

2. WHY EXPLORE VENUS?

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Abstract. This paper develops the rationale for a program of Venus exploration by man.

Venus and Earth are almost twins as planets, or at least it appears that they should be at a first glance. Their radii are almost the same – 6050 km for Venus and 6378 km at the equator for Earth. Their densities differ by only 6%. The difference in their distance from the Sun is so small that Venus receives only twice as much solar energy per unit area as does the earth. If neither planet had an atmosphere and the surface of Venus had the same albedo as that of Earth, the surface temperature of Venus would be 300 K in comparison with 253 K for Earth. And yet we already know that there are several very dramatic differences between these planets. Earth is covered with an atmosphere consisting of 80% nitrogen and 20% oxygen and an ocean of water, nicely conducive to and ‘symbiotic’ with life as we know it. The surface temperature is a pleasant 300 K or thereabouts at temperate latitudes. On the other hand, Venus is blanketed with a hot, dry atmosphere whose pressure is 100 times as great as the surface pressure on Earth and whose temperature near the surface is 700 K. 90% or more of this atmosphere apparently consists of carbon dioxide. There is almost no O₂ or H₂O. The amount of water in the atmosphere is probably about 10²¹ g, a quantity that has to be compared with 1400 × 10²¹ g in the oceans of the earth. Venus is covered with a thick layer of clouds, the top layers apparently consisting of saturated sulphuric acid droplets. Venus, as a whole, rotates very slowly in a retrograde sense once every 243 days, although the tops of its cloud layers near 60 km are in a state of superrotation in most places with wind speeds as high as 100 m s⁻¹. Venus has no magnetic field and yet seems to be differentiated and hence to have a core. An analysis of the surface rocks by Venera 8 suggests that they are like granite rather than basalt, while similar data obtained by Veneras 9 and 10 definitely indicate that those spacecraft landed on a basaltic like terrain.

There is one excellent reason to explore Venus. That is to find out why it differs so much from Earth. Why is a planet that might be our twin a place so hostile to life? Is it because Venus started with certain essential differences from Earth that constrained it to follow a different evolutionary path, or could Earth still evolve in the same sense as Venus? There are other reasons for trying to arrive at a deep understanding of planets Earth and Venus (Mars, Mercury, and the Moon as well, one might add), but this one reason seems to be basic and sufficient.

It is well known that the atmospheres of the terrestrial planets are secondary and have outgassed from their mantles and crusts. The primordial atmospheric

gases could not have been retained by the light planets near the Sun during the high temperature phase of their early history. It also appears that it is possible that about as much CO₂ has outgassed from Earth as has from Venus – about 500×10^{21} g. The difference in the two cases is that all or most of the CO₂ is still in – or has found its way into – the atmosphere of Venus while $\frac{3}{5}$ or more of the Earth's CO₂ can be found in the Earth's crust in the form of carbonate rocks as a result of such processes as



This and similar reactions readily go on in the presence of the 1400×10^{21} g. of H₂O that have outgassed and formed the ocean of Earth – taking advantage, for example, of the solubility of CO₂ in the ocean and the processing of CO₂ by shelled creatures that secrete CaCO₃. Furthermore, the CO₂ can remain in the carbonate phase at the low temperature of Earth's crust. Even if carbonates had been formed at some period in the life of Venus, they would have been reconverted to CO₂ now that the temperature at the surface has reached 700 K.

Our study of the evolution of the Earth's atmosphere and of life on Earth suggests that during about 2.5 or 3 of the first 3.5 or 4 billion years of Earth's history the atmosphere contained first some highly reducing gases and CO₂ together with water vapor. Life existed in the ocean in single cell form, much of it probably generating energy by glycolysis, a process that not only needs no oxygen to work but must indeed proceed in an oxygen poor environment. However, oxygen slowly accumulated in the atmosphere as hydrogen in the water vapor steadily escaped from earth as a result of various thermal and non-thermal mechanisms at a rate that we now believe to have been as high as 36×10^8 cm⁻² s⁻¹. Left behind by this hydrogen were 1.5×10^{12} g of O₂ every year. Taking into account the fact that all but about 2% of this oxygen would have oxidized the crust, there still would have been in the atmosphere about 10% of the present supply of atmospheric oxygen (1.2×10^{21} g) about a billion years ago. This oxygen would have been available to form ozone and to sustain respiratory forms of life. Before the ozone shield began to form, life could not have emerged from the ocean, developed a respiratory mechanism and proceeded to convert atmospheric CO₂ to O₂ by photosynthesis. Afterward, a runaway development of photosynthetic-respiratory life and an oxygen rich atmosphere become possible. The fossil record attests to an explosive development of life using and making O₂ at the beginning of the paleozoic, 600 million years ago.

What prevented this process from occurring on Venus? Clearly the present state of affairs there can be understood because of the absence of 1400×10^{21} g of H₂O in an ocean. But did Venus lose the hydrogen belonging to all of this water? It seems possible in principle to account for the loss of a large fraction of such a large amount of hydrogen if the outgassing occurred early and rapidly under very high temperatures. Then an explosive blow off of hydrogen and oxygen might have occurred. However, the limiting rate of loss was set by the supply of photons

from the sun needed to dissociate the water, about $10^{13} \text{ cm}^{-2} \text{ s}^{-1}$! 30 million years and $8 \text{ ergs cm}^2 \text{ s}^{-1}$ were required, and in the end there would have been left a residue of H_2O – about 10% of the initial value. For this remaining water vapor, the escape rate would have been inhibited by diffusion, by low exospheric temperatures and inadequate sources for non-thermal escape such as sweeping by the solar wind. To get rid of this last vestige of water would have proved very difficult. Hence, it is almost necessary to assume that Venus was formed out of rocks that had essentially no water in them and that the CO_2 that outgassed could not have followed the terrestrial path into the formation of carbonates and the oxygen that oxidized the crust and permitted the development of life.

This alternative creates difficulties in understanding the high atmospheric temperature near the surface. The only viable suggestion for a mechanism so far is one called the run-away greenhouse. Early in the life of Venus, the surface was supposedly cooler than it is now and the atmosphere more like that of Earth. However, infra-red radiation from the surface trapped in the $\text{CO}_2\text{-H}_2\text{O}$ atmosphere took advantage of the 50° head start in intrinsic temperature Venus had over the Earth to raise the gas temperature, the concentration of water in the atmosphere, then again the trapped infra-red, and the temperature in a cycle until the boiling point of water was reached and all CO_2 , if any happened to be there, driven from the crust.

To determine which if either of these scenarios was followed or – more urgently to understand why precisely the atmospheres of Earth and Venus are so different now is of obvious pragmatic importance. Clearly some of the processes suggested for Venus might still occur on Earth. Man himself is causing the amount of CO_2 in the atmosphere to increase by burning fossil fuels. He also seems to be devising various methods for depleting the blanket of ozone in the stratosphere. A conservative man might shrink from suggesting that Earth could follow the evolutionary path of Venus as a consequence. But a cautious man might also recognize the possibility and do all he can to understand the path of evolution followed by each planet.

Another very important reason to explore Venus is to understand its meteorology. Again this has implications for man's needs. Meteorological problems are three-dimensional, time-dependent, non-linear, and hence, all but unmanageable from a purely theoretical standpoint. Particularly is this the case for Earth, which is more complex meteorologically than Mars or Venus, because of the presence of the oceans, and the release of latent heat in the atmosphere that accompanies condensation of water vapor. For understanding the meteorology of Earth it will probably be very helpful to make use of the range of observational conditions provided by the simpler atmospheric systems of these other two planets. The rotation rate (and Coriolis force) is much smaller on Venus than on Earth. It is about the same on Mars as on Earth. Dynamical effects dominate in the massive atmosphere of Venus in the contest between hydrodynamical and radiative effects for control of the lower atmosphere. Radiative effects are stronger in the thin CO_2

atmosphere of Mars. Both are important on Earth. Thus, it is of primary importance to perform a sounding as complete as possible of the atmospheres of Venus and Mars, measuring pressure, temperature, cloud structure, and composition, the divergence of the radiative flux and the vector wind as a function of altitude simultaneously at widely separated locations on the planets.

A complete study of the circulation field is also needed to settle observationally the question of whether a large convective cell, working between the cloud levels and the surface and from subsolar point to antisolar point, can convect heat downward and produce by adiabatic compression the high surface temperatures observed. This mechanism, a rival to the greenhouse as the cause of the extreme temperature reached near the surface of Venus, has recently been discredited theoretically. Still it would be most wise to identify the real heating mechanism by direct observation if possible. Circulation measurements will obviously have a lot to say about the viability of the dynamical model.

Finally, it may be possible from a careful study of the three dimensional distribution of atmospheric constituents, especially minor constituents such as O, CO, and O₂ for example, along with the atmospheric circulation system, to understand more than we now do about the process which transports atmospheric constituents and properties vertically in planetary atmospheres. This process is simulated for calculational or modeling purposes by those interested in atmospheric chemistry by an analog of molecular or Fickian diffusion called eddy or turbulent diffusion. The vertical profile of the coefficient that characterizes this kind of transport along with the rates of chemical reactions and photolysis determines the densities of minor species, such as those controlling the ozone density in the Earth's atmosphere. Evidence accumulated from the low degree of dissociation of CO₂ in the atmospheres of Mars and Venus and the low rate of loss of atomic hydrogen from the top of the Cytherean atmosphere suggest strongly that the effective vertical transport is much more efficient – by two or three orders of magnitude in the effective diffusion coefficient on Venus and Mars. If we can understand the reason for this efficient transport, perhaps we will understand the analogous transport mechanism better on Earth. It is very important for man if he wishes to protect his environment to understand as much as possible about this property of the atmosphere as well as the other that have already been discussed.

Sufficient reason exists to explore Venus, and the time is right for the combined orbital and atmospheric entry probe missions that constitute Pioneer Venus, 1978. Traditionally, logically and successfully NASA has followed a sequence in planetary study that has consisted of a sequence of flyby missions that are essentially exploratory, orbital missions that determine the properties of the planetary environment and surface by a combination of *in situ* and remote sensing observations, and then entry missions. The latter can either combine atmospheric and surface measurements or, as seems appropriate in the case of Venus, concentrate on atmospheric studies to begin with and leave direct surface meas-

urements until later when the great weight required for heat insulation to insure adequately long surface survival can be afforded. Furthermore, the Soviet probes Veneras 9 and 10 – taking advantage of the great payload capacity possessed by the USSR space program – have begun the surface science program already. They have only begun to answer the atmospheric science questions posed here. Thus the Soviet and U.S. Venus programs are complementary and a strong rationale exists for the Pioneer Venus program.