VENUS: WHERE HAS ALL THE WATER GONE?*

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Abstract. Conditions on the surface of venus are reviewed and evidence for the existence of a hydrosphere assessed. Escape mechanisms are examined and found to be insufficient to explain the presumed absence of liquid water on venus. The consequences of a hot, acidic hydrosphere are explored as is marginal evidence for biological activity.

Although Venus is the planet which most closely resembles the earth in size, mass and other physical characteristics, it has been generally depicted as hot, waterless and lifeless. The presumed hostile environment on Venus has even led to speculation that planetary probes designed to enter the Cytherean atmosphere need not be sterilized because the estimated temperatures of the atmosphere and surface are much higher than any contemplated in sterilization procedures (Hunten and Goody, 1969.) Principally, there are two reasons for postulating a complete absence of terrestrial type life forms on Venus; high surface temperatures and the presumed absence of liquid water.

The question of the surface temperature of Venus is open; recent estimates range from less than 350 K to over 800 K depending on the latitude, the solar radiation or the observational method employed. The most popular model used to explain these temperatures, which appear high in comparison to earth, is the 'greenhouse' model originally put forth by Sagan (1961). Briefly, this model explains the high Cytherean surface temperature by postulating an atmosphere that is transparent to the visible spectrum and opaque to the infrared. Hunten *et al.* (1969) have examined the 'greenhouse' model and revealed some flaws. The main criticism is that although the atmosphere must be extremely opaque to the infrared, visible radiation must penetrate with little absorption to great depths. In view of the recent findings on the density of the atmosphere (Johnson, 1968) and the cloud layers, penetration of the necessary amount of radiation becomes questionable. Further, such high temperatures as have been postulated for the surface would necessarily suggest loss of heat through convection currents. Mintz (1961) stated that the differential heating by incoming radiation on a slowly rotating planet should set up large scale meridional circulation which, along with thermal convection, should transport heat vertically and severely limit the greenhouse effect. Even if the greenhouse theory proves to be correct, temperatures may not be excessive. Owen (1965) has predicted a temperature of 540 K as the minimum dark side temperature.

Samuelson (1968) analyzed the particulate medium in the atmosphere of Venus

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and concluded that the 'greenhouse' effect which this cloud cover would provide could only account for a maximum temperature of 507 K at the equator. Presumably polar temperatures would be much less. Carbon dioxide in the atmosphere would increase this figure but convection currents would lower it substantially. He further stated that any cloud cover that could be proposed would scatter and absorb too much radiation to permit average equatorial temperature to reach 600 K, even without adverse effects such as convection. A polar temperature of 470 ± 95 K was published by Pollack and Sagan (1965).

The question of whether or not there is free water on the surface of Venus has been argued but not resolved. Spectroscopic evidence does not give a definitive answer as to the presence of free water, although Firsoff (1968) after reviewing available spectroscopic data (e.g. Dollfus, 1961) concluded that water is not only present but abundant on Venus. Still, it must be remembered that earth-based observations cannot penetrate the uppermost clouds and so are limited to the upper 0.1% of the atmospheric mass (Hunten and Goody, 1969). After reviewing the arguments for and against water on Venus, with particular reference to the nature of the cloud layer, Arking and Potter (1968) decided that uncertainties regarding the principle constitutent of the cloud layer have not been resolved but calculations comparing a model of a terrestrial cloud containing spherical droplets or ice particles provided good agreement with the phase curve of Venus, considerably better than that obtained with other scattering diagrams. Their calculations support a water cloud hypothesis.

Why then, is Venus assumed to be dry? This question warrants consideration. If Venus is indeed without water there can only be two possibilities; one, that the planet never possessed the same amount of water as the earth and two, that Venus has lost all of its water by some mechanism. The first possibility, that Venus never had as much water as did the earth is essentially unanswerable because there is no first hand evidence on the methods by which proto-planets condense and exactly how relative abundances of elements are distributed. However, it is not at all unreasonable to assume that Venus formed in a similar manner as the earth and that elemental abundances on Venus should be reasonably close to those found on the earth. These assumptions are further supported by the fact that Venus has a mass and gravitational field strength that are close to terrestrial values.

If it is assumed that Venus had water proportional by mass ratio to the amount the earth had during formation, examination should be made of all the possible methods by which water can be lost, bound, or in some way excluded from existing in a liquid phase. Four possible methods that can explain the absence of free liquid water on a terrestrial type planet are; loss by photodissociation, binding as water of hydration or absorption, direct loss into space, and existence of water in only the vapor state. These possibilities are considered below.

Photodissociation cannot account for the loss of a large volume of water from Venus. Donahue (1968) stated that if Venus lost as much water as is stored on the surface of the earth an escape flux of 10^{11} atoms-cm^{-2}-sec^{-1} would be needed during a large part of the planet's history. At present, the rate on the earth is 10^{8} atoms-cm^{-2}-

sec^{-1}. It is difficult to see how the photodissociation rate of H_2O, with consequent loss of H_2, could approach the level of 10^{11} atoms-cm^{-2}-sec^{-1}. Further, the decomposition of water cannot occur below the tropopause on Venus because of the absorption of light in the Schumann region. This absorption would be substantially complete if 100 cm-atm of carbon dioxide is present above the tropopause (Urey, 1959). The massive carbon dioxide content of the Cytherean atmosphere would certainly be sufficient for this effect. It may be concluded that if Venus lost all her free water, some mechanism other than photodissociation must be postulated to account for it.

Another possibility is that water on Venus is held as interstitial or absorbed water in the crust of the planet. This is untenable because temperatures of 420 K are sufficient to dehydrate minerals of this type of water (Van Lopik and Westhusing, 1963). The presumed Cytherean surface conditions are sufficient to reduce bound water content. It is extremely difficult to conceive of large volumes of water held by hydration under elevated temperatures.

On the earth and Venus direct loss of water into space is governed by two factors; the escape velocity that a molecule must achieve to leave the planet and the upper atmospheric cold trap. The average velocity of any given molecule is a function of the temperature so the second factor governs the first to a large degree. There is a minimum temperature corresponding to the saturation vapor pressure below which water is prevented from diffusing into the upper atmosphere (Jastrow, 1964). Below 235 K water vapor cannot diffuse upward. Mariner 5 data has shown cytherean exospheric temperatures below this figure (Johnson, 1968). It is unlikely that either the earth or Venus has lost appreciable amounts of water by direct escape.

Could large volumes of water exist on Venus in only the vapor state? Might not this argument be supported by the high temperatures prevalent on Venus? If the total water supply of Venus is assumed to be 81% of that of the earth (Venus has 0.81 earth mass) this leads to a presumed volume of 1.116×10^9 km^3 water in the liquid state. The maximum amount that can exist in the vapor phase, determined for a temperature of 500 K and an atmospheric volume of 18.45×10^9 km^3 is 0.211×10^9 km^3 or 20% of the presumed total. This figure assumes a lower atmosphere 40 km thick. Therefore, if Venus possesses as much water proportionally as does the earth, 80% of it must be in the liquid state. Further, this is a 'worst case' assumption because this figure was calculated for 100% saturation of the entire lower atmosphere and 500 K as a uniform temperature. Lower temperatures due to the lapse rate and lower relative humidity due to local or widespread unsaturation would decrease the amount of water present as vapor to a large degree.

It may be concluded that unless one of the mechanisms explaining the absence of liquid water on Venus described above (photodissociation, hydration, direct loss into space, all water present as vapor) has been seriously underestimated, then Venus should now possess a hydrosphere. The depicting of Venus as hot and consequently dry has in the opinion of the authors been too readily accepted without sufficient proof. An example of this type of thinking is shown in a paper by Vinogradov *et al.* (1968), in which it is categorically stated: "The conditions on Venus obtained by Venera 4 exclude the existence of a hydrosphere because water boils at a temperature higher than 100°C." Water does boil at 100°C but only on the earth at sea level. At 100°C the vapor pressure of water reaches one atmosphere which is ambient pressure for the earth. Venus, however, possesses atmospheric pressures estimated as high as 200 atm (Johnson, 1968). At 200 atm pressure, a temperature of 367°C (640K) is needed to boil water. Figure 1 shows a vapor pressure vs temperature plot for water, below the

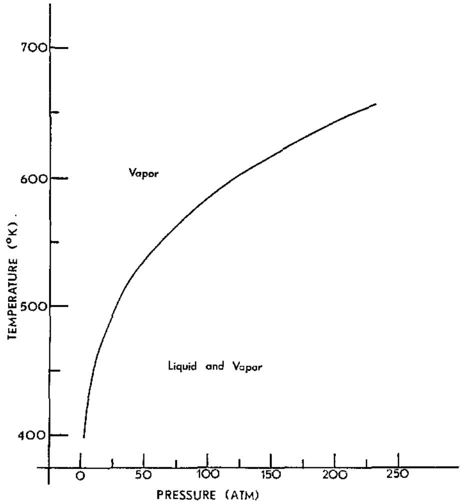

Fig. 1. Vapor pressure of water as a function of temperature.

line water can exist as either a liquid or a vapor (Weast, 1968). If conditions on the surface of Venus are in the temperature-pressure range below the curve, water may exist in the liquid state. The authors suggest that the hot, dry interpretations of Venus need critical examination. Venus should be examined as objectively as possible without misconstrued terrestrial (Ptolemaic) analogies.

In some cases, however, comparisons to earth are necessitated because of complete lack of data. For example, since there is no definitive or even experimental knowledge of the conditions that prevailed during the formation of earth and Venus, the only basis we can theorize on is that elemental abundances were similar for the two forming planets. Although this tenet cannot be proven at present, it is a reasonable assumption.

There have been theoretical explanations that account for a dry Venus. One line of reasoning, made by Urey (1952; see also Dole, 1959), which suggests the absence of water on Venus, was that an excess of atmospheric carbon dioxide could only result from the inability of CO_2 to react rapidly with silicates in the presence of water to be sequestered as carbonates:

$$CO_2 + MeSiO_3 \overset{HOH}{\rightleftharpoons} MeCO_3 + SiO_2.$$

Without water this reaction would be extremely slow and high atmospheric CO_2 contents would be expected, such as found on Venus.

The above reaction is driven to the right under terrestrial conditions of 300 K, ocean pH of approximately 8 and a low CO_2 partial pressure. Under Cytherean temperatures of 500 K, carbonates are unstable; CO_2 and metal silicates are favored. Also with an abundance of CO_2, initially due to outgassing by higher insolation, the pH of the Cytherean hydrosphere would be acid due to massive amounts of dissolved CO_2 forming H_2CO_3. Thus, the higher temperature and CO_2 pressure of Venus would favor decomposition of carbonates under acid pH and would lead to the observed massive atmospheric CO_2 content. On both the hydrosphere of the earth and the pressurized hydrosphere of Venus, pH is determined by the CO_2-carbonate buffer system. However with a 300000 fold excess of CO_2 on Venus this buffer system will be displaced from the mild alkaline terrestrial conditions to a pH under 5.

Acceptance of the above arguments leads to the conclusion that Venus possesses a hot, acidic hydrosphere. Consequently, it may be expected that exposed surfaces (if any) on Venus would be subjected to extremely rapid weathering due to leaching of minerals by the hot, acidic waters. The oceans or seas would be highly saline on account of the rapid weathering process and the elevated solubility of salts in hot water. Large amounts of solutes raise the boiling point of water (or lower the vapor pressure at a given temperature) and increasing amounts of salts would further shift the liquid-vapor equilibrium toward the liquid state. An intriguing, though not necessarily related, consequence of highly saline seas is that biological polymers are stabilized in solutions with high total ionic strength (Tanford, 1962).

Venera 4 data indicate the presence of free oxygen on Venus in concentrations of 0.1–1.0% by volume (Vinogradov *et al.*, 1968). Prior studies substantiate this observation (Prokofyev and Petrova, 1963; Prokofyev, 1964). At a surface pressure of 10^5 mb this corresponds to 10^2 to 10^3 mb partial pressure of oxygen, similar to or exceeding terrestrial oxygen pressures. Berkner and Marshall (1965) have convincingly shown that the preponderance of earth's present high O_2 pressures is due to photosynthesis. In short, a steady state system (i.e. biological) is required to maintain high free atmospheric O_2 levels. There is no apparent reason why this same logic cannot be applied to Venus. Although Cytherean temperatures and pressures are certainly hostile to terrestrial life, no drastic alteration in any facet of general terrestrial biochemistry is required to permit existence of a Cytherean biosphere. On earth, organisms will survive (or grow) at temperatures close to the local boiling point of water (Vallentyne, 1963), under high hydrostatic pressure marine organisms grow at 104°C (ZoBell, 1958). Certainly tertiary structure of terrestrial catalytic proteins will be abolished by thermal dissociation of a small number of weak (hydrogen, van der Waals) bonds. One can imagine local Cytherean selection for proteins which are catalytic when extended and/or for proteins the tertiary structure of which is stabilized by a larger number of weak and ionic bonds. The undoubted extreme high ionic strength of the postulated hydrosphere would also serve in general to stabilize biological tertiary structures.

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