^{-1}, given by Kasting and Pollack (1983). For the sulfuric acid trap function we used the linear function, $f_H = 2 \times 10^{-2}$ $(f_{H_2O}^s)$, given by Kumar *et al.* (1983). Krasnopolsky's treatment of this function is more complex, allowing for the dependence of f_H on the H_2O/SO_2 ratio. The use of the resulting nonlinear sulfuric acid trap function explains why the escape function shown in Fig. 2 exceeds the "diffusion-limited" flux at the upper end of the sulfuric acid trap regime, as the latter was derived using the linear assumption.

The horizontal portion of the curve in Fig. 2 represents the cold trap, with an assumed temperature of 170°K, which is the case for the present-day atmosphere (Krasnopolsky 1985). Here the escape flux becomes independent of $f_{H_2O}^s$ until the H_2O mixing ratio rises to $\approx 10\%$ at the surface, when rapid hydrodynamic escape becomes possible (Kasting and Pollack 1983). The hydrodynamic escape regime is not treated in our model, as the resulting quasi-steady-state water abundances remain well below this value.

The escaping hydrogen was integrated in million-year increments, with the amount of deuterium escaping in each increment equaling the product of the number of escaped H atoms, the instantaneous D/H ratio, and the chosen fractionation factor. In a more rigorous treatment the fractionation factor would also vary with water abundance as the relative importance of the nonthermal escape processes changed.

The number and mass of impacts were calculated at 50-million-year increments. The cumulative mass of small comets with a characteristic time between impacts of less than 50 million years was included as a constant "low mass trickle" in each increment. For the slope index used, this constituted 34% of the total flux. A simple way to modify this model to include the effect of outgassing would be to increase the value of this parameter, although there is no reason to expect that outgassed and cometary water would have the same D/H. For each 50-million-year increment the water mixing ratio, D/H ratio, cumulative cometary mass, and percentage of water of cometary origin were recorded.

MODEL RESULTS

Figure 3a shows the water abundance as a function of time for five model runs employing an impact flux equal to twice the baseline comet flux. This behavior, spikes of high f_{H_2O} corresponding to large impacts, interspersed with periods of declining water abundance, was typical of runs with a wide range of integrated impact fluxes and with diverse assumptions regarding escape behavior. Figure 3b is a histogram showing percentage of time spent in different bins of water abundance for these same five runs. Figures 4a and 4b show the behavior of the water abundance for a flux depleted by a factor of 2 relative to the baseline flux. As can be seen, the behavior is essentially identical, with the system simply spending a larger percentage of time in the lower water-abundance range. Model runs were performed with the integrated impact flux varied over two orders of magnitude, and still the behavior was similar with the histograms becoming more perturbed (Fig. 5).

The histograms each exhibit a sharp cutoff at the low water-abundance end. This corresponds to the level at which the steady "low mass trickle" for the chosen impact flux just balances the escaping hydrogen flux. The low end cutoff in the histogram for many model runs is higher than the observed 20 ppm water abundance. We do not regard this as problematical, as the uncertainties in this measurement and in many model parameters are large. The model is mainly meant to illustrate the character of the behavior to be expected in this system. In most cases however the system spent a considerable amount of time within the range of uncertainty in the current water abundance, which we consider to be 15–100 ppm.

Figure 6 shows the behavior of the D/H ratio for the same runs displayed in Fig. 5. As expected, the stochastic variation of D/H is large but the net trend is toward larger D/H as the steady state evolves. Figure 7 shows the effect of varying the D/H of the cometary hydrogen and holding all other variables constant. Clearly, the evolution of the D/H ratio is much more sensitive to choices of unknown input parameters than is the f_{H_2O} evolution, which was consistent with observations for a very wide range of assumptions. Although the D/H ratio entered the observed range for some reasonable choices of the input parameters, there were many combinations of total flux, escape function, and cometary D/H for which the planetary D/H remained well below the observed value. For example, an impact flux depleted by a factor of 8 relative to the baseline flux did not produce sufficiently enhanced D/H unless the cometary D/H was a factor of 10 greater than terrestrial. Thus our conclusions about D/H evolution based on this model cannot be as robust as those about f_{H_2O} evolution. These results led us to consider the effect of a time-dependent comet flux on the D/H ratio.

Although the model runs described up to this point have assumed no higher ancient cometary flux, this is counter to both the observational evidence contained in the cratering record of the terrestrial planets

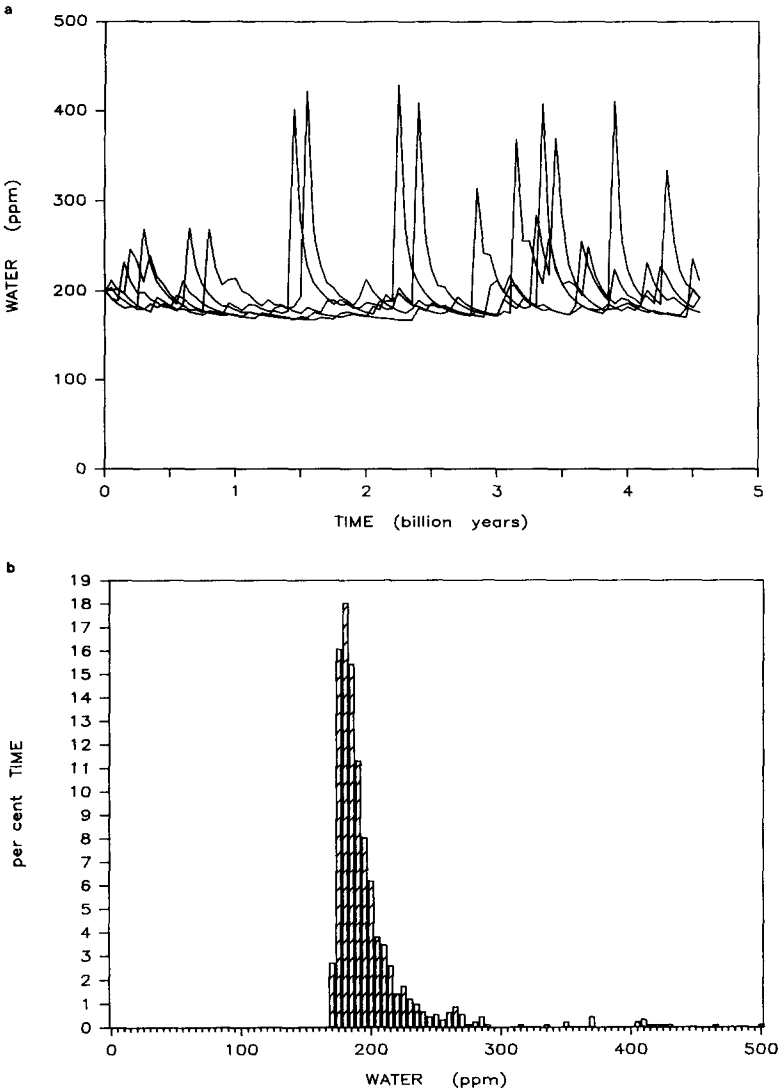

FIG. 3. (a) Five model runs for evolution of water abundance on Venus. These runs employed an impact flux equal to twice the baseline flux shown in Fig. 1. Spikes in water abundance correspond to large comet impacts. (b) Histogram for these five runs showing percentage of time spent in different bins of water abundance.

and the theoretical treatments of outer planet formation and cometary dynamics. We do not wish here to effect a precisely detailed simulation of the time dependence of this flux, but merely to explore the consequences of a past excess in impact rate which mimics to some extent those which have been postulated in the literature. Shoemaker and Wolfe (1982) suggested that the late heavy bombardment of the inner Solar System was due to comets, but Strom (1987) has offered arguments to the contrary based on detailed comparisons of the cratering records of the planets. We simply assume that the proportion of cometary objects in the total impact flux was the same in the past as it is at present.

According to the model of Hartmann

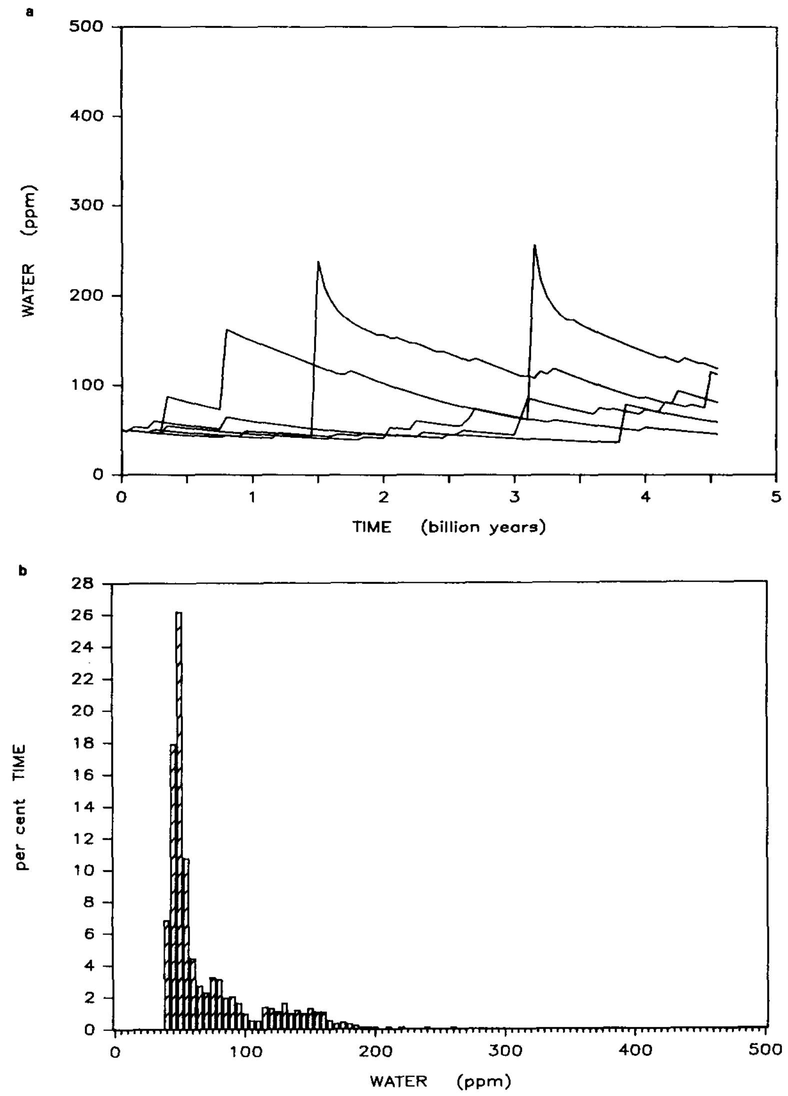

FIG. 4. (a) Results of five runs employing an impact flux depleted by a factor of 4 relative to the runs in Fig. 3. (b) Water abundance histogram for these runs.

(1987), the terrestrial impact flux 4 billion years ago was approximately 10^3 times the current flux, although the earlier, postaccretional flux must surely have been much higher. We modified our model to include an enhancement of the impact rate by 10^3 at $t = -4 \times 10^9$, decreasing with a 150-million-year half-life. This gives a total integrated flux of 2.8×10^{22} g. Compared to the 10^{24} to 10^{25} g which Venus may have received from scattered planetesimals during the formation of Uranus and Neptune (Ip and Fernandez, 1987), this is still a conservative flux estimate. The effect of this time-dependent flux on the evolution of the D/H ratio is shown in Fig. 8. Several more modest time-dependent fluxes were also run. Also shown in Fig. 8 is a run where the baseline flux is depleted by a factor of 4 and the enhancement at $t = -4 \times 10^9$ years is only a

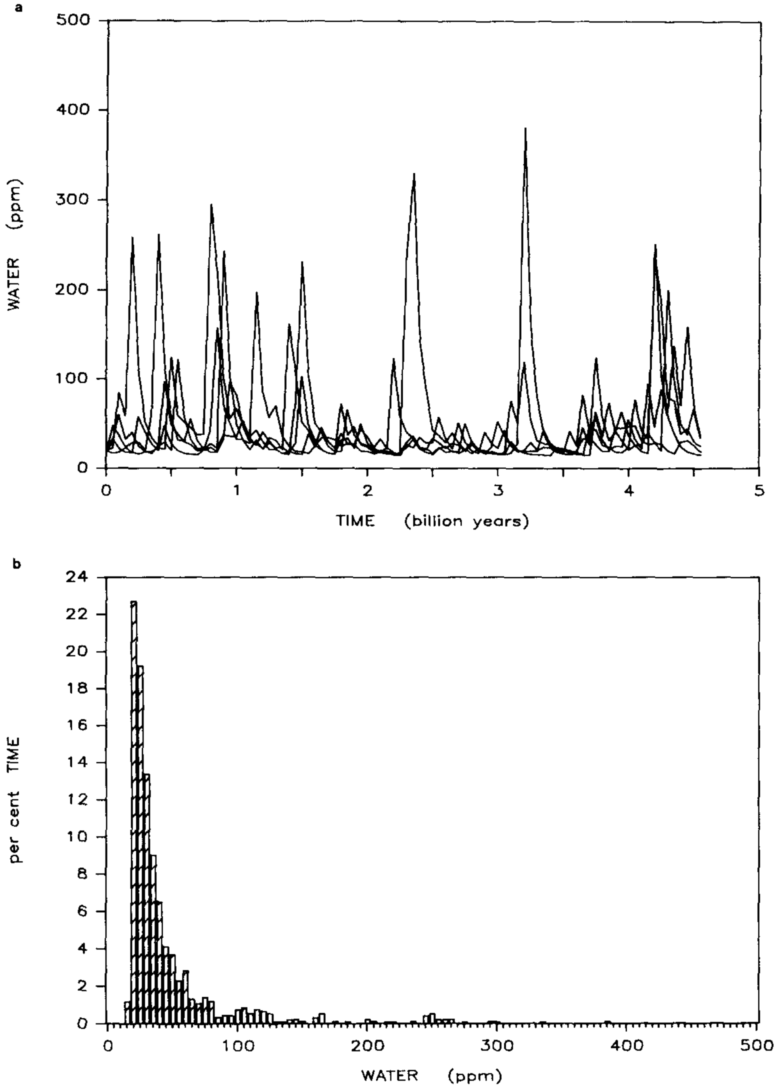

FIG. 5. (a) Five model runs with an impact flux enhanced by a factor of 2 relative to the baseline flux, and with hydrogen escaping at the diffusion limit. (b) Water abundance histogram for these runs.

factor of 500, again decaying with a half-life of 150 million years. The integrated mass of this flux model is 3.3×10^{21} g.

When the effects of such time-dependent fluxes are included, then in nearly every case the current D/H ratio on Venus is exceeded by the model results. In these runs, the large final D/H values are due to a combination of early fractionating water loss and later steady-state evolution. If the steady state were allowed to operate for long enough (several τ) then the final D/H reached would be independent of this early history, but since τ is on the order of the age of the Solar System the resulting D/H ratios are quite enhanced after 4.5 billion years. The water abundance evolution for these time-dependent runs is shown in Fig. 9. This scenario differs from the previously published models of early fractionating wa-

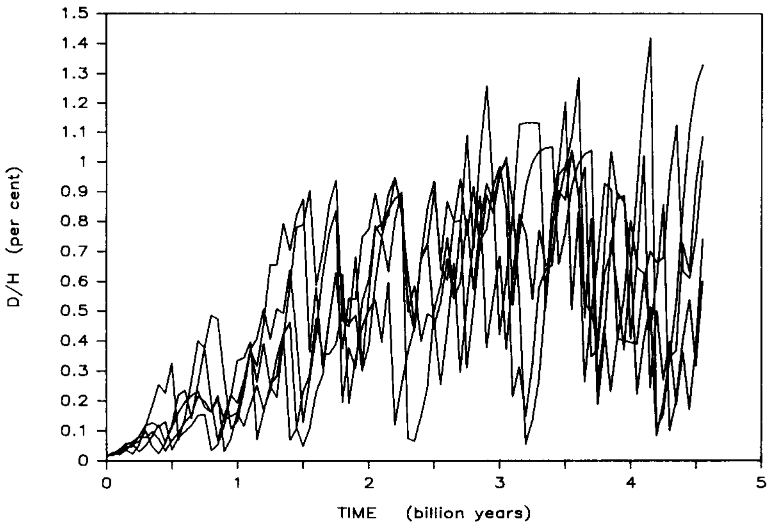

FIG. 6. Evolution of the deuterium-to-hydrogen ratio for the same runs shown in Fig. 5, employing a cometary D/H equal to the terrestrial value of 1.6×10^{-4} and a fractionation factor $f = 0.013$.

ter loss in one important respect: here none of the water excess is endogenous. The large early water abundances are simply the steady-state abundances corresponding to the massive early cometary influxes. The peak water abundances, which are off scale in Fig. 9, are approximately 27,000 and 8000 ppm for the two time-dependent fluxes described above. As the cometary flux declines exponentially to the present-day value, the water abundance declines until the escape flux balances this lower influx.

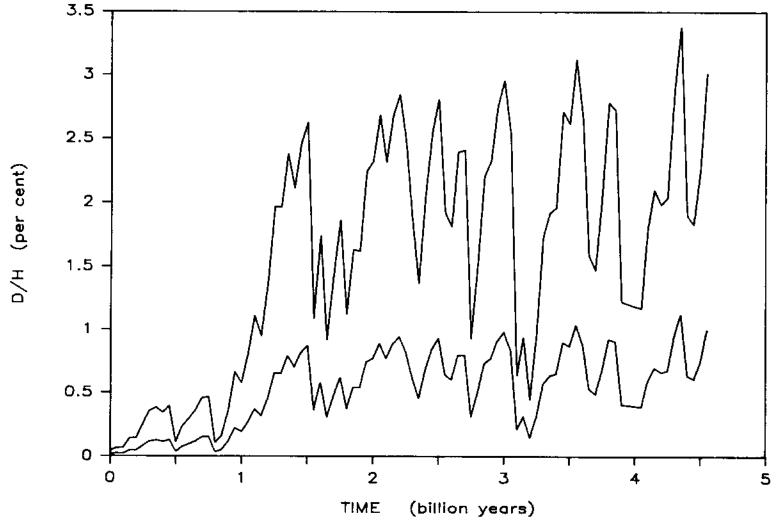

FIG. 7. The effect of cometary D/H on Venus D/H evolution. The lower curve is taken from Fig. 6, employing a terrestrial D/H value. (Note the difference in scale.) The upper curve is the same run, using a cometary D/H value of 4.8×10^{-4}, the observed upper limit for Comet Halley (Eberhardt *et al.* 1987).

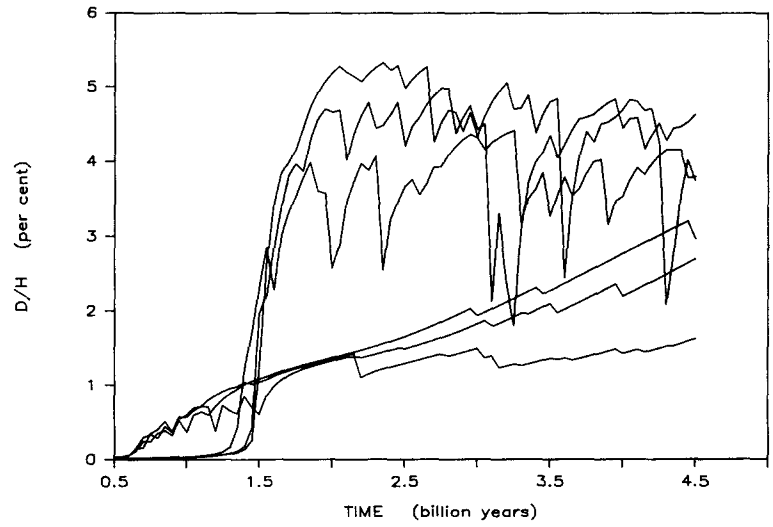

FIG. 8. D/H evolution on Venus for time-dependent comet fluxes. The three upper curves are runs with a flux enhancement of 10^3 at $t = -4.0 \times 10^9$ years, decaying with a half-life of 150 million years. The three lower curves are for a more modest enhancement which is described in the text.

The final results are water abundances which are compatible with the observed abundance on Venus and D/H ratios which are quite enhanced.

DISCUSSION

A consideration of the current lifetime of water on Venus and our model results lead us to conclude that the water abundance on Venus is likely to be in a quasi-steady state, mediated by episodic large comet impacts. Any remnant of an early Earthlike ocean on Venus is obscured by a history of random impacts. Known processes provide an explanation of the observed water abundance and D/H on Venus. There is no need to

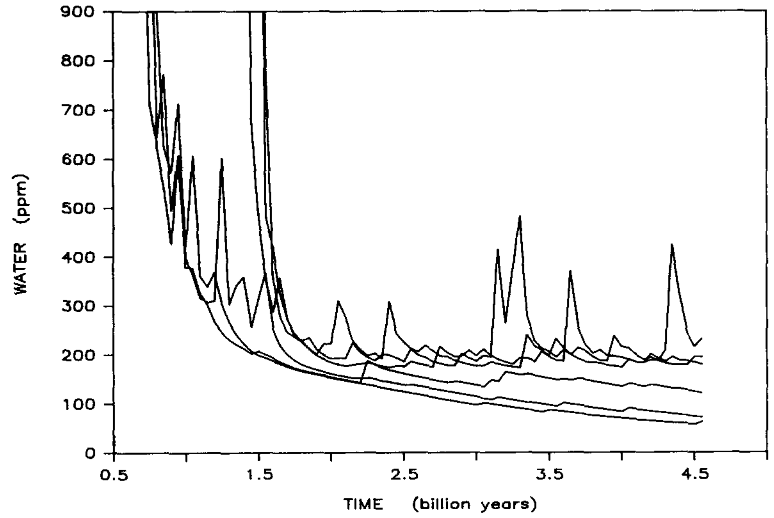

FIG. 9. Water abundance evolution for the same runs shown in Fig. 8. The peak abundances, which are off scale, are discussed in the text.

postulate an unknown source of early water and no evidence that there was one. Outgassing may have contributed as well, but no endogenous source of water is necessary to explain the observations. The water now observed on Venus is quite possibly more than 99% of cometary origin.

The observed deuterium to hydrogen ratio may not be evidence of a "primordial" water excess on Venus. If an early water excess is responsible in part for the current D/H, it is likely to have been the steady-state water abundance for an enhanced cometary flux. This ratio is coupled in a complex relationship to the average cometary D/H, the time-integrated cometary flux and any time dependence in the flux, and the actual mass and D/H of any large comets which may have impacted on Venus in the last several hundred million years.

In a similar fashion, the current water abundance on Venus may depend critically on the recent comet impact history of the planet as well as on the average flux and outgassing history. This stochastic variability, as illustrated in Figs. 3 through 5, must add an unavoidable level of uncertainty to any deterministic interpretations of these observations.

It is possible that these stochastic variations in water abundance will be damped by surface-atmosphere buffering reactions of the kind described by Nozette and Lewis (1982). Characterization of the time scale for this buffering is difficult as it depends on such poorly known parameters as diffusion rates through the surface material, particle sizes, and the rates of many heterogeneous reactions which have not been well studied. If there is not significant damping, these oscillations in water abundance may have important implications for the climate history of the planet; water is an important IR absorber which helps to maintain the strong greenhouse.

When a consideration of the likely time dependence of the comet flux is included in the model, then the problem of explaining the current D/H ratio becomes one of explaining why it is so low compared to model results. This could put constraints on the magnitude of any past increase in the cometary flux. However, the attempt to define such constraints will be hampered by the difficulty in determining how the fractionation factor varies with escape flux. The fractionation factor is likely to be higher than at present for enhanced escape fluxes (Krasnopolsky 1985, Kasting *et al.* 1984). This would lower the final D/H for the time-dependent case, possibly reconciling the enhanced values shown in Fig. 8 with the observed values. Chyba (1987) has used scaling arguments to conclude from the lunar impact record that if a small fraction of the late heavy bombardment impact flux was composed of cometary objects then the Earth's oceans could have been fully supplied by cometary water. Under such a scenario Venus should have received similar amounts of water, yet the low D/H may be problematical. A continuous outgassing of juvenile water, as proposed by Kumar *et al.* (1983) and Kasting and Pollack (1983), could help to lower the D/H. As can be seen by examining Eqs. (2) and (4), this would have the effect of lowering the time constant for the steady-state D/H value to be reached. In this case the steady-state value would be that given in Eq. (3) with α being a weighted average of the outgassed and cometary D/H values. Another possible explanation is that Venus has recently (within 10^8 years) suffered a large comet impact which lowered the D/H ratio to the observed value. If the terminal cretaceous event on Earth was caused by a comet shower, rather than by a single large impact, then the water abundance and D/H ratio on Venus should bear the signature of this same catastrophe.

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