The Pioneer Mission to Venus

This multipart spacecraft spent 14 years scrutinizing the atmosphere, clouds and environs of the nearest planet. The results clarify the stunningly divergent evolutionary histories of Venus and the earth

by Janet G. Luhmann, James B. Pollack and Lawrence Colin

Venus is sometimes referred to as the earth's "twin" because it resembles the earth in size and in distance from the sun. Over its 14 years of operation, the National Aeronautics and Space Administration's Pioneer Venus mission revealed that the relation between the two worlds is more analogous to Dr. Jekyll and Mr. Hyde. The surface of Venus bakes under a dense carbon dioxide atmosphere, the overlying clouds consist of noxious sulfuric acid, and the planet's lack of a magnetic field exposes the upper atmosphere to the continuous hail of charged particles from the sun. Our opportunity to explore the hostile Venusian environment came to an abrupt close in October 1992, when the *Pioneer Venus Orbiter* burned up like a meteor in the thick Venusian atmosphere. The craft's demise marked the end of an era for the U.S. space program; in the present climate of fiscal austerity, there is no telling when humans will next get a good look at the earth's nearest planetary neighbor.

The information gleaned by *Pioneer Venus* complements the well-publicized radar images recently sent back by the *Magellan* spacecraft. *Magellan* concentrated on studies of Venus's surface geology and interior structure. *Pioneer Venus,* in comparison, gathered data on the composition and dynamics of the planet's atmosphere and interplanetary surroundings. These findings illustrate how seemingly small differences in physical conditions have sent Venus and the earth hurtling down very different evolutionary paths. Such knowledge will help scientists intelligently evaluate how human activity may be changing the environment on the earth.

Pioneer Venus consisted of two components, the *Orbiter* and the *Multiprobe.* The *Multiprobe* carried four craft (one large probe and three small identical ones) designed to plunge into the Venusian atmosphere, sending back data on the local conditions along the way. The *Orbiter* bristled with a dozen instruments with which to examine the composition and physical nature of Venus's upper atmosphere and ionosphere, the electrically charged layer between the atmosphere and outer space.

The *Multiprobe* was launched in August 1978 and reached Venus on December 9 of that year. Twenty-four days before its arrival, the *Multiprobe* carrier, or "bus," released the large probe; about five days later the bus freed the three small probes to begin their own, independent courses. The probes approached the planet from both high latitudes and low ones and from both the daylit and nighttime sides. In this way, information relayed by the probes during their descents enabled scientists to piece together a comprehensive picture of the atmospheric structure of Venus.

The *Orbiter* left the earth in May 1978, but it followed a longer trajectory than the *Multiprobe,* so it arrived only five days earlier, on December 4. At that time, the spacecraft entered a highly eccentric orbit that looped to within 150 to 200 kilometers from the planet's surface but carried it out to a distance of 66,900 kilometers. During its closest approaches to Venus, the *Orbiter's* instruments could directly sample the planet's ionosphere and upper atmosphere. Twelve hours later the *Orbiter* would have receded far enough from Venus so that the craft's remote-sensing equipment could obtain global images of the planet and could measure its near-space environment.

The gravitational pull of the sun acted to change the shape of the probe's orbit. Starting in 1986, solar gravity caused the *Orbiter* to pass ever closer to the planet. When the spacecraft's thrusters ran out of fuel, *Pioneer Venus* dove deeper into the Venusian atmosphere on each successive orbit until it met its fiery end.

Well before the arrival of *Pioneer Venus,* astronomers had learned that Venus does not live up to its image as the earth's near-twin. Whereas the earth maintains conditions ideal for liquid water and life, Venus is the planetary equivalent of hell. Its surface temperature of 450 degrees Celsius is hotter than the melting point of lead. Atmospheric pressure at the ground is some 93 times that at sea level on the earth.

Even aside from the heat and the pressure, the air on Venus would be utterly unbreathable to humans. The earth's atmosphere is about 78 percent nitrogen and 21 percent oxygen. Ve-

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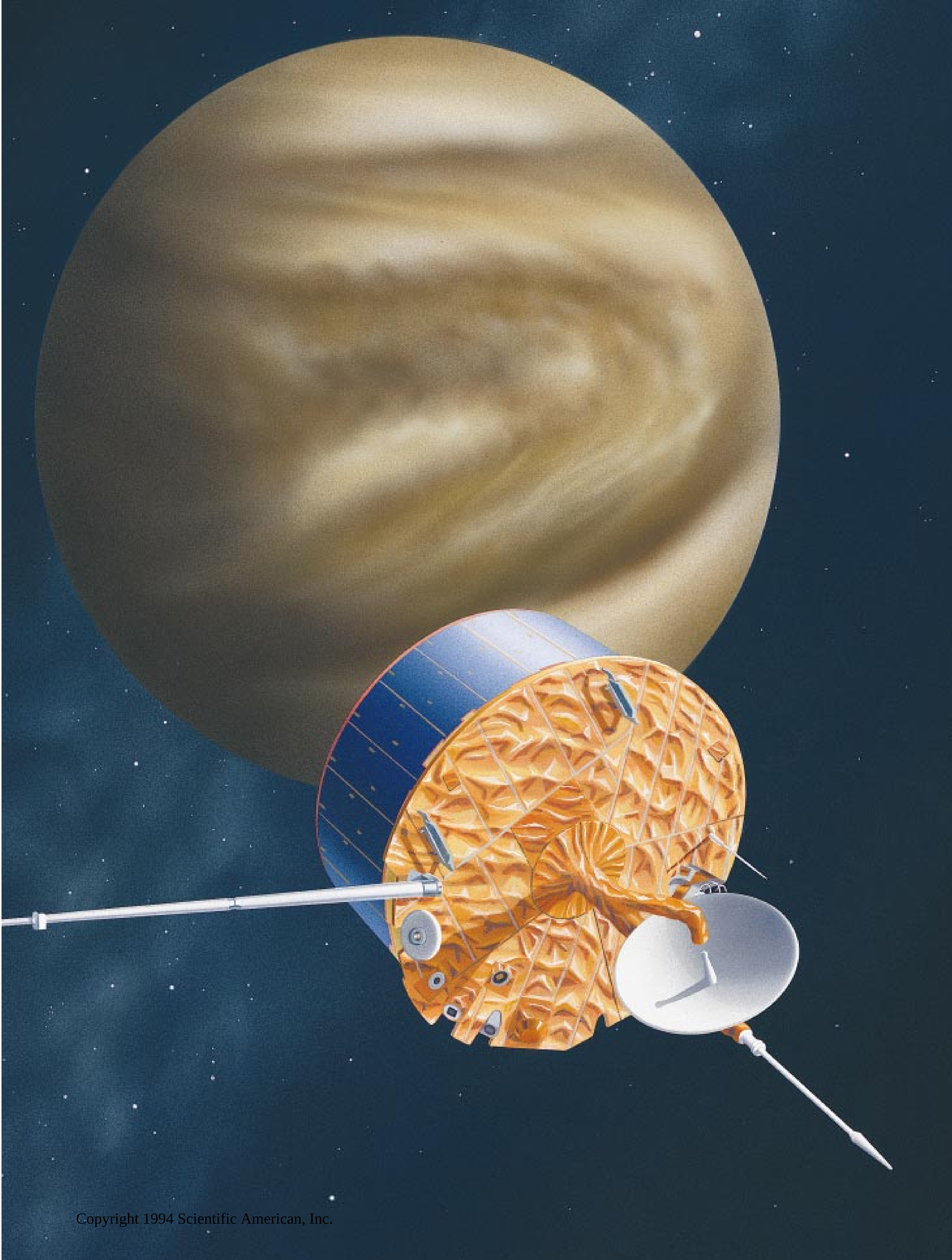
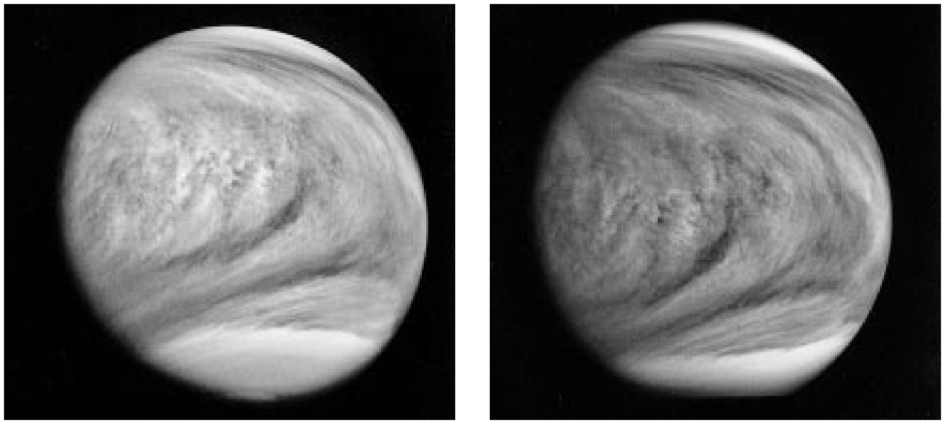
PIONEER VENUS ORBITER **regularly passed less than 200 kilometers above the planet's thick clouds of sulfuric acid, seen in exaggerated contrast in this artist's conception. During its 14-year lifetime, the probe circled Venus 5,055 times, gathering extensive information on the planet's atmosphere and outer surroundings.**



RAPID WINDS at Venus's cloud tops move 60 times as fast as the body of the planet. These false-color ultraviolet images from the *Pioneer Venus Orbiter* (*right*) show the quickly shifting cloud patterns. Atmospheric circulation is driven by solar radiation, which produces a north-south flow, known as a Hadley cell (*far right*). The rotation of the atmosphere transforms Hadley cells into predominantly westward zonal winds, which may be amplified by eddies.

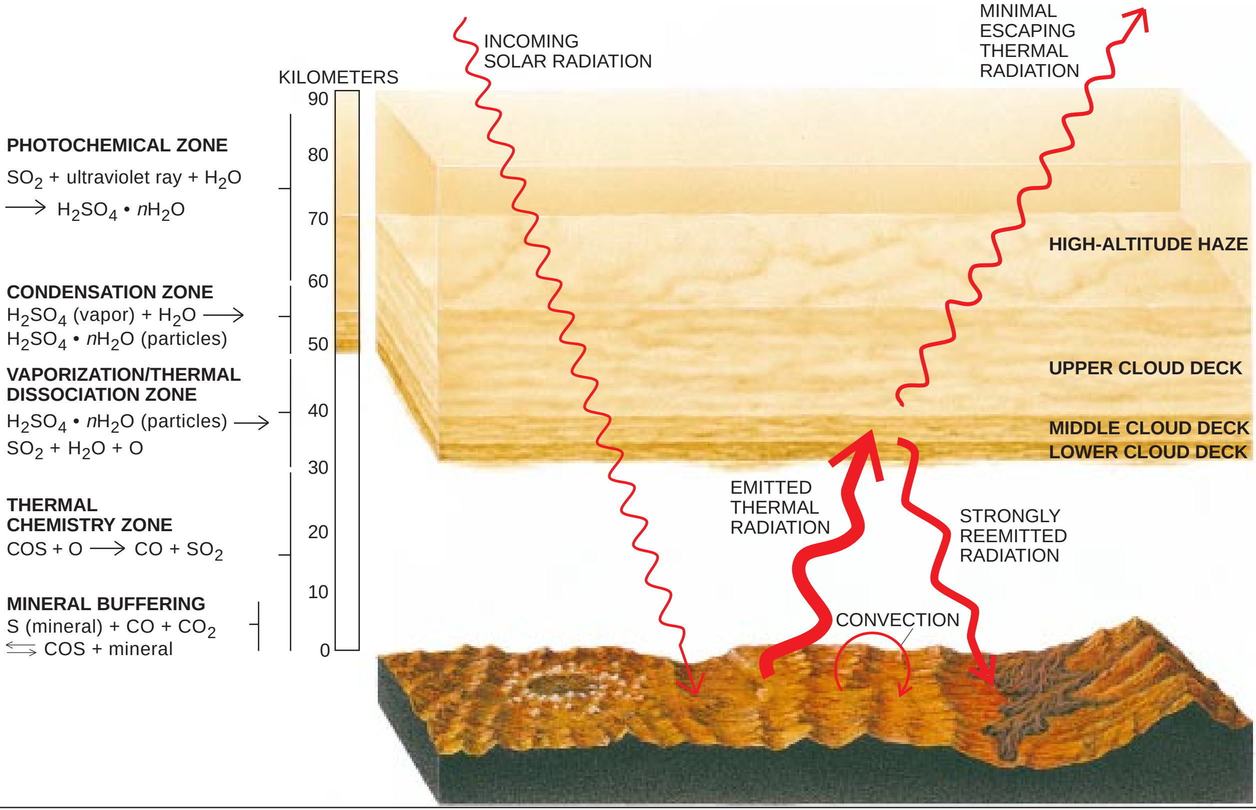


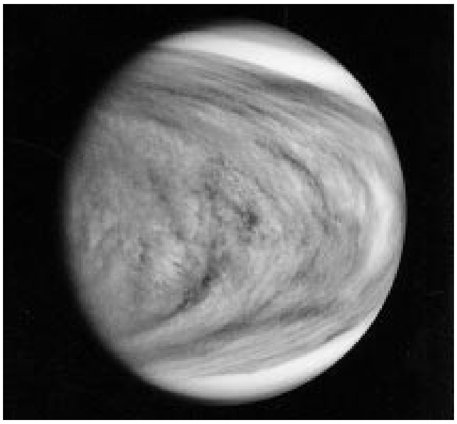
nus's much thicker atmosphere, in contrast, is composed almost entirely of carbon dioxide. Nitrogen, the next most abundant gas, makes up only about 3.5 percent of the gas molecules. Both planets possess about the same total amount of gaseous nitrogen, but Venus's atmosphere contains some 30,000 times as much carbon dioxide as does the earth's. In fact, the earth does hold a quantity of carbon dioxide comparable to that in the Venusian atmosphere. On the earth, however, the carbon dioxide is locked away in carbonate rocks, not in gaseous form in the air. This crucial distinction is responsible for many of the drastic environmental differences that exist between the two planets.

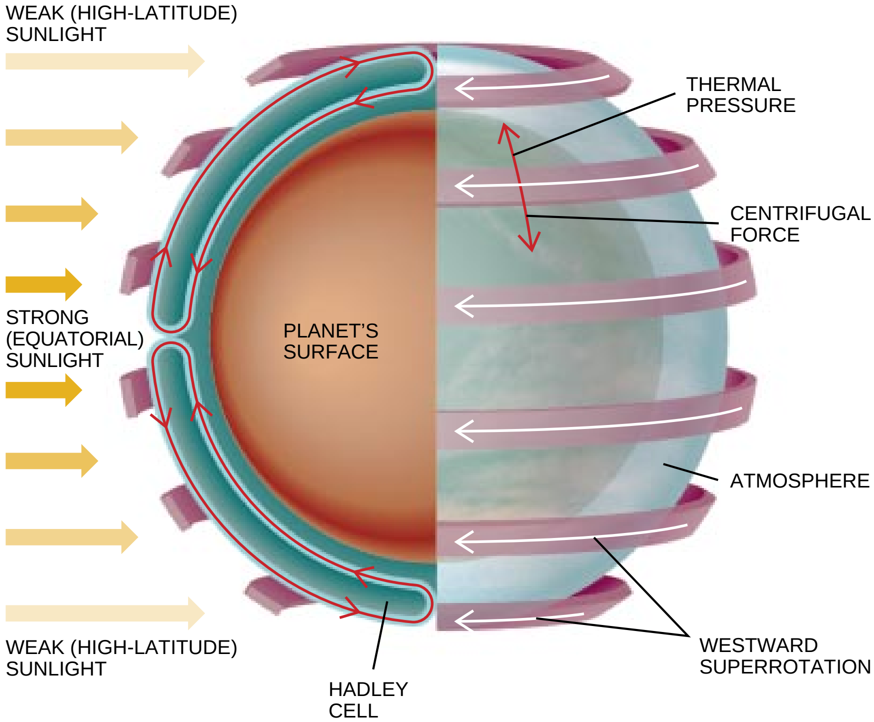
The large *Pioneer Venus* atmospheric probe carried a mass spectrometer and gas chromatograph, devices that measured the exact composition of the atmosphere of Venus. One of the most

The Hot, Poisonous Venusian Atmosphere

The opaque clouds and dense atmosphere of Venus effectively trap and reemit thermal radiation, resulting in a scorching surface temperature of 450 degrees Celsius. Convection acts inefficiently at removing heat from the surface. The clouds are the product of a chemical cycle involving the element sulfur (S). Through the mineral buffering process, sulfur from surface rocks reacts with carbon monoxide (CO) and carbon dioxide (CO_2) in the atmosphere to yield carbonyl sulfide (COS), which in turn interacts with oxygen-rich gases (O) to produce sulfur dioxide (SO_2). In the photochemical zone atop the clouds, sulfur dioxide interacts with water (H_2O) and solar ultraviolet rays, giving rise to sulfuric acid droplets (H_2SO_4). These droplets slowly sink through the condensation zone; along the way, they grow through mutual collisions and through drawing sulfuric acid vapor and water from the air. In the hot regions closer to the ground, the particles vaporize and dissociate into sulfur dioxide and water vapor.







stunning aspects of the Venusian atmosphere is that it is extremely dry. It possesses only a hundred thousandth as much water as the earth has in its oceans. If all of Venus's water could somehow be condensed onto the surface, it would make a global puddle only a couple of centimeters deep.

Unlike the earth, Venus harbors little if any molecular oxygen in its lower atmosphere. The abundant oxygen in the earth's atmosphere is a by-product of photosynthesis by plants; if not for the activity of living things, the earth's atmosphere also would be oxygen poor. The atmosphere of Venus is far richer than the earth's in sulfur-containing gases, primarily sulfur dioxide. On the earth, rain efficiently removes similar sulfur gases from the atmosphere.

Minor constituents of the Venusian atmosphere that were detected by *Pioneer Venus* offer clues about the internal history of the planet. The inert gas argon 40, for instance, is produced by the decay of radioactive potassium 40, which is present in nearly all rocks. As a planet's interior circulates, argon 40 that is trapped in deep rocks works its way to the surface and into the atmosphere, where it accumulates over the eons. *Pioneer Venus* found significantly less argon 40 in Venus's atmosphere than exists in the earth's. That disparity reflects a profound difference in how mass and heat are transported from each planet's interior to its surface. *Magellan* recently found evidence of earlier widespread volcanism on Venus but no signatures of the plate tectonics that keep the earth's surface geologically active and young.

Pioneer Venus revealed other ways in which Venus is more primeval than the earth. Venus's atmosphere contains higher concentrations of inert, or noble, gases—especially neon and other isotopes of argon—that have been present since the time the planets were born. This difference suggests that Venus has held on to a far greater fraction of its earliest atmosphere. Much of the earth's primitive atmosphere may have been stripped away and lost into space when our world was struck by a Mars-size body. Many planetary scientists now think the moon formed out of the cloud of debris that resulted from such a gigantic impact.

Venus's thick, carbon dioxide–dominated atmosphere is directly responsible for the inhospitable conditions on the planet's surface. On an airless body like the moon, the surface temperature depends simply on the balance between the amount of sunlight the ground absorbs and the amount of heat it emits back into space. The presence of an atmosphere complicates the situation. An atmosphere blocks some sunlight from reaching the surface and helps to carry heat upward. But more significantly, the atmospheric gases absorb infrared (thermal) radiation from the ground and reemit it back. The resultant warming of the surface is called the greenhouse effect because the atmosphere functions like a greenhouse: sunlight can get in, but infrared rays cannot get out, causing temperatures to rise.

The intensity of the greenhouse effect depends on how thoroughly the atmospheric gases capture infrared radiation. The principal greenhouse gases on the earth—carbon dioxide and water vapor—absorb complementary parts of the infrared spectrum. Adding more of these gases to the air would, in theory, increase the efficiency of the greenhouse effect, which is why people worry about the climatic impact of carbon dioxide released by human activities. The earth's atmosphere is largely transparent to infrared rays having wavelengths between eight and 13 microns, or millionths of a meter (although ozone, methane, freon and other gases do absorb rays in narrow portions of this band). This open "window" in the atmospheric greenhouse limits the amount of warming that the earth experiences.

Pioneer Venus showed that the greenhouse effect operates much more efficiently on Venus. Data from the four atmospheric probes enabled workers to construct a mathematical model that closely matches the observed temperatures at various altitudes. From that model, it was deduced that carbon dioxide is the most significant greenhouse gas on Venus but that its action is enhanced by the presence of water vapor, clouds, sulfur dioxide and carbon monoxide. The mixture of gases and particles in the Venusian atmosphere blocks thermal radiation at virtually all wavelengths, preventing heat from escaping into space and yielding torrid surface temperatures. These results emphasize the importance of learning more about how human-generated greenhouse gases might affect the terrestrial climate.

Astronomers have long wondered how Venus turned out so hot and dry compared with the earth, especially given that Venus and the earth probably started out with similar overall compositions. According to present theory, the two planets grew by colliding with and absorbing smaller bodies. In the process, each protoplanet would have scattered some smaller bodies into orbits that would have crossed the other protoplanet's path. Hence, the earth and Venus should have accumulated comparable quantities of water-rich bodies even if, at first, water was irregularly distributed through the infant solar system. The roughly equal quantities of carbon dioxide and nitrogen on the two planets support the notion that they once had comparable amounts of water as well.

The young earth and Venus quickly developed thick atmospheres consisting of gases expelled from their interiors and of the vaporized remains of icy, impacting bodies. Water in the earth's atmosphere condensed into lakes and oceans, which proved crucial to the planet's climatic development. Much of the airborne carbon dioxide was quickly sequestered into solid carbonate, a process that occurs through the chemical weathering of rocks in the presence of liquid water.

Venus, too, may have had broad oceans during its youth. The newborn sun was about 30 percent less luminous than it is at present, so temperatures on Venus could have been well below the boiling point of water. (Venus orbits at 0.72 times the earth's distance from the sun.) As the sun brightened, however, surface temperatures on Venus eventually rose above boiling. From then on, any carbon dioxide exhaled by volcanoes or delivered by impacts on Venus could no longer be removed from the atmosphere by chemical weathering. As carbon dioxide accumulated in the atmosphere, the greenhouse effect grew ever more intense. The ultimate result was the sizzling, carbon dioxide–dominated world of today.

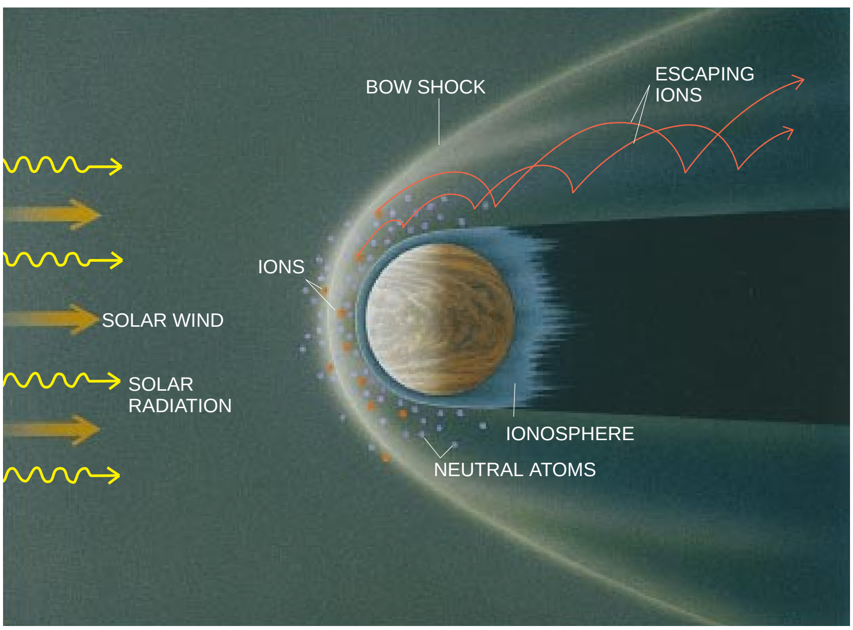
After the oceans boiled, the atmosphere of Venus should have been full of water vapor—in clear contrast to the data. Where has all the water gone?

Pioneer Venus has helped answer that question. The spacecraft documented that even now Venus continues to lose water. Water molecules that wander above the cloud tops react with solar radiation and other molecules. In the process the water molecules split into their oxygen and hydrogen components. The lightweight hydrogen atoms may escape into space by interacting with energetic atoms and ions in the upper atmosphere or with the solar wind, a flow of charged particles that issues from the sun. The leftover oxygen atoms may combine with minerals on the surface, or they, too, may escape by interacting with the solar wind.

A few billion years ago Venus's upper atmosphere contained much more water than it does now; the early sun also emitted far more energetic ultraviolet rays. Both factors greatly hastened the rate at which Venus's water was destroyed and carried off into space. Calculations indicate that over the 4.5-billion-year lifetime of the solar system, Venus could have lost as much water as resides in the earth's oceans.

The earth never experienced such large losses of water because of its moderate surface temperature. Water on the earth stays mostly on the ground or in the lower atmosphere; very little reaches the upper atmosphere, where it may disappear forever. Once the oceans of Venus boiled, in contrast, the planet's atmosphere grew ever hotter, driving more and more water vapor into the upper reaches of the atmosphere.

And yet some water remains. Observations of Venus's upper atmosphere made by the *Pioneer Venus Orbiter* imply that the planet now loses about 5×10^{25} hydrogen atoms and ions each second. At that rate, the entire amount of water in the atmosphere would be gone in about 200 million years. Venus is more than 20 times that old, so some mechanism must replenish the water that Venus is constantly losing. The water most likely derives from a mix of external sources (such as the impact of comets and icy asteroids) and internal ones (through volcanic eruptions or more widespread and steady outgassing to the surface). Because the understanding of Venus's water loss is still quite sketchy, it is possible that *Pioneer Venus* might actually have observed the last trickle from the planet's water-rich early atmosphere.



SOLAR WIND INTERACTS directly with the upper atmosphere of Venus because the planet has no substantial magnetic field. Where the solar wind skirts around the planet, a bow shock forms. Some neutral atoms (*purple*) at the top of the Venusian atmosphere become electrically charged ions (*orange*) that are then carried off in the solar wind. Radiation from the sun also gives rise to a permanent, charged layer, the ionosphere (*blue zone*), which forms at lower altitudes around the planet.

Despite its lack of water, Venus is cloaked in thick clouds that conceal its surface from conventional telescopes. The nature of those clouds has intrigued astronomers for centuries. By the time of the Pioneer Venus mission, planetary scientists had accumulated strong evidence that the clouds were largely composed of concentrated solutions of sulfuric acid and water. They could not determine, however, the source of the sulfur from which the cloud droplets arose.

Pioneer Venus finally settled the question. As the *Orbiter* circled the planet, it scrutinized the tops of the clouds using its ultraviolet spectrometer, which identifies the characteristic pattern of emission and absorption from various atoms and molecules. Also, the gas chromatograph on the large probe measured the composition of the region below the main cloud deck. The results of these studies show that the sulfuric acid in the clouds derives from sulfur dioxide in the atmosphere.

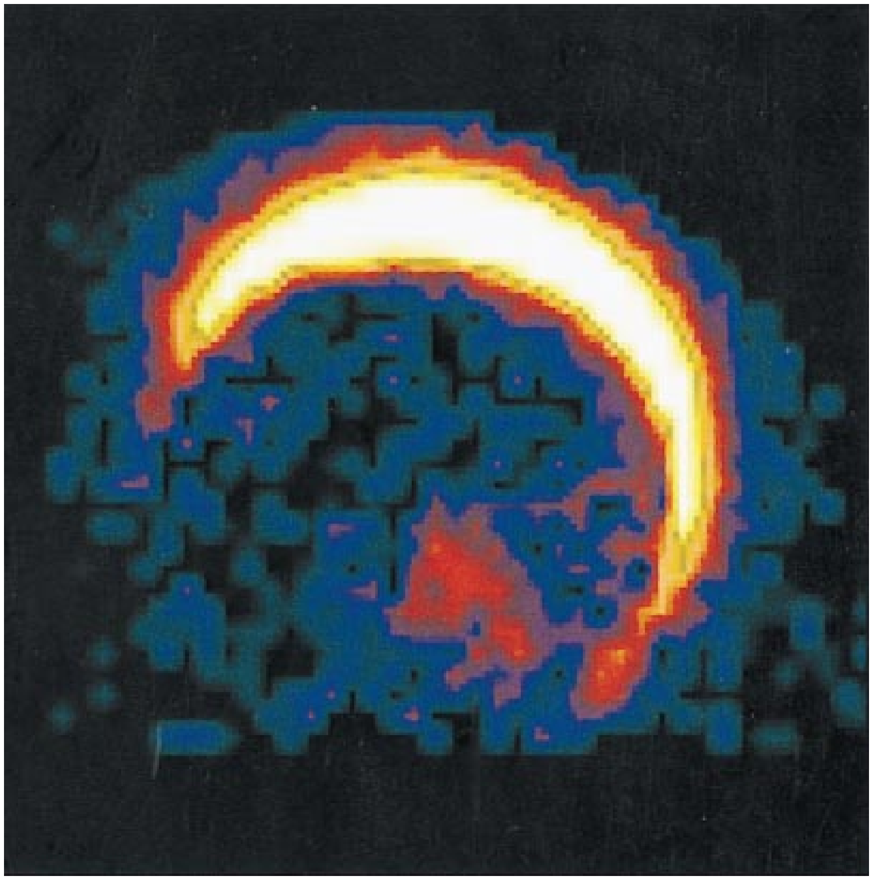
Near the top of the clouds, some 60 to 70 kilometers above the ground, ultraviolet rays from the sun split sulfur dioxide into molecular fragments known as radicals. These radicals undergo a series of chemical reactions with radicals derived from water, ultimately producing tiny droplets of sulfuric acid. Gravity and air currents cause the droplets to migrate downward. As the droplets fall, they grow by colliding with one another and by accumulating sulfuric acid vapor from the air. At and below the base of the clouds, sulfuric acid particles dissociate back into sulfur dioxide and water vapor.

Instruments on the *Pioneer Venus* probes detected tiny particles (less than a thousandth of a millimeter across) at altitudes between 48 and 30 kilometers, just below the base of the cloud deck. Atmospheric motions carry these particles, along with sulfuric acid vapor, to higher, colder altitudes. There the sulfuric acid rapidly condenses onto the particles, producing much larger cloud particles that are concentrated toward the clouds' base. The density of those particles varies from place to place in the lower cloud region, probably because of irregularities in the upwelling and downwelling motions.

A related *Pioneer Venus* observation has stirred great excitement and controversy. In the course of exploring Venus's sulfur chemistry, the *Orbiter* detected an apparent, steady decrease in the concentration of sulfur dioxide near the tops of the clouds. Some workers interpreted that measurement as evidence that a giant volcanic eruption spewed sulfur into the atmosphere just about the time that *Pioneer Venus* arrived—a tantalizing sign that Venus might have active, explosive volcanoes. Once the eruption ceased, the sulfur levels would have begun to drop, as observed. Other investigators have argued that the changes in composition could have resulted from normal variations in the atmospheric circulation. The issue remains frustratingly unsettled.

Although it could not resolve the sulfur dioxide puzzle, *Pioneer Venus* has provided many other intriguing details about the circulation of the Venusian atmosphere. Such information is a tremendous boon for scientists attempting to understand atmospheric dynamics because it shows how weather patterns operate on a planet that differs from the earth in several crucial aspects.

Venus rotates extremely slowly; the earth completes 243 daily rotations in the time it takes Venus to turn once with respect to the stars. Also, because of the dense atmosphere, the surface temperature on Venus is nearly constant, from equator to pole. One might naively assume, therefore, that winds on Venus would be very sluggish.



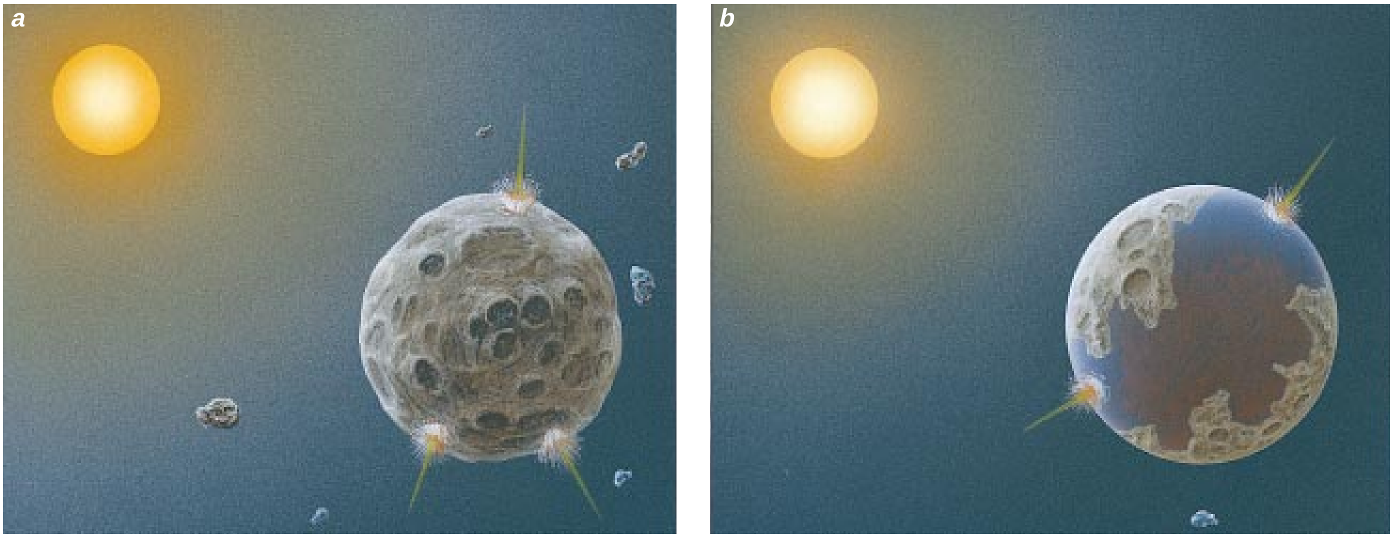
NIGHTSIDE AURORA shows up in this false-color ultraviolet image from the *Pioneer Venus Orbiter*. The bright crescent is the dayside of the planet, which reflects solar ultraviolet rays. The patchy auroras on the nightside occur when energetic particles, possibly from the solar wind, crash into the Venusian atmosphere.

Pioneer Venus proved that assumption false. On the earth, winds at low latitudes move more slowly than the rotation of the planet, whereas those at higher latitudes exceed the speed of the surface, a state known as superrotation. The atmosphere of Venus superrotates at all latitudes and at all heights from close to the surface to at least 90 kilometers above the surface. The winds attain their peak velocity near the cloud tops, where they blow at an unexpectedly rapid 100 meters a second, about 60 times as fast as the rotation of the underlying surface.

Winds in the atmospheres of the earth and the other terrestrial planets are driven by local imbalances between the amount of incoming solar energy and the amount of outgoing, radiated heat. In general, low latitudes, which receive the most sunlight, experience a net heating, whereas high latitudes, which receive the least incident solar energy, undergo a net cooling. As a result, the atmosphere develops a large-scale circulation pattern called a Hadley cell. In this pattern, hot air rises near the equator and travels toward the poles, where it sinks and returns toward the equator.

The spinning of a planet on its axis deflects the north-south (meridional) winds sideways, however, giving rise to east-west, or zonal, winds. Surprisingly, zonal winds almost always end up being much stronger than the north-south winds from which they derived. On the earth, Hadley circulation dominates atmospheric motions at low latitudes. Zonal winds close to the equator move slower than the earth's rotation (and hence are called easterlies); those closer to the poles form superrotating westerlies, culminating in the rapid flow of the jet stream. What is so odd about Venus's zonal winds is that they superrotate at almost all latitudes in the lower atmosphere.

Even now, planetary scientists do not fully understand why the entire lower atmosphere of Venus superrotates. The large fraction of solar energy that is absorbed high in the atmosphere, near the tops of the clouds, probably contributes to the brisk winds. The high-altitude heating of the atmosphere may set up a circulation system that is much less influenced by frictional interaction



EVOLUTIONARY HISTORY of Venus explains its present harsh surface conditions. During the first several hundred million years of its existence (*a*), Venus collected water and other frozen gases from collisions with icy bodies originating in the outer solar system; at the same time, water and other gases in the planet's interior emerged through volcanoes. The early sun may have been dim enough to permit the existence of hot oceans on Venus (*b*). As the sun grew brighter,

with the surface than is the case on the earth. The atmosphere of Venus might therefore be highly susceptible to the formation of eddies that can efficiently transport angular momentum. Such eddies could counteract the ability of the Hadley circulation to prevent superrotation at low latitudes. Cloud images taken by the *Pioneer Venus Orbiter* provide evidence of small-scale, eddylike variations in the winds.

High above the superrotating layers of the Venusian atmosphere lies the ionosphere, an extended zone of electrically charged atoms and molecules, or ions. The ions arise when high-energy ultraviolet rays from the sun knock electrons free from atmospheric gases. Every planet that has a substantial atmosphere possesses an ionosphere, but the one on Venus has a number of unusual traits.

The *Pioneer Venus Orbiter* monitored the passage of radio waves through the ionosphere and, during close approaches to the planet, measured its temperature, density and composition directly. As one might expect, Venus's ionosphere is densest in the center of the dayside hemisphere, near the equator, where the incoming sunlight is most direct. Because of the abundant chemical reactions occurring among the particles, Venus's ionosphere consists primarily of oxygen ions, even though carbon dioxide is the dominant gas at lower levels.

Unlike the earth and most other planets, Venus has no significant global magnetic field, for reasons not fully understood. The absence of a magnetic field significantly affects the structure of Venus's ionosphere. The *Orbiter* detected a weak ionosphere that extends beyond the day-night boundary. This finding was intriguing because, in the darkness, ions and free electrons should quickly recombine into neutral atoms. An instrument on the *Orbiter* found that on Venus ions from the dayside are able to migrate to the nightside. On the earth, the planetary magnetic field in the ionosphere inhibits such horizontal flow.

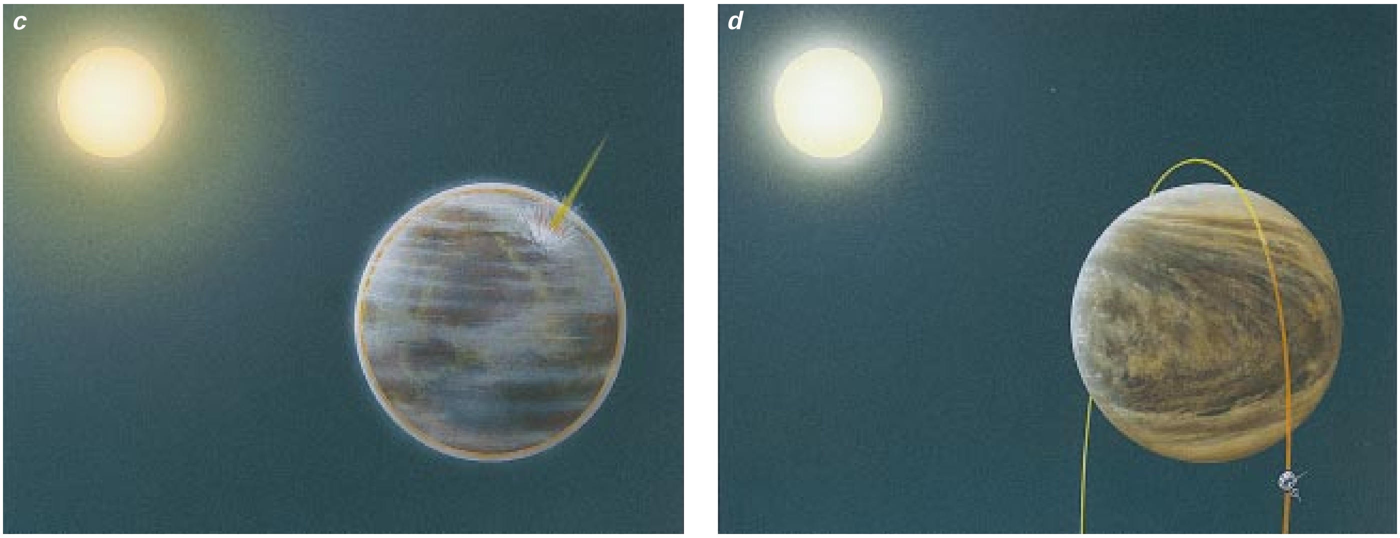
Images of the planet in ultraviolet radiation, obtained using the *Orbiter's* ultraviolet spectrometer, detected a previously unknown, patchy aurora on Venus's shadowed hemisphere. Scientists attribute the aurora to energetic particles, probably fast-moving electrons, that crash into the atmosphere on the nightside. When these particles strike gas molecules in the atmosphere, they excite and ionize the molecules, further contributing to Venus's nighttime ionosphere. The excited molecules soon return to their normal, low-energy state by emitting radiation, which shows up as the aurora.

As is the case for terrestrial auroras, the particles that cause the auroras on Venus derive their energy from the solar wind. The solar wind is the sun's extended, rarefied outer atmosphere. It consists of plasma, or charged particles (primarily protons and electrons), racing from the sun at supersonic speeds. At the orbit of Venus the solar wind has a density of 15 protons and electrons per cubic centimeter and a velocity of 400 kilometers per second. As the solar wind blows past the planets, it carries part of the sun's magnetic field with it.

The intrinsic magnetic fields around the earth and other planets act as obstacles to the electrically charged solar wind. The wind flows around those fields along a surface (the magnetopause) where the pressure of the wind equals the opposing magnetic pressure. The extent of the deflection depends on the strength of the planetary magnetic field. Venus, which has virtually no field at all, creates an obstacle scarcely bigger than the planet itself.

Nevertheless, the spacecraft found that solar-wind plasma was clearly being diverted around Venus. That discovery confirmed theoretical predictions that a planet's ionosphere can effectively block the solar wind even in the absence of a substantial magnetic field. Like a magnetic field, the ionosphere exerts pressure against the wind, but in this case it is the thermal pressure of the charged gas that counters the force of the solar wind. On average, the balance point lies at a 300-kilometer altitude near Venus's noontime equator and at 800 to 1,000 kilometers above the day-night boundary.

The deflection of the solar-wind flow around large obstacles (such as planets) is preceded by a "bow shock," a sharp boundary closely analogous to the shock that forms in front of a supersonic aircraft. During most of its lifetime, the *Pioneer Venus Orbiter* crossed the bow shock twice each lap, enabling it to monitor continuous changes in the magnetic environment around Venus. The craft found that the bow shock expands and contracts in step with the 11-year cycle of solar activity. The ra-



the oceans boiled away, filling the atmosphere with water vapor and leading to significant greenhouse heating. Water in the upper atmosphere broke down into oxygen and hydrogen, which escaped into space (*c*). In the absence of oceans, carbon dioxide from volcanoes accumulated in the atmosphere, further intensifying the greenhouse effect. Sulfur derived from the surface formed sulfuric acid in the clouds. Thus, Venus acquired its present attributes (*d*).

dius of the shock in the plane of the day-night boundary ranges in size from about 14,500 kilometers at solar maximum to 12,500 kilometers at solar minimum. The expansion and contraction probably result from changes in Venus's upper atmosphere associated with the varying radiation flux from the sun.

Just downstream of the bow shock, the solar wind grows more dense, slows down and changes its direction of flow. Magnetic-field lines are frozen into the solar wind because it is completely ionized. After the solar wind passes through the shock, the frozen-in interplanetary magnetic field piles up.

Pioneer Venus mapped the large-scale magnetic-field geometry around Venus. These data give the impression that the magnetic-field lines eventually slip around the obstacle and into the wake that it creates in the solar wind. Researchers refer to this wake structure as an induced magnetotail because it derives from the interplanetary magnetic field rather than from the planet's own field, as is the case for the earth's own, much larger magnetic tail.

Because of its lack of a significant internal field, Venus interacts more directly with the solar wind than does the earth. Over the age of the solar system, that interaction has affected the atmosphere of Venus. The planet's upper atmosphere, where atomic oxygen predominates, extends well above the point at which the solar wind is diverted around the planet. This gas remains largely unaffected by the solar-wind plasma as long as it remains electrically neutral. If an oxygen atom is struck by an ultraviolet ray or if it collides with a particle in the solar wind, it can become ionized. The oxygen ion couples to the flowing plasma, which may carry it away from the planet and out of the solar system.

Instruments on board the *Pioneer Venus Orbiter* confirm that the solar wind truly does scavenge Venus's upper atmosphere. Measurements of the density of the Venusian ionosphere indicate that the uppermost layers—those above the deduced height of the solar-wind obstacle—appear to be missing. Evidently the ions created above the obstacle have been carried off in the manner just described. The *Orbiter* has also detected the oxygen ions escaping tailward in the solar wind. In essence, *Pioneer Venus* has captured a snapshot of one of the processes by which Venus evolved into a world so unlike the earth.

The extensive archive of data generated by *Pioneer Venus* has proved a wonderful resource for scientists studying the planet's atmosphere and near-space environs. Those data are all the more precious given that no nation has any plans for a follow-up venture. At present, major basic science projects face tight funding prospects in all developed countries. Nevertheless, the intriguing questions raised by *Pioneer Venus* have inspired studies for a possible return to the earth's cloud-enshrouded neighbor.

Even relatively inexpensive missions to Venus could deliver valuable results. A simple chemical composition probe, for example, could elucidate the nature of the atmospheric chemistry at various altitudes. A series of small craft deployed simultaneously all around Venus could yield a sharper picture of the planet's global weather patterns. A specialized orbiter could carry instruments to search for lightning storms and to measure in more detail the ions and atoms that escape from the planet. These scientific goals might be accomplished under the auspices of NASA's upcoming series of fast, low-cost "Discovery-class" planetary expeditions.

A better understanding of the global environment on Venus could be considered a worthwhile goal in itself. It also provides a perspective on the nature of the environment on the earth and on the delicate balance of physical processes that keep our world habitable. Planetary missions such as Pioneer Venus clarify the earth's unique place among the worlds of the solar system. For this reason, and to satisfy the fundamental human drive to explore, we hope such missions continue to receive support in the U.S. and abroad.

FURTHER READING

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