3

Venus: A Search for Clues to Early Biological Possibilities

L. Colin and J. F. Kasting

Extant life on Venus is out of the question. The current atmospheric environment at the surface of the planet is far too hostile, by benign terrestrial standards, to support life or to participate in the origin of life. In the first part of this paper, we will summarize the extensive evidence for this assertion.

If the assertion is correct, then why are exobiologists at all interested in Venus? One answer to this question involves the possibility of *extinct* life. Although few scientists would consider this to be very likely, life may have had some chance to originate on Venus because Venus may have been considerably more Earth-like in its past. A second answer is that the study of Venus may teach us something about life on Earth, even if Venus itself has always been lifeless. In particular, Venus may tell us what the physical limits are on the habitability of

an Earth-like planet and how likely it is that other habitable planets exist elsewhere in the galaxy.

In the second part of this paper, we will address these fundamental questions. But before we do so, we must discuss the current state of the planet and its environment. Knowledge of origin and evolution can only be inferred using the knowledge of the present state of the planet along with appropriate theory and modeling.

It should be noted that for Mars, the possibility of *extant* life has not been ruled out, even by the Viking missions. Future missions to the red planet will thus be instrumented to search for signs of both *extant* and *extinct* life, although the latter is being given highest priority. For Venus, only *extinct* life is feasible, but the environment is so hostile that it will be very difficult, and probably impossible with current technology, to even plan for such a mission in this century.

Current State of Venus and its Environment

Venus has been the target of more unmanned, scientifically instrumented, interplanetary spacecraft than any other object in the solar system (table 3-1). The Soviet Union, until recently when it announced its intention to switch its focus to Mars for the remainder of the century, at least, has historically concentrated its solar system exploration program on Venus. From 1961 through 1985 they sent Venera and Vega planetary flybys, planetary orbiters, atmospheric entry probes/surface landers, and balloons to our nearest neighbor.

The United States, although spreading its resources on spacecraft missions designed to visit most of the planets of the solar system in a more "balanced" program, also launched Mariner and Pioneer planetary flybys, planetary orbiters, and atmospheric entry probes to Venus from 1962 to 1978. The Pioneer Venus Orbiter, after 13 years in orbit, continues to collect and telemeter valuable data back to Earth. Magellan, an orbiter dedicated to high resolution surface mapping and gravity observations of Venus, was launched in 1989. It is currently on an extended phase after completing its highly successful nominal mission. The result of these many, sophisticated missions is a set of data and understanding unmatched by any planet except our own. In this part of the paper, we summarize only that data and understanding critical to the questions posed by exobiologists.

When one looks at those critical characteristics of a planetary environment most pertinent to exobiology, one is immediately struck by the extreme values associated with Venus (table 3-2). For example, the average surface temperature of Venus is 464°C (867°F)—about twice as hot as the maximum setting on a kitchen oven! Furthermore, the surface temperature does not vary from this figure by more than a few degrees centigrade from noon to midnight, or from equator to pole, perhaps 5-15°C. This contrasts sharply with an average surface temperature of 15°C (59°F) on Earth, with noon-midnight average differences of 10°C and equator-pole average differences of 45°C.

Table 3-1: Planetary Spacecraft Missions to Venus

Name	Launch date	Remarks
Venera 1	2/12/61	Attempted flyby. Contact lost 2/27/61. Estimated to have passed within 100,000 km of Venus and continued into heliocentric orbit. Considered failure.
Mariner 1	7/22/62	Attempted flyby. Booster destroyed by ground control after 5 min of flight. Considered failure.
Mariner 2	8/27/62	Flyby 12/14/62 at 34,833 km closest approach. First successful probe to another planet.
Venera 2	11/12/65	Flyby 2/27/66 at 24,000 km closest approach. Communication failed just before flyby. Considered failure.
Venera 3	11/16/65	Atmospheric entry probe. Communication link failed just before entry 3/1/66. Considered failure.
Venera 4	6/12/67	Atmosphere entry probe. Entered 10/18/67. Radio transmitter failed at 27 km altitude. First successful USSR mission.
Mariner 5	6/14/67	Flyby 10/19/67 at 3391 km closest approach.
Venera 5	1/5/69	Atmospheric entry probe/soft lander. Entered 5/16/69. Radio signals from probe ceased at 25 km altitude.
Venera 6	1/10/69	Atmospheric entry probe/soft lander. Entered 5/17/69. Radio signals from probe ceased at 11 km.
Venera 7	8/17/70	Atmospheric entry probe/soft lander. Entered 12/15/70. Transmitted onsurface for 23 min.
Venera 8	3/26/72	Atmospheric entry probe/soft lander. Entered 7/22/72. Transmitted on surface for 50 min.
Mariner 10	11/3/73	Flyby 2/5/74 at 5793 km closest approach.
Venera 9	6/8/75	Combined orbiter and atmospheric entry probe/soft lander. Orbit insertion and entry 10/22/75. Transmitted on surface for 53 min.
Venera 10	6/14/75	Combined orbiter and atmospheric entry probe/soft lander. Orbit insertion and entry 10/25/75. Transmitted on surface for 65 min.
Pioneer Venus 1	5/20/78	Orbiter. Inserted 12/4/78. Spacecraft still functional.
Pioneer Venus 2	8/8/78	Multiple atmospheric entry probes (4) plus upper atmosphere probe (Probe Bus). Entered 12/9/78.
Venera 11	9/9/78	Combined flyby and atmospheric entry probe/soft lander. Entered 12/21/78. Transmitted on surface for 95 min. Flyby 12/21/78 at 25,000 km closest approach.
Venera 12	9/14/78	Combined flyby and atmospheric entry probe/soft lander. Entered 12/25/78. Transmitted on surface for 110 min. Flyby 12/25/78 at 25,000 km closest approach.
Venera 13	10/30/81	Combined flyby and atmospheric entry probe/soft lander. Entered 3/2/82. Transmitted on surface for 127 min.
Venera 14	11/4/81	Combined flyby and atmospheric entry probe/soft lander. Entered 3/5/82. Transmitted on surface for 53 min.
Venera 15	6/2/83	Orbiter Radar Mapper. Inserted 10/10/83.
Venera 16	6/7/83	Orbiter Radar Mapper. Inserted 10/14/83.
Vega 1	12/15/84	Combined balloon and atmospheric entry probe/soft lander. Entered 6/10/85. Balloon operated at 55 km altitude for 2 days. Transmitted on surface for 56 min.
Vega 2	12/21/84	Combined balloon and atmospheric entry probe/soft lander. Entered 6/15/85. Balloon operated at 55 km altitude for 2 days. Transmitted on surface for 57 min.
Magellan	1989	Orbiter Radar Mapper. Spacecraft still functional.

Table 3-2: Venus-Earth Comparisons

Parameter	Earth	Venus
Mass (Earth = 1)	1.000	0.815
Mean radius, km	6378	6051.5
Oblateness	0.003	0
Mean planet density, gm cm^{-3}	5.52	5.24
Surface gravity (Earth = 1)	1.00	0.88
Escape velocity, km sec^{-1}	11.2	10.4
Mean solar distance, AU	1.000	0.723
Solar constant, kw m^{-2}	1.38	2.62
Solar revolution period, days	365.26	224.7
Rotational period	$23^h56^m23^s$ E	243.01 days W
Sol-Earth days	1	117
Orbital eccentricity	0.017	0.007
Inclination to orbit plane, deg	23.45	177.4*
Orbit inclination to ecliptic, deg	3.394	0.000
Magnetic moment, gauss cm^{-3}	7.91×10^{25}	$<10^{22}$
Bond albedo	0.30	0.77
Effective temperature, K	255	229
Average surface temperature, K	288	737
Greenhouse magnitude, K	33	508
Mean surface pressure, bars	1.013	95
Atmosphere/planet mass	8.8×10^{-7}	9.81×10^{-5}
Total surface relief, km	20	13

*Inclinations >90° imply retrograde rotation.

It is tempting to explain the difference in average surface temperatures between Venus and Earth by the fact that Venus is much closer to the Sun. This fact is, of course, true and, furthermore, it is certainly true that solar radiation is overwhelmingly the most important energy source for heating the terrestrial atmospheres. Internal heat sources are important only for the outer, giant gas planets.

The solar flux at the mean orbital distance of Venus is some 1.9 times that at Earth, since Venus' mean distance from the Sun is 0.72 astronomical units (AU) compared with the Earth value of 1.00 AU (fig. 3-1). However, the Bond albedo of Venus is significantly higher than that of Earth, 0.77 versus 0.30, so that a much larger fraction of the incident solar flux is reflected back into space. The net result is that Venus absorbs almost 40% less energy than does Earth, or only slightly more energy than is absorbed by Mars.

Venus' albedo is larger than that of Earth primarily because of the ubiquitous nature of its clouds. Venus is 100% cloud covered at all times, whereas Earth is about 50% cloud covered at any time. On Venus, most of the absorbed solar radiation occurs in the clouds, and only a small percentage reaches the ground. On Earth, most of the incident solar radiation is absorbed at the ground.

All of this suggests that the surface temperature of Venus should be colder than the surface temperature at Earth, not hotter. If the amount of absorbed solar energy were the only important factor, Venus and Earth would have surface temperatures of –44°C and –18°C, respectively.

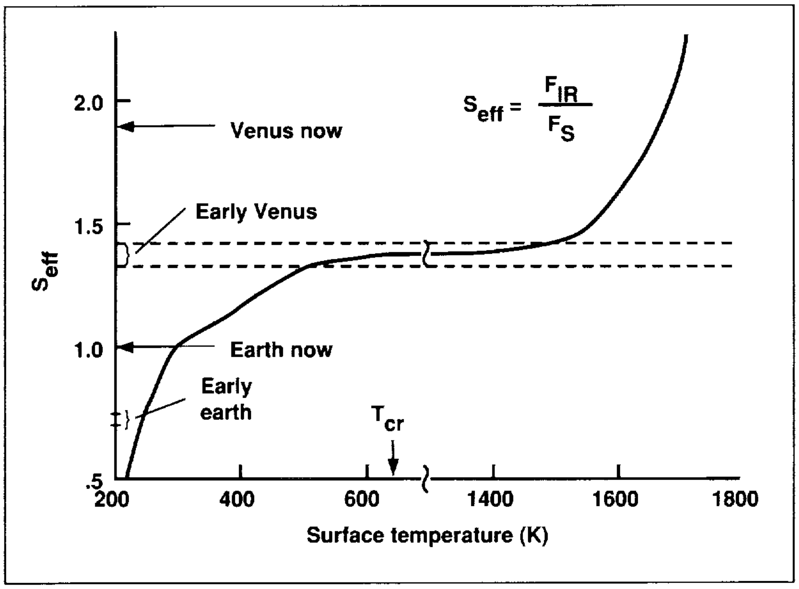


Figure 3-1. Effective solar constant S_{eff}. The horizontal dashed lines represent estimates of the solar flux at Venus orbit 4.6 billion years ago. There is a break in the horizontal scale between 700 and 1300 K.

Eventually, a balance is struck between the incoming solar energy and the outgoing infrared energy resulting in a stable temperature at the surface. The average temperature of the Earth is 15°C, or some 33°C higher than it would have been without the Greenhouse Effect. For Venus, the average temperature is 464°C, 508°C of which is caused by greenhouse warming. The much larger Greenhouse Effect on Venus is a consequence of its dense carbon dioxide atmosphere (fig. 3-2).

Clearly, something has been left out of our argument—the Greenhouse Effect. The Greenhouse Effect has become a household word in recent years as the Earth's atmosphere has been warmed by the injection of carbon dioxide and other pollutants. Briefly, the way this effect works is as follows. The solar radiation is spread out over a fairly broad fraction of the electromagnetic spectrum—from the ultraviolet through the visible into the infrared. However, the bulk of the energy is concentrated in the visible, where the atmosphere of Earth, and to a lesser extent the atmosphere of Venus, is largely transparent. Thus, visible radiation reaches the surface and heats it. The heated surface reradiates this energy as heat, or infrared radiation. Certain atmospheric gases, notably carbon dioxide and water vapor, absorb strongly in the infrared, rendering the atmosphere partially opaque at those wavelengths. Thus, the atmosphere itself becomes heated, and radiates in the infrared. Some of this energy escapes to space and some of it heats the surface still further.

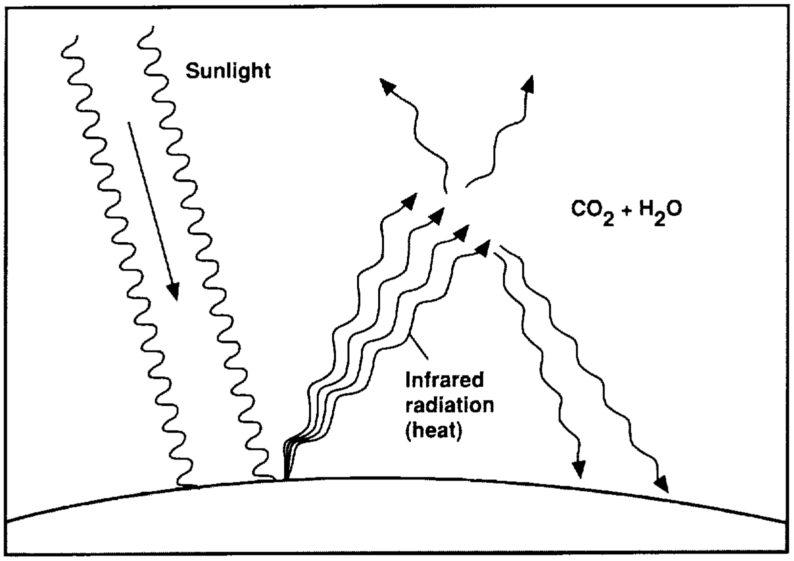


Figure 3-2. Greenhouse Effect occurs when certain gases, notably carbon dioxide and water vapor, warm the surface of a planet. Such gases allow light from the sun to reach the planet, but they intercept the infrared rays (heat) that the planet radiates into space and reradiate much of this energy toward the surface. The gases raise the Earth's surface temperature some 35°C above what it would be if they were absent.

Another interesting difference between Venus and Earth concerns short-term (diurnal) temperature variations. It is important to recognize that a day on Venus is much different than on Earth. Because of Venus' comparable orbital period (about the Sun)—224.7 days—and spin period (about its axis, retrograde)—243 days—Venus has a "day" equal to 117 Earth days. Thus, the observation that the noon and midnight surfaces differ in temperature by only a few degrees is even more impressive. There would appear to be plenty of time for a region in the long night sector to cool off, by radiating its heat to space. Since this is not the case, we must conclude that the flow of heat around the planet is efficient and very rapid. A more precise way of stating this is to say that the time constant for heat transport is much shorter than the time constant for radiative transport. The radiative time constant at the surface of Venus, that is the heat capacity of the atmosphere divided by the outgoing infrared flux, is about 127 Earth years, much longer than the lengthy Venus day. The equivalent time constant for Earth is about four months.

Seasonal variations are also much smaller on Venus. One reason is that Venus has a very small orbital eccentricity about the Sun (0.007) compared with a value of 0.017 for Earth. Thus, the distance between Venus and the Sun varies only slightly from "summer" to "winter." Venus' obliquity, that is, the angle between its spin axis and the normal to its orbital plane, is also very small, 2.5°, compared to 23.5° for the Earth. Thus the northern and southern hemispheres receive essentially equal amounts of radiation year round.

The cause of these extreme temperature conditions on Venus is its extremely massive atmosphere. At the mean planet radius, the atmospheric pressure is 95 bars (1.013 bar = 1 atm = 1.013×10^6 dynes cm^{-2}). Since the mean molecular weight is 43.44, the atmospheric column density is about 65 kg m^{-3}. Thus the Venus atmosphere is nearly 100 times denser than that of Earth.

The Venus atmosphere near the surface is composed of two major gases: carbon dioxide (CO_2) and molecular nitrogen (N_2). The volume mixing ratios of these two gases are about 96.5% and 3.5%, respectively. Many other gases have been measured in trace amounts and others are suspected. For many of the measured trace constituents there is significant controversy as to their precise relative abundances.

It may seem surprising to the uninitiated that CO_2 is the major gas in the Venus atmosphere given that it is only a minor constituent (0.034%) in the Earth's atmosphere. It is, of course, an important trace constituent to the life cycle because of the role it plays in photosynthesis. Most of the CO_2 on Earth, however, is locked up as (calcium and magnesium) carbonates in rocks. These carbonate rocks are formed by reactions that take place in liquid water. The lack of an ocean and thus a hydrological cycle on Venus has allowed nearly all the planet's CO_2 to remain in the atmosphere. The total inventory of CO_2 on each planet is, in fact, practically the same. As on Earth, other trace atmospheric constituents play important roles in the physics and chemistry of the planet, e.g., as catalysts in chemical and photochemical processes, in meteorological processes, and in atmosphere-surface interactions. Unlike Earth, these processes are strictly abiotic on Venus. On the Earth, the two major gases, molecular nitrogen (N_2) and molecular oxygen (O_2), and many of the trace constituents have biological processes as their major sources and major sinks. On Venus, the source of N_2 is outgassing from the interior of the planet, and sinks are non-existent. Attempts at measuring O_2 have not been successful. The important role that life plays in the chemical make-up of Earth's atmosphere makes any comparison of the atmospheres of Venus and Earth almost moot. Earth's atmosphere would not be anything like it is today, had life not formed and flourished.

Another trace gas (with a maximum mixing ratio of 1×10^{-7}) on Earth of critical importance to the survival of life is ozone (O_3). Found mainly in the stratosphere, it effectively absorbs solar ultraviolet radiation that would be lethal to life. Scientists have so far been unable to identify any ozone at Venus, but have been able to set an upper limit to its mixing ratio of 1×10^{-6} to 1×10^{-7}.

From an exobiologist's viewpoint, liquid water on the surface and water vapor (H_2O) in the atmosphere are essential. Liquid water cannot exist on the surface of Venus because the surface temperature exceeds the critical temperature of water, 374°C. (The critical temperature is the highest temperature at which the liquid phase can exist.) Thus, any liquid water that may once have existed on the surface of Venus would have evaporated into the atmosphere. However, today we find very little water vapor in the atmosphere. The precise volume mixing ratio is controversial, but it appears to be 2×10^{-4} or less in the lower atmosphere. The variable mixing ratio of water vapor in the Earth's atmosphere is about 4×10^{-2} or less; here, of course, atmospheric water vapor is in contact with a much larger water reservoir—the oceans.

Whether Venus formed with liquid water on its surface, acquired it somehow in its early history and lost it through evaporation, is unknown and controversial. It is the subject of the second part of this paper. But if it did have an ocean and lost it through evaporation to the atmosphere, then where did the water vapor go?

One likely possibility is that the vapor was photolyzed by solar ultraviolet radiation into hydrogen and oxygen. One might then expect to find these remnants in the atmosphere. However, current measurements suggest only trace amounts of each, perhaps 0.002% to 0.003% by volume. If these gases are not in the atmosphere, where else might they be?

The hydrogen molecules may have been photolyzed into hydrogen atoms which, being light, may have escaped Venus' gravity into space. The oxygen atoms from the photolyzed water vapor may have reacted with surface materials to become locked in the regolith and lithosphere. At any rate, the question of water on Venus in its earlier history is still open.

Another non-biological reason for the importance of water is its role as an infrared-active gas in the "Runaway Greenhouse Effect." Recall that we postponed distinguishing it, with its apparent important part it plays at Venus, from the "ordinary" Greenhouse Effect operative for Earth. The following "idea experiment" nicely illustrates the Runaway Greenhouse Effect.

Suppose we were to move Earth from its current position (1.00 AU) to the position of Venus (0.72 AU). The consequences would be

1. Oceans become warmer;

2. More water evaporates;

3. Increased water vapor in the atmosphere blocks infrared radiation from the surface, thereby increasing the surface temperature.

The cycle would repeat until

1. Oceans boil away, the atmosphere becomes very hot and full of water vapor, which rises into upper levels of the atmosphere;

2. At high altitudes, ultraviolet light breaks water molecules into hydrogen and oxygen;

3. Hydrogen escapes from the planet, oxygen remains to combine with rocks, atmosphere becomes dry and full of CO_2. (Carbonates cannot form without liquid water, CO_2 is continually added to the atmosphere by volcanoes.);

4. Earth resembles Venus!

So the Runaway Greenhouse Effect requires an ever-increasing amount of evaporated water in the atmosphere from the oceans to cause the atmospheric temperature to rise to exceptional levels. CO_2 cannot do this alone; there are too many infrared leaks to space. The above scenario nicely illustrates what would happen to Earth if it were moved to Venus' orbit position. Whether it describes how Venus' current environment evolved depends on whether Venus had a sizable ocean earlier in its history.

Table 3-3: Composition of the Venus Troposphere (from Prinn and Fegley)

Gas	Volume mixing ratio	Major source	Major sink
CO_2	9.63×10^{-1}	Outgassing	$CaCO_3$ formation?
N_2	3.5×10^{-2}	Outgassing	—
CO	2×10^{-5} (22 km), 10^{-3} (100 km)	Photochemistry (CO_2)	Photooxidation
SO_2	1.5×10^{-4} (22 km), 5×10^{-8} (70 km)	Photochemistry	$CaSO_4$ formation
^{36}Ar	3.7×10^{-5}	Outgassing–	—
^{38}Ar	3.7×10^{-5}	(primordial)	—
^{40}Ar	3.3×10^{-5}	Outgassing (40 K)	—
H_2O	10^{-4} (22 km), $(1\text{-}40) \times 10^{-6}$ (70 km) *	Outgassing, impacts	Silicate hydration, Fe^{++} oxidation H escape
H_2	$<2.5 \times 10^{-5*}$	Photochemistry	Escape as H
^4He	1.2×10^{-5}	Outgassing (U,Th)	Slow escape
H_2S	$(3\text{-}40) \times 10^{-6*}$	Outgassing (FeS_2)	Photooxidation
COS	$<4 \times 10^{-5*}$	Outgassing (FeS_2)	Photooxidation
^{20}Ne	7×10^{-6}	Outgassing–	—
^{22}Ne	7×10^{-6}	(primordial)	—
^{80}Kr	$7 \times 10^{-7*}$	Outgassing–	—
^{82}Kr	$7 \times 10^{-7*}$	(primordial)	—
^{84}Kr	$5 \times 10^{-8*}$	Outgassing,	—
^{86}Kr	$5 \times 10^{-8*}$	^{235}U	—
HCI	4×10^{-7}	Outgassing (NaCl)	NaCl formation
HF	5×10^{-9}	Outgassing (CaF_2)	CaF_2 formation

*Important disagreements exist between the different instruments that have measured these species.

Many other gases have been detected on Venus, but we have discussed those that are most closely connected with exobiology. Table 3-3 lists the volume mixing ratios of all of these, including their major sources and sinks. A similar table is reproduced for Earth (table 3-4).

The ubiquitous clouds that veil Venus are found at high altitudes, 50 to 70 km, above the surface, but at approximately the same pressure and temperature levels as on Earth. Unlike the water condensation clouds on Earth, the clouds of Venus are primarily composed of aqueous solutions of sulfuric acid (H_2SO_4). This sulfuric acid is produced from the photolysis of SO_2 that diffuses up from the lower atmosphere. As discussed earlier, the clouds absorb or reflect most of the incident solar radiation allowing only a small amount to reach the surface. Another potential surface effect is acid rain; there were some indications on earlier Venera

Table 3-4: Composition of the Earth Troposphere
(from Prinn and Fegley)

Gas	Volume mixing ratio	Major source	Major sink
N_2	$7.81 \times 10^{-1*}$	Biology	Biology
O_2	$2.09 \times 10^{-1*}$	Biology	Biology
^{40}Ar	$9.3 \times 10^{-3*}$	Outgassing (^{40}K)	—
H_2O	$<4 \times 10^{-2}$	Evaporation	Condensation
CO_2	3.4×10^{-4}	Combust., biology	Biology
^{36}Ar	3.7×10^{-5}	Outgassing–	—
^{38}Ar	3.7×10^{-5}	(primordial)	—
^{20}Ne	1.82×10^{-5}	Outgassing–	—
^{22}Ne	1.82×10^{-5}	(primordial)	—
^{4}He	5.24×10^{-6}	Outgassing (U, Th)	Escape
CH_4	$1.7\text{-}3 \times 10^{-5}$	Biology	Photooxidation
^{80}Kr	1.14×10^{-6}	Outgassing (^{235}U)	—
^{82}Kr	1.14×10^{-6}	Outgassing (^{235}U)	—
^{84}Kr	1.14×10^{-6}	Outgassing (^{235}U)	—
^{86}Kr	1.14×10^{-6}	Outgassing (^{235}U)	—
H_2	5×10^{-7}	Photochem. (H_2O)	Escape as H
N_2O	3.1×10^{-7}	Biology	Photodissociation
C_2H_4, etc.	$<7 \times 10^{-7}$	Incomplete comb.	Photooxidation
C_2H_2, etc.	$<2 \times 10^{-7}$	Incomplete comb.	Photooxidation
C_4H_{10}, etc.	$<2 \times 10^{-7}$	Incomplete comb.	Photooxidation
Toluene, etc.	$<1 \times 10^{-7}$	Incomplete comb.	Photooxidation
CO	$(0.4\text{-}2) \times 10^{-7}$	Photochemistry	Photochemistry
^{128}Xe	8.7×10^{-8}	Outgassing (U, I)	—
^{132}Xe	8.7×10^{-8}	Outgassing (U, I)	—
^{134}Xe	8.7×10^{-8}	Outgassing (U, I)	—
^{136}Xe	8.7×10^{-8}	Outgassing (U, I)	—
O_3	$(0.1\text{-}1) \times 10^{-7}$	Photochem. (NO_2)	Photochemistry
CH_3O_2H, etc.	$\sim 1.0 \times 10^{-9}$	Photochemistry	Photochemistry
HCl	$\sim 1.0 \times 10^{-9}$	Acidification	Rainout
NH_3	$(0.1\text{-}1) \times 10^{-9}$	Biology	Photooxidation
HNO_3	$(0.05\text{-}1) \times 10^{-9}$	Photochem (NO_2)	Rainout
COS	5×10^{-10}	Biology	Photodissociation
CH_3Cl	5×10^{-10}	Biology	Photooxidation
NO, NO_2	$(0.2\text{-}5) \times 10^{-10}$	Comb., biology	Photooxidation
$(CH_3)_2S$	$\sim 4 \times 10^{-10}$	Biology	Photooxidation
CF_2Cl_2	3.7×10^{-10}	Industry	Photodissociation
SO_2	$\sim 3 \times 10^{-10}$	Comb., photochem.	Photooxidation
$CFCl_3$	2.2×10^{-10}	Industry	Photodissociation
H_2S	$\sim 2 \times 10^{-10}$	Biology	Photooxidation

*Values quoted are for dry air.

missions that a light cloud haze might extend well below the main cloud deck. On the other hand, any acid rain could evaporate, due to the very high temperatures at lower altitudes, before reaching the surface.

Several of the gases listed in table 3-3 are cloud progenitors, particularly SO_2, H_2S, and CO_S. Volcanic eruptions or reactions of H_2O and CO_2 with volcanic surface rocks yield CO_S, H_2S, S_2, and SO_2. Various photochemical reactions and reactions with H_2O convert these species to concentrated H_2SO_4 or elemental sulfur particles in the clouds. The H_2SO_4 evaporates at and below the cloud base, producing SO_3, which can then either recondense or be reduced to SO_2. Reactions of SO_2 with Ca^{2+} in rocks provide a sink that must be balanced by the volcanic and surface sources.

Both the Soviet and United States spacecraft have suggested the presence of lightning on Venus. Although one Soviet observation has been optical, all of the other observations have been of low-frequency radio "static." On Earth, this static has been correlated with visible lightning bursts. It is not as clear-cut on Venus, and great controversy surrounds the observations and their interpretation. Lightning, if present, may be an important energy source for the production of new chemical compounds not possible through normal solar photochemical processes.

We conclude this first part of our discussion with a short synopsis of our knowledge of the surface of Venus, as this is the most likely platform for the existence of extant or extinct life. Also, as mentioned many times above, surface-atmosphere interactions and outgassing from the interior through the surface play important roles in the formation of the atmosphere and the chemical cycles controlling atmospheric species.

We begin with a review of the global topography. (The following review is based primarily on Pioneer Venus Orbiter Radar Mapper data. The Magellan data were not available when this chapter was written.) Variations in the radius of Venus range from 6049 km to 6062 km, a spread of 13 km. Since the mean radius (which we use as a reference on Venus in the absence of "sea level") is 6051 km, these extremes are –2 km to +11 km about the mean. Although the elevated terrain comprises a number of separated components, much less in number than on Earth, it is dominated by a massive equatorial region the size of South America. The total relief on Venus (13 km) is about two-thirds that on Earth (20 km).

Of the total surface, 60% lies within 500 m, and 20% lies within 125 m of the mean radius. The planetary polar ellipticity is nearly zero (upper bound of 4×10^{-5}). The surface of the planet may be divided into three provinces: upland rolling plains, making up 65% of the surface, lying between 6051 km and 6053 km; highlands, about 8% of the surface, between 6053 km and 6062 km; and lowlands, about 27%, between 6049 km and 6051 km. Numerous dark circular features in the rolling plains province may be lava-filled impact basins. A "granitic" composition for the rolling plains has been inferred; thus, this province may represent most of the planet's ancient crustal material.

Aphrodite Terra, centered at latitude 5° south between longitudes 80 and 190° east, and Ishtar Terra, centered between latitudes 60 and 75° north at longitude 0°, compose most of the highland province and in many ways resemble continents on the Earth. Their highest points stand 11.1 and 5.7 km above the mean planetary radius, respectively. Aphrodite appears to be highly disrupted tectonically, and degraded. Ishtar is made up of an uplifted plateau and great volcanic construct and is the site of the highest point, 11.1 km, Maxwell Montes (latitude 63.8° north, longitude 2.2° east), on Venus. Note that its elevation above the Venus datum is greater than the height of Mount Everest on Earth above sea level, which is 8.8 km. Gravity and altimetry data indicate that the highlands are compensated isostatically, probably as a result of crustal thickening or lateral variations in the crust and mantle, that is, by either passive or dynamic mechanisms.

The lowlands province of the planet includes several crudely circular low areas with low relief within the highlands. All lowland regions may be covered by younger basaltic lavas that have filled depressions where the crust is thinner. The lowest point on Venus is in a rift valley or trench named Diana Chasma, at latitude 14° south and longitude 156° east, where the elevation is 6049 km, or 2 km below datum. In comparison with terrestrial depths, this trench is deeper than the Dead Sea Rift but is less than one-fifth the maximum depth of the Mariana Trench, which is 11 km below sea level.

An integrated global pattern of subduction troughs or mid-basin ridges, indicative of active global plate tectonism, has not been identified. However, complex ridge-and-trough regions east of Ishtar Terra and in southern Aphrodite Terra, and a tectonically disrupted region between Beta Regio and Aphrodite Terra, may be the result of large-scale crustal motion. Beta Regio appears to consist of two giant irregular shield volcanoes, Theia Mons and Rhea Mons. Their relief profiles (both features reach elevations of more than 4.5 km above the datum) and the presence of a summit depression aligned on an axial trough suggest a basaltic compostion. This interpretation is supported by actual measurement of basaltic compositon of rocks directly east of Beta.

Despite the major bulk similarities between Venus and Earth, geologically interesting differences in atmospheric composition, atmospheric and lithospheric temperature, and possibly mantle composition suggest that the rock cycle on Venus is very different from the rock cycle on Earth. Exposed rocks on the surface of Venus have been sampled and appear to be similar to common igneous rocks on Earth. If differences of atmospheric pressure and temperature with altitude, and the probable wind transport of weathered regolith, are taken into consideration, then it is possible thermodynamically for the minerals in these common rocks to be decomposed by reaction with the atmosphere. Existing data are consistent with weathered igneous rocks, or compacted and partially cemented sedimentary rocks, or both.

Venus' Early History

We started this chapter on planetary exobiology with the assertion that extant life on the surface of Venus is out of the question. We have presented conclusive and dramatic evidence to support this assertion. This now leads us to the possibility of *extinct* life on Venus. Was there a period of time in Venus' 4.5 billion year history when the planet possessed those Earth-like characteristics (oceans and moderate surface temperatures) necessary for life to exist?

We begin with the most fundamental, and as yet unanswered question: Did Venus form with a large inventory of water, or did it form dry? The hypothesis for a dry origin for Venus is a prediction of the equilibrium condensation model for planetary formation. This model assumes that the bulk of Earth's (and Mars') water was incorporated into the planet in the form of hydrated minerals, such as tremolite [$Ca_2Mg_5Si_8O_{22}(OH)_2$] or serpentine [$Mg_3Si_2O_5(OH)_4$]. Formation of such minerals is predicted thermodynamically at the relatively low temperatures thought to prevail in the solar nebula beyond the orbit of proto-Earth, but would have been precluded in the warmer regions near the orbit of proto-Venus. This model presumes that the cooling time of the solar nebula was slow compared with the time for the planetesimals to form, so that the material that condensed at a given radial distance from the center of the nebula would have had a nearly uniform composition.

The equilibrium condensation model predictions have been seriously questioned in recent years, for two good reasons. First, the model presumes that the planets formed exclusively from material that condensed from the nebula in their immediate vicinity. It has been shown that radial mixing of planetesimals during the accretion process could have resulted in substantial exchange of material formed in different regions of the nebula. Indeed, this model predicts that the four innermost, terrestrial planets should all be composed of the same material. In reality, there are known compositional differences between these planets, so the actual degree of mixing was probably less than predicted.

Another approach to this question is to ask whether it is possible to build the terrestrial planets from a combination of known meteorite types. This, again, presumes some nebular mixing. The carbonaceous chondrites have been suggested by some researchers as the source of Earth's volatiles. These meteorites contain water (about 10%, by weight) in the form of hydrated minerals, along with substantial amounts of carbon in saturated organic compounds ('CH_2' for short). Oxidation of this organic carbon by ferric oxides contained in such planetesimals would have yielded carbon dioxide, ferrous oxide, and water:

$$CH_2 + 3\ Fe_3O_4 \rightarrow CO_2 + H_2O + 9\ FeO$$

The H_2O/C ratio after oxidation is about 4.5.

Other researchers have suggested that Earth's volatiles were obtained from ordinary chondrites. These meteorites are less highly oxidized and have much lower volatile contents than do carbonaceous chondrites. Their carbon exists mainly in amorphous, elemental form. Oxidation of this carbon would have yielded CO_2 and elemental iron, but no water:

$$C + 2\ FeO \rightarrow CO_2 + 2\ Fe$$

Ordinary chondrites do, however, contain H_2O (about 2%, by weight) in hydrated minerals. The H_2O/C ratio is about 2.

If the carbon in Venus' 95-bar, CO_2 atmosphere was derived from one of these sources, some 50 to 120 bars of H_2O, roughly one-fifth to one-half of a terrestrial ocean, would have entered at the same time. Thus, such material would have to have been completely excluded from the neighborhood of proto-Venus for Venus to have formed dry. The equilibrium condensation model circumvents this problem by suggesting that Venus' CO_2 was derived from metal carbides dissolved in an H_2O-deficient iron matrix.

The second problem with the equilibrium condensation model is that it does not consider the effects of comets. A large number of comets are thought to have been scattered into the inner solar system as a result of outer, giant planet orbit perturbations, where they could have collided with the recently formed terrestrial planets. The flux of comets during the first several hundred million years of solar system history may have been 10^4 to 10^5 times greater than today. It has been calculated that the H_2O in the Earth's oceans could have been derived entirely from H_2O-bearing comets, if they were responsible for 10% of the impacts recorded on the moon (meteorites and asteroids providing the other 90%). Studies of recent lunar impacts suggest that 10-50% are due to comets and the remainder are from asteroids. Of course, there is no reason why the ratio of comets to asteroids should have been the same early in solar system history; however, if Earth gained even a small fraction of its H_2O in the form of a late cometary veneer, then Venus should have received a comparable amount.

There is an important possible difference in timing between the late veneer, the cometary model, and the other models for water acquisition. If Earth's and Venus' H_2O were provided by comets, then it would probably have been supplied over a period of several 100 million years. (The heavy bombardment of the moon apparently continued until 3.8 billion years ago.) In contrast, H_2O obtained from inner solar system planetesimals would have been incorporated into the terrestrial planets within the first 100 million years. The time scale for H_2O loss for Venus, discussed later, is of the order of 100 million years or even less. A "late veneer" model for Venus might, therefore, have never had its full complement of H_2O present at any one time. This could make it less likely that any of this water condensed to form oceans. The atmosphere at the time, however, would still have been very wet compared to today.

Another argument that has been used in favor of a dry origin for Venus is that it would have been impossible to get rid of large amounts of water. The proposed mechanism for water loss involves photodissociation of water vapor in the upper atmosphere of Venus, followed by escape of hydrogen to space and loss of oxygen by chemical reactions at the surface. Conceptually, this scenario is logical; however, there are potential difficulties when one examines the process in detail.

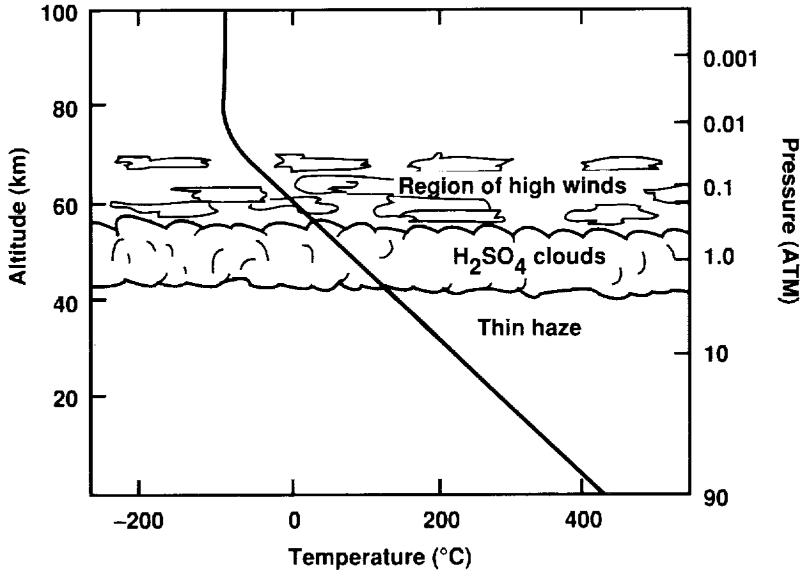


Figure 3-3. Venus' vertical temperature profile showing an atmospheric cold trap.

The suggested escape mechanism for hydrogen during the early stages of water loss involves hydrodynamic outflow. Theory indicates that the hydrodynamic outflow is highly efficient if the upper atmosphere was hydrogen-rich. However, there is a catch—water vapor, hence hydrogen, could have been effectively confined to the lower atmosphere by an atmospheric cold trap (fig. 3-3). The cold trap is that region of the atmosphere where the fractional concentration of water vapor is held to a minimum by condensation. In the Earth's atmosphere the cold trap occurs between 9 and 17 km altitude; it is coldest and thus most effective near the equator. Earth's cold trap limits the concentration of water vapor in the stratosphere to only a few parts per million by volume. The escape rate of hydrogen from Earth's atmosphere is consequently far too low to affect the amount of water stored in the oceans.

Early Venus would have been different. Climate models predict that a cold trap does not work well when the lower atmosphere contains more than about 10% water vapor by mass. A wet early Venus would have at least this much water vapor in its atmosphere. When so much moisture is present, the amount of latent heat released by condensation and cloud formation is so large that the cold trap moves up to very high altitudes. There, the ambient pressure is comparable to the saturation vapor pressure of water, so condensation has little effect on the water concentration. Water vapor can, thus, make its way unimpeded into the upper atmosphere, where it can be photodissociated and the hydrogen lost to space.

J. S. Lewis has focused on the difficulties of disposing of the oxygen left behind after the hydrogen has escaped, to support his dry-origin Venus theory. In the carbonaceous chondrite model for terrestrial planet formation, Venus would have been left with approximately 110 bars of O_2 from its initial 120 bars of H_2O. If this oxygen was consumed in oxidizing ferrous oxide to magnetite:

$$3\ FeO + 1/2\ O_2 \rightarrow Fe_3O_4$$

and if Venus' crust was approximately 10% FeO (like Earth), some 80 km of crustal rock would have been needed to take it up. This would require exposing 60 km^3 of fresh material each year, an amount 15 times greater than the volume of new crust created annually at the midocean ridges on Earth by plate tectonics.

Whether this poses a problem for the wet origin model depends in part on when the water was acquired. If much of the water came in during the accretion period itself, then the planet's surface would have been molten and the entire mantle should have been convecting vigorously. The amount of oxygen that could have gone into the mantle under these circumstances is virtually unlimited.

Indeed, water would probably have reacted with elemental iron in the melt and generated hydrogen directly:

$$H_2O + Fe \rightarrow H_2 + FeO$$

This hydrogen would have been outgassed and made its way to the top of the atmosphere unhindered by condensation. If sufficient solar extreme ultraviolet (EUV) energy was available to allow it to escape, it would have done so at that time. If the inner solar system was still filled with dust from planetesimal collisions obscuring the EUV light, the hydrogen would have remained in Venus' atmosphere until the nebula cleared and then escaped. In either case, large amounts of water could have been lost without creating any free oxygen.

Disposing of cometary water acquired after the main accretion period would have presented a bigger problem. Roughly 1/30 of a terrestrial ocean (or an average depth of 100 meters) could have been disposed of by oxidizing an amount of fresh crustal material comparable to that presently generated on Earth. This figure could be multiplied by a factor of two or three if Venus, like Earth, was more tectonically active in the past.

But there are other possible sinks for oxygen that could accommodate large quantities of cometary water. For example, Venus' CO_2 may have been originally outgassed as CO instead of being released in a fully oxidized state as the reactions above would suggest. Some 30 bars of H_2O, or one-tenth of a terrestrial ocean, could have been consumed in oxidizing this CO.

A second possibility is the escape of oxygen to space. A hydrodynamic hydrogen escape flux in excess of 2×10^{13} H atoms cm^{-2} s^{-1} would have been sufficiently vigorous to drag some oxygen atoms along with it. Such an escape rate is energetically possible on Venus during the first 500 million years of solar system history, given an enhanced solar EUV flux at that time. (Large EUV enhancements have been predicted for the young Sun based on observations of T-Tauri stars and on stellar evolution theory.) Indeed, from an energetic standpoint it is possible for Venus to have lost several oceans of water, including the oxygen, during the first 100 million years of solar system history. The actual efficiency would depend on the opacity of the inner solar sytem to EUV during this time period.

The real Achilles' heel of the Runaway Greenhouse Effect hypothesis lies in getting rid of the last part of the original water endowment. Venus' water would have been lost readily until the mass mixing ratio of water vapor in the lower atmosphere had fallen below 0.1. At this point, a cold trap should have developed, blocking water vapor transport to the upper atmosphere. If Venus had its massive 95-bar CO_2 atmosphere at this time, roughly 10 bars of H_2O would have remained in its lower atmosphere. It is difficult to estimate exactly how fast this water could have escaped, but it may be impossible to lose this much water even over the course of several billion years.

The problem is compounded further by sulfur photochemistry. At some stage in the water loss process, sulfuric acid clouds would have started to form. These clouds are extremely hygroscopic (water-absorbing) and could have dried out the Venus upper atmosphere even more, further reducing the escape rate.

Thus, the classical runaway greenhouse model for Venus, in which the water is all in the vapor phase, encounters significant problems in losing the water. This has led one of us (Kasting) and his colleagues at NASA's Ames Research Center to revisit the climate models to try to resolve this problem.

If one takes an Earth-like planet with an ocean-covered surface and calculates how much solar heating is required to completely vaporize that ocean, Kasting's climate model predicts that you need a flux about 1.4 times greater than the current flux (S_0) at Earth's orbit. This calculation assumes no change in cloud cover. If cloudiness increases with increasing surface temperature, as seems likely, the critical solar flux could be considerably higher. The current flux at Venus' orbit is 1.91 S_0, well above Runaway Greenhouse limit of 1.4 S_0. However, the Sun was approximately 30% less bright shortly after it was formed, so the flux incident on primitive Venus was only 1.34 S_0. This is close enough to the Runaway Greenhouse limit to lie within the uncertainty of the model calculation. However, the inclusion of cloud feedback would cool the planet considerably and make a true Runaway Greenhouse Effect unlikely.

Hence, if Venus did start out with an Earth-like water endowment, much of that water should have condensed to form a hot ocean. The temperature of that ocean depends on the climatic effect of the clouds and on the amount of CO_2 present, but it would likely have been between 100 and 200°C. The corresponding vapor pressure of water is 1 to 15 bars. A fully vaporized terrestrial ocean, by comparison, would produce a surface pressure on Venus of about 250 bars. Liquid water should therefore have been stable on early Venus even if the total water endowment was only a fraction of Earth's. We call this modified, ocean-stable greenhouse model the "Moist Greenhouse" to distinguish it from the oceanless Runaway Greenhouse.

There is more than just semantics or labels involved here. The Moist Greenhouse model leads to very different predictions concerning Venus' early history. The presence of an ocean on early Venus should have caused large changes in the composition of the atmosphere. On Earth, water provides a medium for weathering silicate materials and converting them into carbonates.

Atmospheric CO_2 is consumed in the process. The simplest such reaction involves wollastonite reacting with the carbon dioxide to produce calcite and quartz:

$$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$$

Reactions like this, which occur readily in the presence of liquid water, would have reduced the atmospheric pressure by sequestering CO_2 in the planet's crust.

Somewhat counter-intuitively, this reduction in atmospheric CO_2 should have facilitated the escape of water. Suppose, for example, all of Venus' CO_2 was converted into carbonates in this manner. The remaining atmosphere would have been a mix of roughly 2 bars of N_2 plus however much water vapor was present at saturation. If the surface temperature was 100°C or higher, the concentration of water vapor in the lower atmosphere would have been 25% by mass, or more. The cold trap would have been ineffective, and hydrogen would have escaped from the top of the atmosphere at a rapid, hydrodynamically controlled rate. This rapid water loss would have continued until the water concentration dropped below about 10% by mass, at which point only about 0.2 bar of water would have remained in the atmosphere—the ocean should have already evaporated by this time. Because this atmosphere is 50 times thinner than the present one, some 50 times less water would remain after the cold trap formed and the hydrodynamic escape process stopped.

The presence of liquid water would also have helped to solve the problem of the water-trapping sulfuric acid clouds. All of the common sulfur gases—SO_2, H_2S, H_2SO_4—are soluble in water to some extent. If an ocean were present, they would have dissolved to form sulfite, sulfide, and sulfate. These species, in turn, would have combined with available cations to form various sulfur-containing minerals. The sulfuric acid clouds could not have formed until the ocean had dissappeared and sulfur was recycled into the atmosphere by volcanic activity. CO_2 would have been regenerated in a similar manner. Since Venus, like Earth, was producing heat in its interior, its mantle must have been convecting and its surface must have been reprocessed by some form of tectonic activity: point volcanism, perhaps, if not plate tectonics. If such reprocessing was occurring, carbonate rocks would have undergone metamorphism and gaseous CO_2 would have been recycled back into the atmosphere. Over billions of years, volcanic outgassing of CO_2 and SO_2 would have caused the atmosphere to evolve to its current state.

Let us recap (fig. 3-4), then, a reasonable theory for the history of water on Venus. Venus started off wet because it would have received a certain percentage of the same volatile-rich material which formed the Earth. Once the initial accretion period was over, the combination of lower solar luminosity and a high albedo caused by the clouds would have resulted in a relatively cool surface temperature. If Venus had anything approaching Earth's water inventory, much of this water would have condensed to form oceans. Carbon dioxide that was originally present in its atmosphere would have been slowly converted to carbonate rocks, and the atmosphere would have thinned. Water would

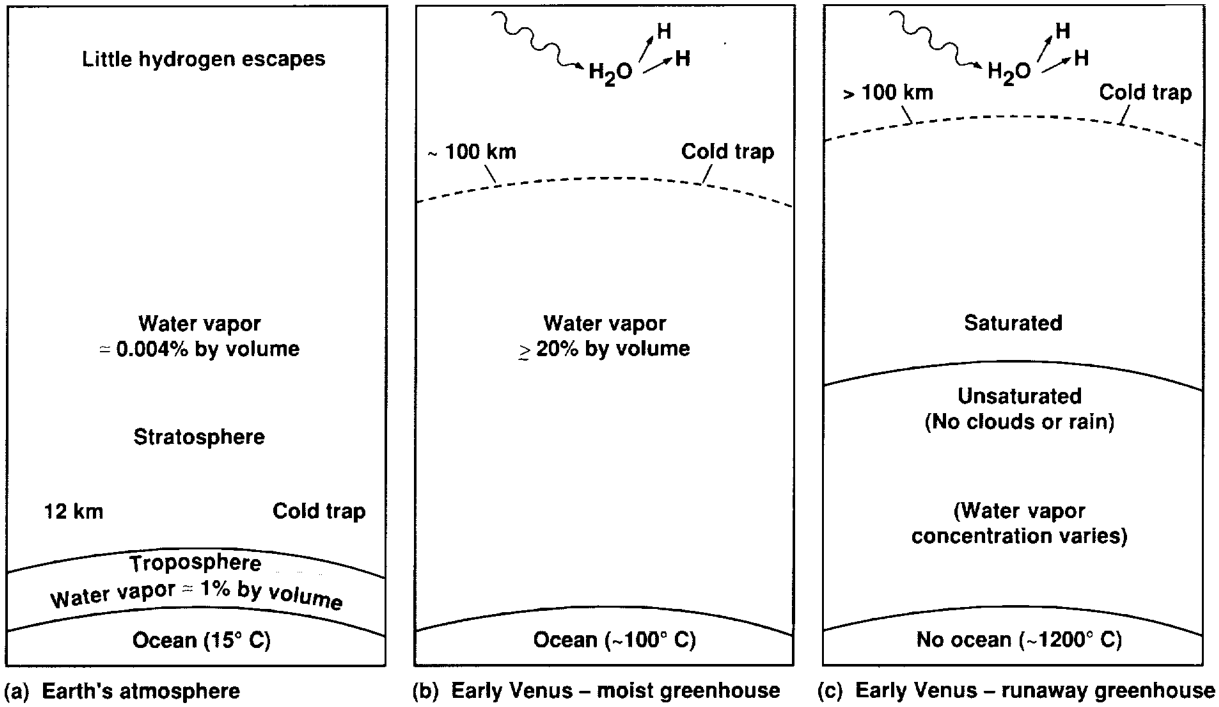


Figure 3-4. Tendency of water vapor to escape from the Earth is minimal; the same cannot be said for early Venus. On the Earth (a) water in the troposphere is blocked from entering the stratosphere by a cold trap, the region where cold temperature and relatively high ambient pressure combine to minimize the concentration of water vapor. When vapor reaches the trap, most of it condenses out. On early Venus the lower atmosphere, though warm by the Earth's standards, may have been cool enough for water to condense and form an ocean. The sea would in time have been lost, however, to a "Moist Greenhouse" (b), a condition that arises when a high surface temperature enables water vapor to constitute more than about 20% of the lower atmosphere. The cold trap then moves to a high altitude and becomes inefficient at preventing water vapor from rising into the upper atmosphere. Although some vapor condenses out as rain, the steam at the top dissociates and its constituent hydrogen atoms escape into space. Venus might have been so hot that a Runaway Greenhouse (c) developed instead; all the water released by the planet turned to steam instantly, and no ocean formed. The water essentially traversed a one-way route: up and away.

have remained a major atmospheric constituent throughout this period, its abundance gradually decreasing with time as a consequence of photodissociation followed by hydrogen escape. Some of the oxygen released by this process may have been dragged off into space along with the hydrogen; the rest would have been consumed by oxidizing carbon monoxide and by reactions with reduced minerals (primarily ferrous oxide) in the planet's crust. Because the atmosphere was thinner than it is today, hydrodynamic escape would have removed all but a few tenths of a bar of Venus' original water endowment.

The remainder was lost over billions of years by slower, non-thermal escape processes. The disappearance of water allowed the CO_2 and SO_2 released by volcanoes to accumulate, and the atmosphere gradually approached its present state.

So it appears to be quite possible that Venus possessed a sizable water inventory and a cooler climate (100-200°C) in its early history, perhaps for as long as a few hundred million years. Even 100°C would probably still be considered too hot for life to originate from the viewpoint of many exobiologists. On the other hand, Earth may have been much hotter than today when life formed on this planet. A more serious problem may have been the effects of late impacts. If the impact rate for Venus was as high as we think it was for the Earth and the Moon, life may have been repeatedly wiped out even though other environmental conditions were favorable.

Is there experimental evidence for the existence of water in large quantity on Venus during its past? There is a positive result inferred from the mass spectrometer experiment on-board the Pioneer Venus Large Probe. As the probe descended through the clouds of Venus on December 9, 1978, its inlet became clogged, apparently by a large H_2SO_4 cloud particle, for a period of time. During the time the instrument was "failing," two groups of experimenters were able to analyze in detail the cloud particle trapped in the spectrometer. They were able to deduce the deuterium (heavy hydrogen) to normal hydrogen ratio, and found it to be 1.0 to 1.6×10^{-2}, or about 100 times higher than the same ratio on Earth.

They concluded that the present ratio on Venus is a residue from selective escape of at least 100 times the current water abundance. In other words, if the original D/H ratios were the same for Earth and Venus, the current high ratio on Venus is due to the fact that the lighter, normal hydrogen escaped more readily than the heavier deuterium. Of course, 100 times the present water abundance would still be only about 0.1% of a full terrestrial ocean. However, Earth-sized oceans on Venus are possible if there was significant deuterium escape as well.

These inferences have recently been questioned. The formation of the inner planets is not understood well enough to assume that the original ratios for Venus and Earth were about the same. Furthermore, the high ratio may not be evidence for Venus' proposed oceans anyway. The water seen today could have resulted from the sporadic infall of cometary material for which the D/H ratio is largely unknown; the ratio was determined for comet Halley and is terrestrial within a factor of three. These calculations assumed a water abundance of 10 parts per million; they do not work if the abundance is above 200 parts per million.

Thus, this indirect evidence for early Venus oceans is highly controversial. More direct evidence, e.g., evidence of fluvial channels as seen on Mars in Viking orbiter images, has not been reported on Venus.

What kind of experiments should be designed to look for evidence of extinct life on Venus? Probably they should be similar to those being planned to look for evidence of extinct life on Mars on the proposed Mars Rover Sample Return (MRSR) mission. The technology for a MRSR on the surface of Mars, with its thin, cold atmosphere, is available today. The technology for a Venus Rover Sample Return mission on the the surface of Venus is beyond our capabilities and will probably remain so for two or three decades, at least.

Prior to the advent of the space age, Venus was often referred to as Earth's "twin." This was the result of the similarities in bulk properties (size, mass, density) and the fact that Venus is our nearest planetary neighbor. As spacecraft revealed the remarkable differences between the two planets, the appelation lost its relevance. However, the recent studies of early Venus and early Earth have revealed potentially new similarities, and the new tectonic inferences add to this picture. Thus, we may be forced to revive the twin analogy—perhaps twins at birth that evolved along substantially different paths to maturity.

Additional Reading

Donahue, T. M.; Hoffman, J. H.; Hodges, R. R.; and Watson, A. J.: Venus was Wet: A Measurement of the Ratio of D to H. Science, vol. 216, 1982, p. 630.

Grinspoon, D. H.: Was Venus Wet? Deuterium Reconsidered. Science, vol. 238, 1987, p. 1702.

Hunten, D. M.; Colin, L.; Donahue, T. M.; and Moroz, V. I., eds.: Venus. University of Arizona Press, 1983.

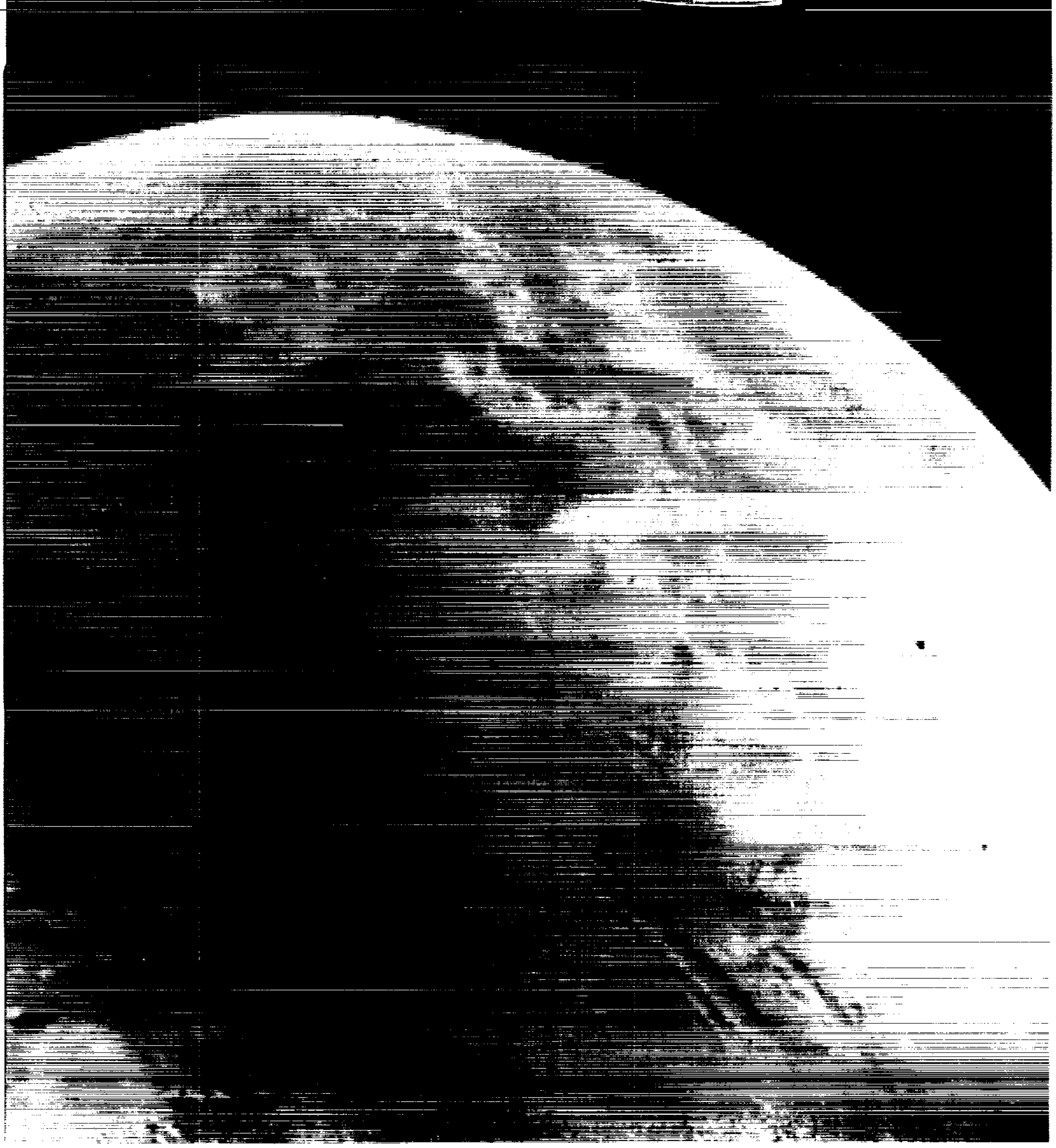
Kasting, J. F.: Runaway and Moist Greenhouse Atmospheres and the Evolution of Earth and Venus. Icarus, vol. 74, 1988, p. 472.

Kasting, J. F.; Toon, O. B.; and Pollack, J. B.: How Climate Evolved on the Terrestrial Planets. Scientific American, vol. 256, 1988, p. 90.

Lewis, J. S.; and Prinn, R. G.: Planets and Their Atmospheres. Academic Press, 1984.

Prinn, R. G.: The Volcanoes and Clouds of Venus. Scientific American, vol. 252, 1985, p. 46.

Schubert, G.; and Covey, C.: The Atmosphere of Venus. Scientific American, vol. 245, 1981, p. 66.



ORIGINAL PAGE
COLOR PHOTOGRAPH