National d'Etudes Spatiales, is planning a mission that would deliver an orbiter with a microwave sounder for continued atmospheric profiling, and a network of four landers to carry out seismological and meteorological measurements These missions will continue to add to our knowledge of the meteorology and climate of Mars.

See also

Aerosols: Physics and Chemistry of Aerosols. **Boundary Layers:** Neutrally Stratified Boundary Layer. **Chemistry of the Atmosphere:** Principles of Chemical Change. **Climate:** Overview. **Climate Variability:** Seasonal to Interannual Variability. **Clouds:** Climatology. **Evolution of Atmospheric Oxygen**. **Evolution of Earth's Atmosphere**. **General Circulation:** Overview. **Planetary Atmospheres:** Jupiter and the Outer Planets; Mars; Venus.

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Venus

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Introduction

Venus is the Earth's sister planet, 0.723 times as far from the Sun as is the Earth. Its radius (6052 km) and mass (4.869×10^{24} kg) are 95% and 82% of the Earth's. Thus, in size and distance from the Sun it is quite similar to Earth, but its atmosphere is strikingly different from the Earth's. The atmosphere of Venus is much more massive, with a mass per square meter of 10.8 kg m^{-2} compared to 0.1 kg m^{-2} on Earth. It is composed of carbon dioxide (96.5% mole fraction) and molecular nitrogen N_2 (3.5%) plus traces of other gases. A hydrosphere is absent on Venus. There is a very low abundance of water in any form. These compositional differences point to a drastically different evolution of the Venusian and terrestrial atmospheres through geological history.

The current state of the Venusian atmosphere also shows great differences from that of the Earth. There is a strong greenhouse effect, which raises the surface temperature to about 735 K (462°C), despite the fact that cloud cover strongly reflects sunlight so that less heat flux is absorbed on Venus than on the Earth. The cloud deck itself is extremely interesting. It is optically thick, and observed from Earth or from space. Venus appears featureless in visible light. The cloud is composed of droplets of a strong solution of sulfuric acid. Its maintenance depends on a cycling of sulfur compounds between the upper atmosphere, where sunlight produces H_2SO_4 by photochemistry, and the lower atmosphere, where high temperatures destroy the acid.

The solid body of Venus rotates very slowly, with a period of 243 days, in the opposite direction to the general rotation of the solar system. The general circulation of the Venus atmosphere is dominated by rotation of the atmosphere in the same direction as that of the solid planet but increasing in speed with height from the surface up to the cloud tops. It reaches maximum speed near the cloud tops, where the rotation period is about 4 days. Atmospheric dynamics are thus very different on Venus and on Earth. Coriolis forces are relatively weak because of slow planetary rotation. Instead, the atmosphere itself develops a rotation by internal mechanisms that are not yet fully understood.

History and Evolution of the Venusian Atmosphere

The total quantity of atmosphere on Venus is known from measurement of surface pressure by probes dropped through the atmosphere. Four of these were flown to Venus by the NASA *Pioneer Venus* spacecraft in 1979, and several were flown by the Russian *Venera* spacecraft program between 1965 and 1985. The surface pressure was found to be about 9.3 MPa. When divided by the acceleration of gravity (8.87 m s^{-2} on Venus), the pressure yields the atmospheric mass per unit area. Most of this mass is carbon dioxide. On the Earth, a similar quantity of carbon is buried in the crust, primarily in the form of carbonate minerals. On the other hand, the Earth's oceans contain a total quantity of water equivalent to a layer with basal pressure of a few hundred kPa, compared to much smaller traces on Venus. Thus two questions are raised by compositional differences: Why is carbon dioxide on Venus in the atmosphere instead of in crustal minerals as on Earth? Why does Venus have so little water?

Venus and Earth are similar in size and density and are composed of approximately the same array of elements, and are thought to have formed in similar ways during the birth of the solar system. Thus the same inventories of volatile compounds were probably present on both planets at the time of planetary formation. The most abundant of these were water and carbon dioxide. Current differences are thought to be due to evolutionary effects rather than to initial conditions. In particular, Venus is closer to the Sun and the solar flux onto the top of the atmosphere is 1.9 times larger than on Earth. This is thought to have been large enough to push Venus into a runaway greenhouse state, in which water vapor feedback drove the temperature high enough that all water was forced into the atmosphere as vapor or cloud. Water in the upper atmosphere was then exposed to ultraviolet radiation and dissociated. The hydrogen escaped to space and the oxygen was chemically combined with crustal materials; the consequence was rapid loss of most of the initial water inventory.

In the presence of liquid water and relatively low temperatures, carbon dioxide over geological history on Earth has largely precipitated out in the form of carbonates such as calcite ($CaCO_3$). These Urey reactions remove carbon dioxide from the ocean–atmosphere system. On Venus, the high surface temperature pushes the equilibrium of the Urey reactions toward higher CO_2 pressures. The major portion of the initial inventory of CO_2 on Venus may still reside in the atmosphere.

These ideas regarding the compositional evolution of the Venusian atmosphere remain speculative because of the absence of detailed geological information from the surface of Venus. For example, detailed chemical analysis of surface minerals has not yet been performed, and sedimentary cores such as those used to investigate past epochs on Earth do not exist for Venus.

Thermal State of the Venusian Atmosphere

Figure 1 displays a temperature profile obtained from entry probes. The shape of the profile divides the atmosphere into two regimes. The middle atmosphere is approximately isothermal and is analogous to the Earth's middle atmosphere, but without the warm layer due to absorption of ultraviolet solar radiation by ozone on Earth. The lower atmosphere shows temperatures decreasing with height, and is analogous to the Earth's troposphere. The heat balance in the middle atmosphere is dominated by heating due to absorption of sunlight in near infrared CO_2 bands and cooling to space from the 15 μm CO_2 band. In the lower atmosphere the heat balance is more complicated and not fully understood. The solar heating is well constrained by direct measurements of solar flux

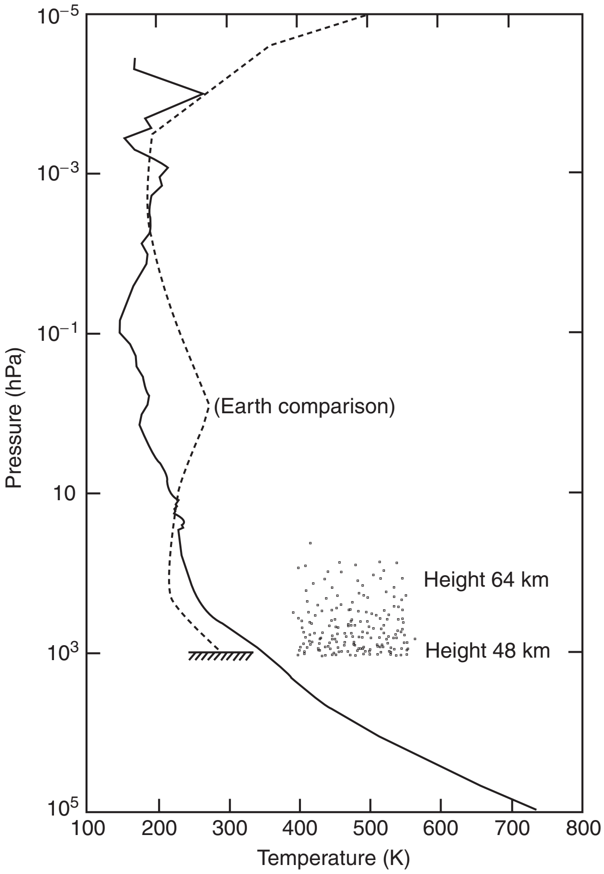

Figure 1 Temperature and pressure in the Venusian atmosphere. Measurements are from the *Pioneer Venus* sounder probe, which entered near the equator (Sieff *et al.* 1980). The dotted line shows a mean profile for the Earth's atmosphere and indicates the Earth's surface pressure. Absorption of ultraviolet by ozone on Earth produces a stratospheric temperature maximum with no counterpart on Venus. The approximate location of the Venusian clouds is indicated.

by entry probes. About 76% of the insolation is reflected. The global average absorption is about $F = 157\,\mathrm{W\,m^{-2}}$, which implies an effective temperature for emission to space of 229 K. Thus the net energy input is smaller than on Earth (where it is approximately $240\,\mathrm{W\,m^{-2}}$, giving an effective emission temperature of 255 K) because of the high reflectivity of the Venusian cloud deck. More than half of the solar energy is absorbed in the cloud deck, between heights of about 50 and 70 km. About 10% of the solar absorption is at the planetary surface. The remainder is smoothly distributed gas absorption. The large heat input in the cloud deck, about 60 km, or five scale heights, above the surface, is a very different driver for meteorology compared with that on Earth, where the bulk of the solar heating is near or at the surface.

Thermal radiation flux is less well understood than the solar flux. The high infrared opacity of the major constituent, CO_2, is important in producing a strong greenhouse effect. But even a small spectral 'window' for leakage of radiation to space can greatly reduce the effectiveness of a greenhouse, and trace gases such as SO_2 and H_2O are important in filling spectral windows on both sides of the 15 μm CO_2 band on Venus. SO_2, H_2O and other trace gases are spatially and temporally variable on Venus, and measurements of their distribution are sparse. Furthermore, at the high temperatures and pressures of the lower atmosphere of Venus, the opacities of many gases are not well known. The spectral distribution of the thermal radiation flux has not been directly measured within the Venusian troposphere. Nevertheless, radiative modeling based on the best estimates of composition has successfully reproduced the Venus greenhouse, and the greenhouse explanation for high surface temperature on Venus is widely accepted.

Four *Pioneer Venus* entry probes measured temperature profiles in 1979, at different latitudes. The profile displayed in **Figure 1** was near the equator. The troposphere temperature increases monotonically with depth but the gradient is not uniformly close to the adiabatic gradient. There is a stable layer near 0.3 MPa pressure, and another near 3 MPa. The middle atmosphere, where the pressure is less than 0.03 MPa, is of course also stably stratified. Thus the vertical structure comprises alternating layers, each a scale height or two thick, with nearly adiabatic, low-stability regions within the cloud deck near 0.1 MPa pressure, below the clouds near 2 MPa, and possibly also near the surface. All four of the profiles measured by *Pioneer Venus* showed similar stratification properties. A pair of Russian balloon probes in 1985 gave evidence for strong vertical motions, probably due to convection, in the low-stability layer within the cloud deck. The layered stability structure of the Venusian troposphere is probably important in controlling atmospheric dynamics, but wind measurements are too limited to reveal the effects.

The orbital period of Venus is 224.70 Earth days. Its spin about its axis is in the opposite direction, with a period of 243.02 days. In combination, these motions produce a solar day on Venus of 116.75 days. In spite of this long time, there is very little day–night temperature contrast in the lower atmosphere. A radiative time constant based on the average thermal cooling rate and the entire atmospheric mass is $t_R = c_p p T_M/(gF)$, where c_p is the heat capacity, p is the surface pressure, T_M is the mean atmospheric temperature, g is the acceleration of gravity, and F is the average thermal flux to space. With $c_p = 800\,\mathrm{J\,kg^{-1}}$, $p = 9.2\,\mathrm{MPa}$, $T_M = 600\,\mathrm{K}$, $g = 8.87\,\mathrm{m\,s^{-2}}$, and $F = 157\,W\,m^{-2}$, one obtains $t_R \sim 100$ years. On the other hand, a radiative time constant based on the atmospheric mass near and above the cloud deck is only a few days, and indeed measurements have shown that thermally driven tides are significant at these heights, with an amplitude of a few kelvins.

There is very little latitudinal temperature contrast in the lower atmosphere of Venus. Here again the large thermal time constant is probably responsible. As long as dynamical transport times are shorter than the radiative time constant, heat should be well mixed laterally. The situation is probably analogous to that in the deep ocean basins on Earth. Within the clouds, however, there is a latitudinal temperature gradient, cooler toward the poles by about 20 K. At higher elevations the temperature gradient reverses.

Chemical Stability of the Venusian Atmosphere

Above the cloud tops, absorption of solar UV radiation by CO_2 leads to its dissociation into CO and O. Most of the O atoms recombine to form O_2. The restoration of CO, O, and O_2 back to CO_2 is effected by catalysis involving chlorine atoms derived from the photolysis of trace amounts of HCl in the Venusian atmosphere. The catalytic mechanism is similar to that proposed for the destruction of the terrestrial ozone layer by chlorine atoms derived from anthropogenic chlorofluorocarbons. Chlorine chemistry also catalyzes the oxidation of SO_2 to H_2SO_4. The essence of the chemical scheme may be summarized as in **Scheme 1**. $ClC(O)O_2$ is the peroxychloroformyl radical; ClCO is the chloroformyl radical; and M is a third body (ambient atmosphere).

On decadal time scales, the composition of the atmosphere may be subject to perturbations by episodic volcanic eruptions. However, there is no proof that the reported secular variations in SO_2 abundance can be attributed to volcanic processes. It is conceivable that the observed changes are the result of a coupled upper atmosphere and lower atmosphere oscillation (the analogue of El Niño in the terrestrial tropical atmosphere). Over geological time scales, both H_2O and SO_2 are unstable. The loss and resupply of these gases might have induced profound climatic changes and could provide an explanation of the tectonic deformations of the crust observed by the *Magellan* mission radar mapping.

$$\begin{aligned}
&Cl + CO + M \rightarrow ClCO + M\\
&ClCO + O_2 + M \rightarrow ClC(O)O_2 + M\\
&ClC(O)O_2 + Cl \rightarrow CO_2 + ClO + Cl\\
&SO_2 + h\nu \rightarrow SO + O\\
&SO_2 + O + M \rightarrow SO_3 + M\\
&SO_3 + H_2O + M \rightarrow H_2SO_4 + M\\
&SO + ClO \rightarrow SO_2 + Cl\\
&\overline{\hspace{16em}}\\
&CO + O_2 + SO_2 + H_2O \rightarrow CO_2 + H_2SO_4
\end{aligned}$$

Scheme 1

The Venusian Clouds

The Venusian clouds are featureless and opaque in the visible. Absorption in the blue gives the planet a slight overall yellowish tint to the eye. Absorption becomes strong at ultraviolet wavelengths, and also shows contrast that reveals cloud patterns. **Figure 2** displays an ultraviolet image taken by the *Pioneer Venus* spacecraft in 1980. The identity of the ultraviolet absorber is unknown, but is most likely polysulfur. The principal component of the cloud is a haze of sulfuric acid droplets of radius about 1 μm. The gaseous precursor of the sulfate particles is SO_2, but the ultimate source of sulfur is COS from the surface. Once transported to the upper atmosphere, COS is readily oxidized to SO_2, using the oxygen derived from CO_2 photolysis. The oxidation of SO_2 to H_2SO_4

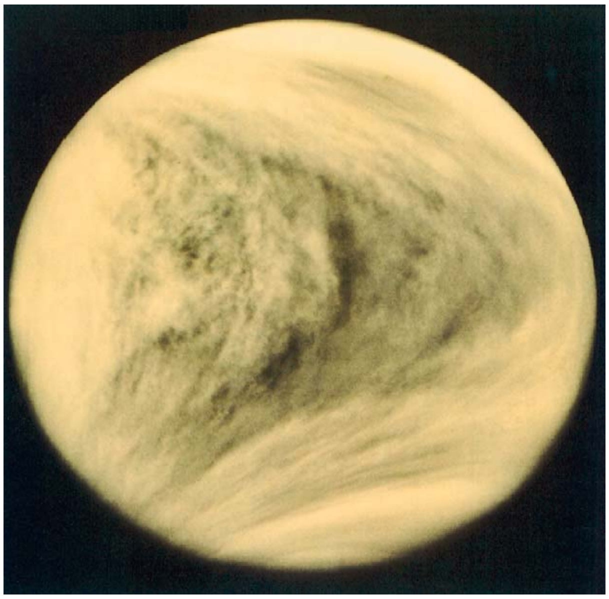

Figure 2 Ultraviolet image of Venus from the *Pioneer Venus* orbiter (Rossow *et al.* 1980). North is at the top. The general circulation is from east to west (toward the left) and appears to spiral toward the poles. The large-scale dark pattern centered on the image is the 'Y' discussed in the text as a possible traveling wave.

has been described in the previous section. However, in regions of the atmosphere where O_2 is deficient, COS may be reduced to S_x, (polysulfur). Visibility within the haze is a few kilometers. The base of the cloud is at approximately 48 km elevation, where the pressure and temperature are about 0.13 Mpa and 365 K. Near the cloud base the *Pioneer Venus* probes detected a relatively thin layer, about 2 km deep, containing larger particles and higher number densities than in the main cloud. There is no sharp top to the cloud. The density tapers off gradually between 60 and 75 km elevation. At 65 km the pressure and temperature are about 0.01 Mpa and 245 K. In addition to their obvious impact on climate, the clouds of Venus have an important effect on atmospheric chemistry. The sulfate particles completely dehydrate the upper atmosphere. The process is analogous to the removal of water vapor by the cold trap at the tropopause of the Earth's atmosphere.

The General Circulation

Figure 3 displays wind velocities measured by the four *Pioneer Venus* probes in 1979. Numerous Russian probes have produced similar results. The flow is dominated by an easterly zonal wind increasing with height up to approximately the top of the visible clouds, where it reaches about 100 m s^{-1}. This represents a rotation of the atmosphere in the same direction as that of the solid planet, but with a period of about 4 days within the cloud, about 50 times faster than the rotation of the solid planet. **Figure 3** shows that meridional (south–north) velocities are much smaller than zonal winds in the deep atmosphere.

The falling *Pioneer Venus* probes were only able to measure wind between the surface and about the 65 km level within the clouds. The ultraviolet features shown in **Figure 2** are slightly higher, near the cloud tops, probably at about 65–70 km elevation. Tracking of these features shows zonal motions consistent with probe measurements, but with the advantage that a complete latitudinal profile can be measured. These profiles vary over time scales of a year or so. Sometimes a well-defined high-latitude jet exists, and at other times the profile shows nearly constant angular velocity. The cloud top measurements also show poleward drift with a speed of roughly 10 m s^{-1} in both hemispheres. This may represent the upper branch of a Hadley circulation, and indeed the general appearance of **Figure 2** suggests a flow spiraling toward the poles. The Hadley interpretation may be premature, however, since cloud tracking is not possible on the dark side of the planet and a true zonal mean has not been measured. Solar-fixed tides are known to exist, and may make the day-side measurements unrepresentative of the mean.

The ultraviolet patterns in the Venusian clouds give evidence for large-scale traveling waves. One wave appears in the shape of a 'Y' lying over the equator with its base pointed eastward. The branches of the

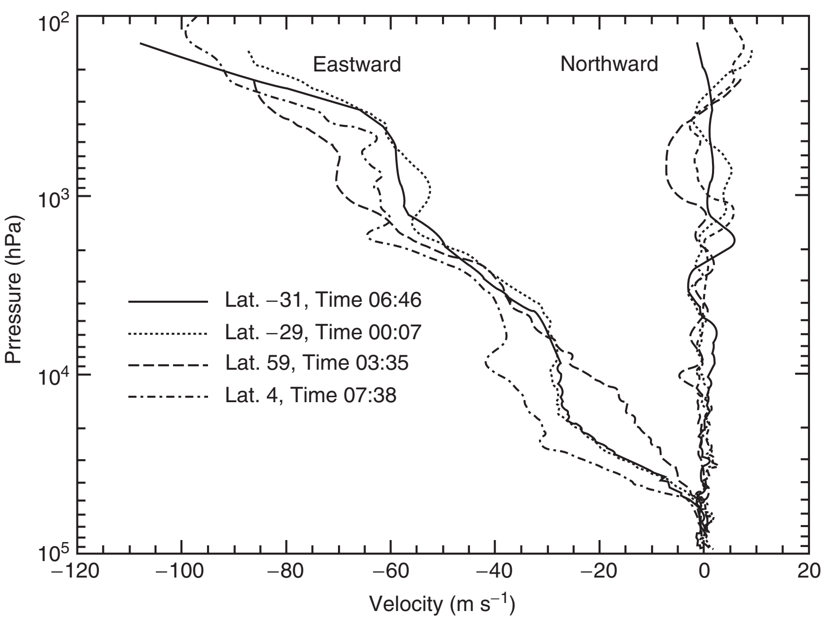

Figure 3 Wind measurements from drifts of *Pioneer Venus* probes (Counselman *et al.* 1980). The east–west component of the velocity is far larger than the south–north component. Vertical shear is smallest at heights where the temperature gradient is closest to adiabatic.

fork in the 'Y' merge into the poleward spiral at mid-latitudes. The pattern remains coherent over many rotations and travels with approximately the same velocity as the cloud top circulation. Another wave is occasionally observed at mid-latitudes, traveling with a slightly slower velocity. The two waves are thought to be Kelvin and Rossby modes respectively, but details of their structure and the nature of their excitation are not known.

The Venusian atmosphere is in *cyclostrophic* balance. Coriolis accelerations are weak because the planet rotates slowly. Cyclostrophic balance is the analogue of Coriolis balance but with centrifugal replacing Coriolis accelerations. An ideal gas atmosphere in hydrostatic and cyclostrophic balance obeys an analogue to the ordinary thermal wind equation of meteorology (eqn [1]),

$$H\frac{\partial}{\partial z}u_a^2 = -\cot\phi\left[\frac{\partial}{\partial \phi}(RT)\right]_{p\ \mathrm{constant}} \quad [1]$$

where the scale height $H = RT/g$, R is the gas constant, z is height, u_a is the absolute zonal velocity in a nonrotating frame, ϕ is latitude, and T is temperature. The latitudinal derivative of temperature is taken at constant pressure. The rotation of the solid planet represents an equatorial velocity of $u_E = 1.8\ \mathrm{m\,s^{-1}}$, and therefore u_a is the same as u displayed in **Figure 3**, but with a small correction equal to $u_E \cos\phi$. In the deep atmosphere this thermal wind equation can be used to infer temperature gradients from the measured vertical wind shear, and one finds that equator-to-pole contrasts of a few degrees are expected, with the high latitudes cooler. More probes at high latitudes would be necessary to measure this directly. Above the cloud tops, where no direct wind information exists, the measurements of temperature increasing toward the poles indicate that the atmospheric circulation decays with height in the middle atmosphere.

The remarkable spin of the Venusian atmosphere is one of the major puzzles in atmospheric science. In the absence of forcing mechanisms, friction and wave drag would be expected to bring the atmosphere into co-rotation with the solid planet. Theories fall into two classes. In one, vertically propagating waves transport momentum from the surface into the atmosphere. The waves would need to be selected or sorted by some process, so that those carrying momentum in the direction of the planetary spin are dominant. This explanation is similar to the accepted explanation for the quasi-biennial oscillation (QBO) in the Earth's stratosphere at low latitudes. The QBO reverses direction approximately every 2 years, however, and, over the 40 years that it has been observed, the direction of the Venus rotation has never reversed.

The other theory relies on a Hadley circulation plus large-scale eddies. The Hadley circulation on Venus is not well measured, but the general appearance of the cloud-top circulation suggests that it extends from the equator to high latitudes. Rising motion at low latitudes transports angular momentum upward in such a circulation. Poleward drift in the upper branch leads to formation of jets at middle and high latitudes. According to the theory, large scale eddies cause erosion of the jets and act to transfer their angular momentum back toward low latitudes. The joint action of the Hadley circulation and the large-scale eddies can maintain the spin, or superrotation, of the atmosphere. This process has been successfully simulated with numerical models. Observational test of the theory is not possible at present, however, because data on the Hadley circulation and on eddies are incomplete.

See also

Evolution of Earth's Atmosphere. **Planetary Atmospheres:** Jupiter and the Outer Planets; Mars.

Further Reading

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