Venus: Not Simple or Familiar, But Interesting

The Pioneer Venus mission has struck the final blow to Venus's image as Earth's twin

The convenient idea that Venus, because of its size, heavy atmosphere, and proximity, might in many ways be similar to Earth seems finally to have been given up for good. Images of verdant Venusian jungles or carbonated oceans began to fade as early as 1956 when radio astronomers detected searing temperatures at the planet's surface. Then, Venus appeared increasingly inhospitable and alien as Soviet and American spacecraft first flew by and later orbited the planet. Six Soviet landers have managed to survive only briefly on the surface before expiring.

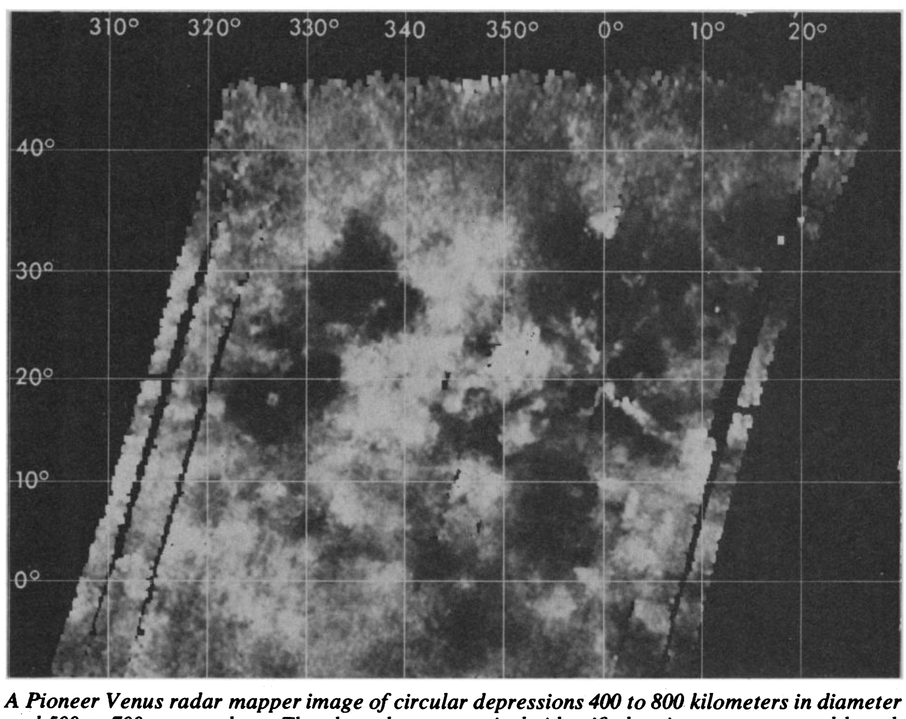
Pioneer Venus, a combination of an orbiter and five atmospheric probes, has now confirmed that the cloud-shrouded surface of Venus is not exactly like the horizontally mobile surface of Earth or the old, stable crust of Mars. In spite of its similarity in size to Earth, Venus seems to have followed its own geological development. In fact, chemical analyses of its atmosphere suggest that some conditions during Venus's formation, when events critical to its geological evolution occurred, were quite different than during Earth's.

One difference seems to have been the incorporation into Venus of the volatile elements, the ones that form atmospheres, oceans, and life itself. The discovery of large amounts of argon, a noble gas, in the Venusian atmosphere has provided a clue about how highly volatile elements, such as noble gases, carbon, hydrogen, and nitrogen, became incorporated into the planets. All of the instruments that have measured argon (the Pioneer and Soviet gas chromatographs and mass spectrometers) have found about 10 to 80 parts per million of argon-36 in the lower atmosphere. Argon-36 was the principal isotope of argon present when the solar system formed. Although this large spread in values has been a matter of intense scrutiny for experimentalists (see box on pages 290 and 291), for theorists it is accurate enough. It appears to them that Venus, when it formed, managed to hold on to 20 to 100 times more argon per gram of rock than Earth did.

This abundance of argon-36 surprised many theorists because it ran counter to the expected trend. That is a bit of a disappointment because researchers had hoped that the amounts of inert, noble gases in a planet's atmosphere could be used to estimate the amounts of volatile but reactive elements, which could be chemically tied up within the planet. It now seems that the incorporation of the volatile elements in the planets occurred in more than one step, so that the amounts of carbon, hydrogen, and nitrogen are not linked to the amounts of the noble gases.

To account for an additional step in the incorporation of volatile elements, theorists have had to postulate a new set of conditions within the ball of gas and dust that preceded the solar system, so that temperature did not always control how much of each volatile element was incorporated. Before Pioneer Venus, some theorists suggested that the temperature of the presolar nebula dropped sharply from its center, where the sun was born at some point, out to its edge. In that case, the lower temperature of the gas and dust near the present orbit of Earth would have allowed more of the volatile elements to be incorporated into the dust grains there than into the hotter ones near the orbit of Venus. It was these dust grains that eventually clumped together to form each planet. In a hypothesis proposed since Pioneer, James Pollack and David Black of Ames Research Center at Moffett Field, California, have suggested that when the noble gases became incorporated in the accreting grains of dust, the temperature increase toward the center of the nebula was not as sharp as had been thought. In that case, the higher pressure near the present orbit of Venus would have forced more noble gases to be adsorbed onto the dust grains than near the orbits of Earth or Mars. Thus, Venus would be argon-rich and Mars would be argon-poor, as has been observed. The incorporation of the reactive volatiles, which must depend on the formation of certain minerals rather than on simple adsorption, would still have responded to varying temperature conditions, perhaps at a different stage of planet formation, rather than to pressure.

The argon results from Venus have



A Pioneer Venus radar mapper image of circular depressions 400 to 800 kilometers in diameter and 500 to 700 meters deep. They have been tentatively identified as impact craters, although they are much shallower than impact craters on other bodies. [Source: National Aeronautics and Space Administration]

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shaken up the field of planetary geochemistry, but in a field in which, according to one researcher, "there are a horrendous number of variables to play with," they have hardly been definitive. Alternative scenarios for the chemical evolution of the early solar system will undoubtedly abound, but the rare gases and the reactive volatiles seem to be separated forever.

Unlike the argon results, the mapping of the surface of Venus by the Pioneer orbiter's radar has confirmed previous tentative conclusions. The radar mapper detected a striking variety of surface features, including volcanoes, plateaus, mountain ranges, craters, and great valleys. Pioneer's special contribution has been to identify most of these features more firmly and to expand the coverage of the surface to show that Venus is a place of its own.

Geologists had had problems deciphering the radar images obtained from Earth because of some inescapable limitations (*Science*, 30 April 1976, p. 454). By an unexplained quirk in the motion of Venus, the same side of Venus is toward Earth each time the two planets are closest together, when the best images can be obtained. Also, ground-based radar must always observe Venus from nearly above its equator. As a result, the sharpest ground-based images, having a resolution of 5 to 15 kilometers, have been limited to narrow bands of latitude on one side of the planet.

The equipment pressed into service to observe Venus, which had been designed for other purposes, also imposed certain limitations. Richard Goldstein and his colleagues at the Jet Propulsion Laboratory in Pasadena, using the Goldstone Deep Space Network Tracking Station antennas, measured both elevation and surface scattering or radar brightness, which is a measure of how rough the surface is on a scale of tens of centimeters. Most of their high-resolution images, however, have been limited by their system's low sensitivity to the vicinity of the equator. Donald Campbell and his colleagues at the National Astronomy and Ionosphere Center at Arecibo, Puerto Rico, have ranged to higher latitudes using their more sensitive 300-meter antenna nestled in a natural bowl in the hills, but they cannot determine elevations, only scattering.

Possible craters appeared in the early images from the JPL group, and their later observations revealed a greater variety of features. Michael Malin of Arizona State University and Stephen Saunders of JPL suggested on the basis of these data that Venus not only has craters, but also has a great troughlike valley (2 kilometers deep and 1400 kilometers long), chains of smaller craters, hills, ridges, and plateaus dotted with mountain peaks. The most striking feature that they described, called Beta, appeared to be a broad volcano, perhaps 10 kilometers high, reminiscent of the huge volcano Olympus Mons on Mars. At Arecibo, Campbell, Barbara Burns, and Val Boriakoff found evidence that a similar variety of features extend over the 30

Doing Science in an Inferno

Exploring other planets has always been a difficult business. Instruments must be tuned up on Earth, rocketed across hundreds of millions of kilometers of space, and then operated under rather inhospitable conditions. The planet Venus has proved to be about the most difficult place in the solar system to study so far. No one thought dealing with an atmospheric pressure 95 times that of Earth, temperatures twice that of a home oven, and mists of concentrated sulfuric acid would be easy, so researchers took precautions with the probes ejected into the Venusian atmosphere by the Pioneer Venus spacecraft in December 1978.

In the end, only one of the experiments that plunged through the Venusian atmosphere for almost an hour finally succumbed. One probe, contrary to plan, even survived for an hour after its crash landing on the surface. But a critical instrument, the mass spectrometer designed to analyze the chemical composition of the atmosphere, gagged on a sample it took in the high clouds of Venus and never quite recovered. The lessons learned could be crucial to a similar experiment that will be launched in 1984 to probe Jupiter's atmosphere.

The mass spectrometer experiment was, everybody knew, an ambitious experiment. Robert Murphy, program scientist for Pioneer Venus, recalls that "We said to ourselves, 'Here are some important characteristics we want to measure, so we're going to try some very difficult things.' "

One of the greatest difficulties was that a mass spectrometer must maintain a high vacuum (one hundred-millionth of an atmosphere of pressure) within itself while allowing gas for analysis to enter from the atmosphere. If too much gas accumulates in the instrument, the individual molecules cannot be ionized, magnetically separated, identified, and quantified. As in Earth-bound instruments, "pumps" were used to remove gases from the Pioneer Venus mass spectrometer before they flooded it completely.

The problem is that no one kind of pump can remove all types of gases. Two kinds of pumps are required—one that removes reactive gases, such as carbon dioxide, by combining them chemically with a metal alloy, and one that removes inert gases, such as argon, by magnetically slinging their ionized atoms into a metal surface and burying them there. The proportions of each compound that the instrument sees during the descent depend on how well each of these pumps does its job. Determining their performance at Venus after 7 months in space, through the use of a backup mass spectrometer under Venusian conditions in the laboratory, is difficult, as John Hoffman and his colleagues at the University of Texas at Dallas report. As a result of these difficulties, the amount of argon is known well enough to prompt new thinking about the formation of the solar system (see accompanying story), but the mass spectrometer has provided only broad bounds on the accuracy of the accompanying gas chromatograph, rather than independently confirming it.

The mass spectrometer's high-vacuum operation indirectly caused another problem when cloud droplets of sulfuric acid on the order of 1 micrometer in size clogged the sample inlet, preventing any analysis of the atmosphere between 50 kilometers and about 30 kilometers. The inlet, a submicron slit at the end of a tantalum oxide tube, had to be small in order to limit the flow of atmospheric gases into the instrument to about 6 millionths of a cubic centimeter percent of the planet that they have surveyed. They noted, though, that "only a small number of possible impact craters have been found and only one area of what could be described as cratered terrain."

"The types of features deduced from ground-based data have been confirmed in every way by Pioneer Venus," according to Gordon Pettengill of Massachusetts Institute of Technology, team leader of the orbiter's radar mapper experiment. The wide-ranging Pioneer has confirmed the existence of some of the previously identified features, expanded coverage greatly, and made minor and not-so-minor revisions in interpretation.

Beta, the proposed volcano, has shrunk in height a bit in Pioneer's elevation data, from a maximum of 10 kilometers to about 4 kilometers above the average elevation of the planet. But Beta is now considered only a part of a chain of apparently volcanic prominences that extends from a similar summit north of Beta along a ridge to the south, stretching farther than the 2000-kilometer length of the Hawaii-Midway volcanic chain in the Pacific.

Beta may have shrunk, but a feature called Maxwell, with similarly bright radar scattering in ground-based images, has taken on huge proportions. Pioneer found it to be 12 kilometers high, the height of Mount Everest; unlike Everest, however, Maxwell towers alone above the surrounding plains and plateaus. On its western side, a pear-shaped feature assumed to be a depression on the basis of ground-based reflectivity data popped up into a plateau 3 kilometers high and twice the size of the Tibetan plateau. It is bounded on the west by a range of mountains 6 kilometers high. This area is now called Terra Ishtar after the Babylonian goddess of love.

To the east of Maxwell is complex terrain composed of ridges and troughs reminiscent of the basin and range pattern of the western United States, according to Harold Masursky of the U.S. Geological Survey in Flagstaff, a radar mapper team member. To the east of this complex terrain is a closed depression, a sag in the crust of Venus larger than the 500,000 square kilometers of the Michigan Basin. Another arrangement of a plateau (called Terra Aphrodite), volcano, and complex terrain has now been identified in the southern hemisphere.

Although many of these features can be compared at this point with some on Earth or Mars, even to the point of calling the plateaus continental masses, researchers are leaning toward Venus's having its own style of surface features. A major reason for this thinking is the curious dearth of great basins on Venus. Like Earth, Venus has high spots that, though few in number, approach a height of 12 kilometers above the average elevation of the planet. But Earth also has extreme depressions below the average elevation, and Venus does not. The tectonic forces that have shaped the surface of Venus have raised only 5 percent of the surface into "continental masses" and left only 15 to 20 percent of it as basins, according to Masursky; Earth's

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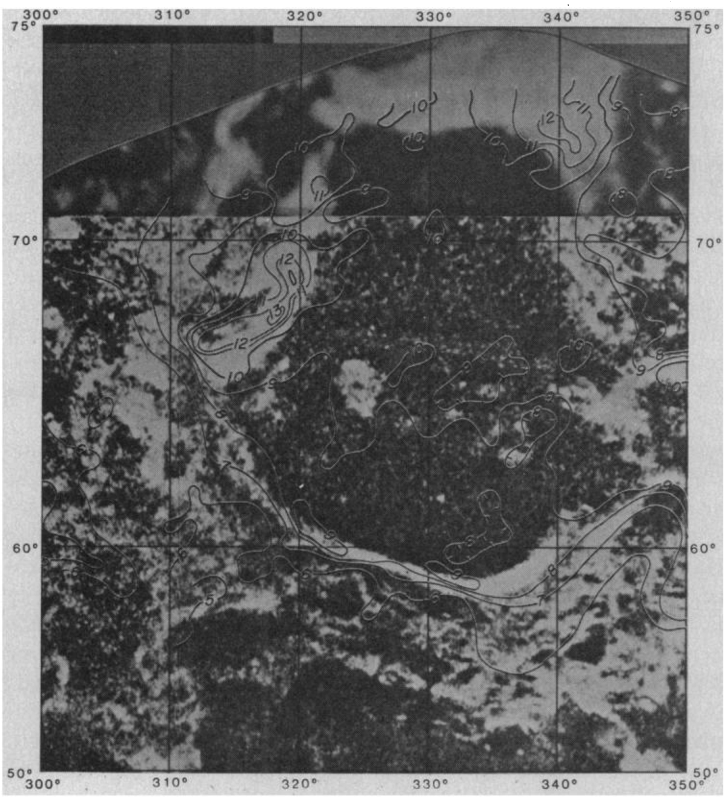
per minute. Even after the blockage cleared itself by evaporation in the hotter lower atmosphere, an apparent reaction of the residual sulfuric acid with the tantalum oxide or other instrument components produced new sulfur compounds. In a laboratory simulation of the clogging, carbonyl sulfide, which was hypothesized by some to play a major role in the cycling of sulfur through the clouds, was produced in increasing amounts after the inlet cleared. Because of these reactions, only one sulfur compound of the several expected, hydrogen sulfide, could be unambiguously identified in the lower atmosphere.

A number of other problems, familiar to mass spectrometrists everywhere, cropped up as well. Water vapor contamination, which was either incompletely removed before launch or which leaked in from the probe's atmosphere during transit, has so far frustrated attempts to place a practical upper limit on the concentration of water vapor from U.S. data. One is needed in order to see if the greenhouse effect alone can account for Venus's high temperature. Hydrocarbons of many sorts showed up in the initial evaluation, but, as with ground-based instruments, most of them can be attributed to lingering residues from components of the instrument. Even the measurement of true atmospheric components by mass spectrometers is not unambiguous, allowances being required for the contribution of larger molecules that split into pieces during analysis and add to the amount observed of another smaller compound. The actual amount of oxygen must, for example, be separated from the uncertain contribution from carbon dioxide.

The American mass spectrometer team has not been alone in its labors to decipher data from Venus. Soviet scientists have not yet released data on several of the reactive gases from their Venera 11 and 12 Venus probes of last December, although values for inert gases have been reported. American specialists surmise that the reactive gases may have been entrapped on the surface of the stainless steel sampling tube that protruded from the Soviet probe.

Despite the difficulties, mass spectrometer analysis of planetary atmospheres appears to be the only practicable means of acquiring some of the data essential to the central goals of the space program—understanding the origin and evolution of the solar system, the origin of life, and in turn Earth itself. Early attempts by Soviet researchers to use "Lavoisier chemistry" to measure individual gases one at a time pointed out the great difficulties with that approach. A gas chromatograph, the usual complement to a mass spectrometer, can measure many atmospheric constituents, but only a mass spectrometer can measure isotopic ratios, which provide a powerful tool in the study of the early solar system and planetary evolution.

A mass spectrometer will be on the next American atmospheric probe, the Galileo mission to Jupiter, where the conditions will be quite different but no less challenging. No gas chromatograph will be aboard because of weight limitations, much to the consternation of some planetary scientists. In the aftermath of Pioneer Venus, redoubled precautions are being taken against the large amounts of reactive hydrogen and inert helium and the presence of small particles in Jupiter's atmosphere. The success of the analyses, which are unlikely to be repeated for decades, may depend on how well researchers can allow for the unexpected.—R.A.K.



Topographic map of the Venusian surface superimposed on a radar image of the Terra Ishtar region. Both are based on Pioneer Venus data. The closer the contour lines, the steeper the slope. Sharp slopes mark the southern edge, and high mountains are to the west of the 3-kilometer-high plateau. Numbers refer to the height above an arbitrary elevation. [Source: National Aeronautics and Space Administration]

ocean basins, however, which are a direct result of plate tectonics, account for 70 percent of its surface.

"There's no question that Venus is geologically active," Masursky says, "but we don't see, at least to this point, any of the features that should be there if there were active plate tectonics. Maybe Venus is dominated by vertical tectonics." If so, Venus might be a tough place to figure out. Most vertical movements of Earth's crust, such as mountain building and the formation of ocean basins, fit nicely with the horizontal movement of crustal plates. Some features, though, such as the Michigan Basin and the Colorado Plateau, have resisted any plate tectonic explanation, leaving their origins enigmatic. Malin of Arizona State suggests that most of Venus's surface features may result from modified, "sticky" plate tectonics rather than from purely vertical tectonic forces. According to this idea, the rocks of Venus's mantle, beneath the visible crust, could be more viscous or "sticky" because of a relatively low water content. If the mantle slowly circulates beneath the Venusian crust, as it is thought to do on Earth, its greater viscosity might lead to different shapes in Venus's crust than on Earth.

So far, it seems that whatever style of tectonics prevails on Venus, it has been fairly efficient in destroying the craters formed by the impact of large meteorites since the formation of the solar system. "There are few, very few, features that Pioneer Venus has seen that I would want to call impact craters for sure," says Pettengill. Although ground-based radar data support the scarcity of craters compared to their abundance on the moon, Mercury, or Mars, Venusian craters are peculiarly difficult to detect in elevation data. Being tens or even hundreds of kilometers across and only 200 to 700 meters deep, many might elude the 20- to 30-kilometer horizontal resolution and 200-meter vertical accuracy of the orbiter's radar. Their extreme shallowness, "as if a rock were dropped into chocolate pudding" as one researcher puts it, may be due to the softening of the crust by the 400°C surface temperature.

Compared with more readily observable planets, detailed interpretations of Venus's surface features will require the continued close cooperation of scientists using both spacecraft and Earth-based data. First impressions could be changed, but a clearer look from a spacecraft must await the Venus Orbiter Imaging Radar (VOIR), a project with an uncertain future.

Unlike the study of Venus's surface, the study of some aspects of its atmosphere has been stymied by insufficient or irreconcilable data. The 360-kilometer-per-hour winds that carry the cloud tops around the entire planet in 4 days have fascinated researchers for years, but the dozen U.S. and Soviet probes that have penetrated the atmosphere and thousands of U.S. cloud photographs have not revealed what drives the winds. Pioneer scientists believe that the driving forces involve the winds that blow from the equator toward the poles and winds in the form of eddies, but both of these are so slow that they have not been detected yet. In fact, no winds in any direction have been reliably detected below an altitude of 10 kilometers, where 50 percent of the atmosphere's mass lies. The best guess at the moment is that two conveyor-like patterns of circulation, called Hadley cells, slowly carry hot air from the equator toward the poles and back. The cells, one above the other, appear to be kept entirely separate by a stable layer just below the cloud layer.

Why there are cloud layers, what they are made of besides sulfuric acid, and how they affect the chemistry of the atmosphere below them also remain unknown. The analysis of trace components of the atmosphere by the mass spectrometer ran into considerable problems (see box), and the gas chromatograph provided data that upset previous explanations of how sulfur cycles through the clouds and atmosphere. Carbonyl sulfide has been replaced by sulfur dioxide as the principle gaseous compound of sulfur in the atmosphere, but no reasonable process has been found to explain its low concentration just above the clouds.

Perhaps the most perplexing of the atmospheric problems lingering after Pioneer is the 460°C temperature at the bottom of the atmosphere. The much ballyhooed greenhouse effect of Venus's carbon dioxide atmosphere can account for only part of the heating, and evidence for other heating mechanisms is now in a turmoil. The question concerns how the sun's energy behaves once it penetrates the highest clouds. When Pioneer Venus's probes looked at the amount of radiant energy passing through the atmosphere, each one found more energy being radiated up from the lower atmosphere than enters it as sunlight. At first blush, it would seem that the atmosphere violates the laws of thermodynamics by transferring heat energy from the cool clouds to the hot lower atmosphere, from which it is then radiated. To further complicate the situation, the size of the apparent upward flow of energy varies from place to place by a factor of 2, which was a disturbing discovery about a planet thought to be relatively uniform.

Possible explanations for this apparent quandary cover a range of speculations. Problems with the instruments are still an issue, but a year of recalibration and analysis in the laboratory has revealed significant errors in only one of the three types of instruments involved. A 10-year-old suggestion that heat could be "convected" downward (opposite the usual direction) would not be sufficient to account for the discrepancy, according to calculations by Andrew Ingersoll of the California Institute of Technology.

A real variability from place to place in the effectiveness of the greenhouse must also be considered a possibility, says Martin Tomasko of the University of Arizona. A greenhouse that uses water vapor to trap the heat energy leaking past the carbon dioxide might be sufficient to account for the high temperature and the observed variability, Tomasko says, if the amount of water vapor varies around the planet. In that case, the probes may not have sampled enough different places to determine a proper global average.

One of the most speculative ideas to date comes from Yuk Yung of Caltech, who suggests that energy might reach the lower atmosphere in the form of high-energy chemical compounds rather than as sunlight or heat. Such compounds, formed in the high atmosphere by interaction with sunlight, could drift downward and release heat when they decompose. No detailed calculations have been made by anyone for a "chemical greenhouse" but there are a few hints that such a process may not be so farfetched. The anomalous faint "glow" in the lower atmosphere, first reported as the "fiery glow of a Venusian hell" by some reporters, is still unexplained, according to Boris Ragent of NASA Ames Research Center. And Soviet reports of lightning, a possible energy source for chemical reactions, are apparently being confirmed by sensors on the Pioneer orbiter, according to Frederick Scarf of TRW, Inc., in Redondo Beach.

A more conventional explanation for the missing source of heat, though not of the apparent anomalies in the lower atmosphere, is a greenhouse effect involving four factors, according to Pollack. Drawing on the Pioneer data, he calculates that the trapping of infrared energy by carbon dioxide, water vapor, sulfur dioxide, and the clouds would produce temperatures "in the same ballpark as those observed."

In spite of the onslaught of American and Soviet missions to Venus, Earth's "sister planet" still clings to much of her mystery. Further analysis of the Pioneer data during the next year should help, but some areas, such as the circulation of the lower atmosphere, will remain obscure. The next major step will probably be the Soviet attempt to fly an instrument-laden balloon in Venus's upper atmosphere in 1984.

—RICHARD A. KERR

Venus and Science's Fringe

The planet Venus is the pivotal object in the grandest catastrophe theory of them all. Immanuel Velikovsky, who died at the age of 84 last 17 November, envisioned Venus as an awe-inspiring vagabond of the solar system. Ripped from the core of Jupiter more than 2600 years ago, the comet-like Venus caused havoc in the inner solar system as it careened by Earth before finally settling down in its present orbit. According to Velikovsky and his supporters, Venus still bears vestiges of its fiery origin and subsequent travels.

Spacecraft missions to the planets have provided new but not always convincing arguments for the supporters of Velikovsky in their sometimes heated exchanges with establishment science. The Pioneer Venus mission is no exception, but the defenders of the fringe may actually be in a smaller corner than before Pioneer.

The inability of scientists to find a complete, conventional explanation for the high temperature of Venus's atmosphere (see story), would seem to leave an opening for Velikovsky supporters. Because of its origin in the core of Jupiter (where scientists believe the temperature to be 20,000°C) Venus is a source of heat, according to Velikovsky. He wrote in 1967 that the ashen light, a brightening of the dark side of Venus sometimes seen from Earth, "seems more properly to be incandescence glowing through the [cloud] envelope." He also suggested that "its body was all molten or plastic not so long ago." Current reports of an apparent flow of heat up from the surface into the lower atmosphere might soon be used to support such a thesis, but observations from the Pioneer orbiter suggest that the planet as a whole is not acting like a radiator.

The orbiter instrument measuring the absorption and radiation of energy by the planet has not found that Venus is losing any more heat than it is absorbing from the sun. Although the precision of the measurements (± 15 percent) is not yet as great as it will be, Frederic Taylor of the Jet Propulsion Laboratory in Pasadena believes that there is little room left, if any, for a source of heat on Venus.

Velikovsky assumed for various reasons that "Venus must be rich in petroleum gases. . . . Venus must have hydrocarbons and carbohydrates in its clouds." Supporters claimed that early reports of possible high levels of methane in the Venusian atmosphere substantiated the Velikovsky prediction, but Pioneer team members now assume that the methane was mostly in the mass spectrometer, not in Venus's atmosphere. A duplicate instrument in a methane-free atmosphere in the laboratory also saw large amounts of methane, apparently because methane used as a calibration gas was recycled through the instrument. Between the gas chromatograph and the mass spectrometer, the only hydrocarbon detected in the atmosphere was ethane at a concentration of a few parts per million. Even when the mass spectrometer sucked in a cloud droplet, no petroleum hydrocarbons or carbohydrates appeared.

The picture of Venus as a planet of mountains, broad craters, expansive plateaus, and towering volcanoes, which is being supported by the orbiter's radar mapper, is receiving less attention than heat and hydrocarbons. David Morrison of the University of Hawaii has suggested that all of these features indicate that Venus's crust was not recently molten or plastic but is rigid. Harold Masursky of the U.S. Geological Survey in Flagstaff has also suggested that at least some parts of the crust are very old because it would have taken millions of years to accumulate the large craters already tentatively identified.

Although numerous counterarguments will undoubtedly be made to these establishment interpretations of the Pioneer Venus data, few converts to the fringe position are likely. In the long run, the number of converts is probably the best measure of the power of the catastrophists' arguments. During less than a decade, the once-ridiculed idea of moving continents won over nearly the entire earth science community. After 18 years of spacecraft studies of Venus, the fringe still stands alone.—R.A.K.